Geothermal Exploration in Kenya

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ABSTRACT

There are three geothermal areas in Kenya, all located in the Rift Valley, which runs north-south about 50 miles west of Nairobi. Two exploration holes were drilled during 1957–58 in the Olkaria area south of Lake Naivasha but failed to produce the expected results. Toward the end of the 1960s interest revived in further work and in 1970 an exploration project was started, financed jointly by the United Nations Development Programme and the E. A. Power & Lighting Co. Limited. Extensive geological, hydrogeological, geophysical, and chemical field surveys were carried out in the three geothermal areas, and considerable effort was directed toward bringing into production one of the original exploration holes in Olkaria. This was eventually achieved, although the output was small and cyclic.

The final phase of the joint UNDP/EAPL project was the drilling of four further exploration holes, one to a depth of 1003 m and three to 1350 m at Olkaria which have demonstrated that considerable geothermal resources exist in a reservoir below 600 m. Early test results suggest the presence of dry steam, as the wells have a shut-in pressure of 35 bars, but output is restricted by poor permeability. Further well testing and exploration drilling is planned before the installation of a turbine generator plant.

INTRODUCTION

There are a number of areas in the Rift Valley which have active surface geothermal manifestations, but only three of these have been surveyed—Lake Hannington, Eburru, and Olkaria (Fig. 1). Around the shores of Lake Hannington there are a number of hot and boiling springs and some fumaroles, but geothermal activity in the other two areas is confined mainly to widespread fumaroles, which have often been used to supply the local population with water by condensing the steam in sloping galvanized pipes and collecting condensate at the lower end. Steam from a shallow well is also used at Eburru as a source of heat for drying pyrethrum flowers.

Kenya has no natural fuel resources in the form of coal or oil. The rivers have highly seasonal flow patterns, which make their exploitation for hydropower generation expensive. The attraction of a large source of geothermal power available relatively close to the main electrical load center, Nairobi, is therefore very great. Early in the 1950s a consortium of companies, which included the E. A. Power & Lighting Company, was formed to carry out exploration drilling. At that time Lake Hannington was in a closed area and provision of suitable access roads would have been very expensive. With no suitable source of water supply at Eburru for drilling purposes and with only limited funds available it was decided to drill at Olkaria (Fig. 2).

EARLY EXPLORATION

A hole designated X-1 was started in May 1956 using a percussion rig, and reference to the drilling reports by D. L. Marriott shows that progress was slow due to continual

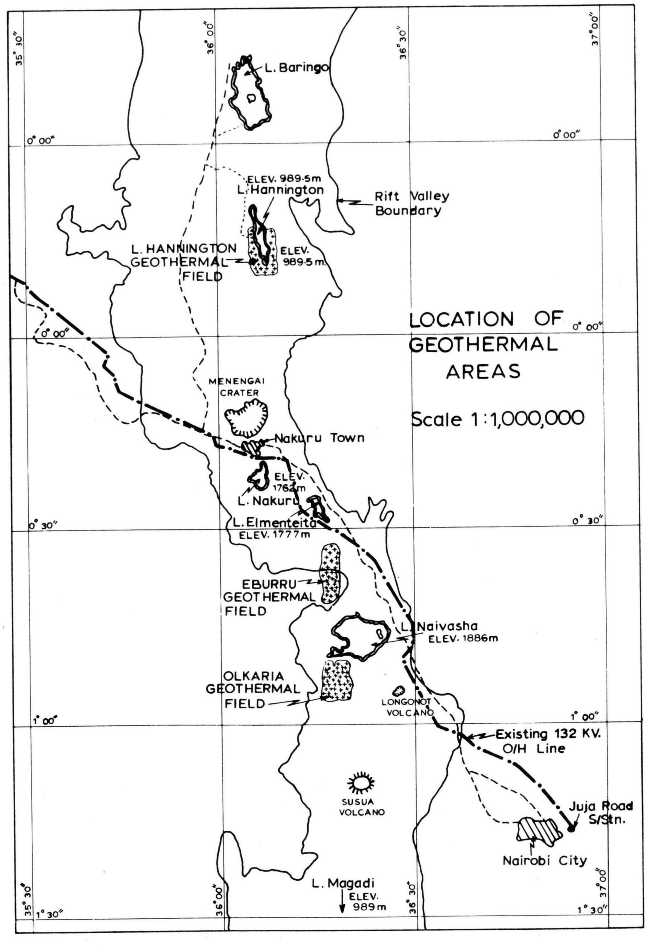

Figure 1. Location of geothermal areas.

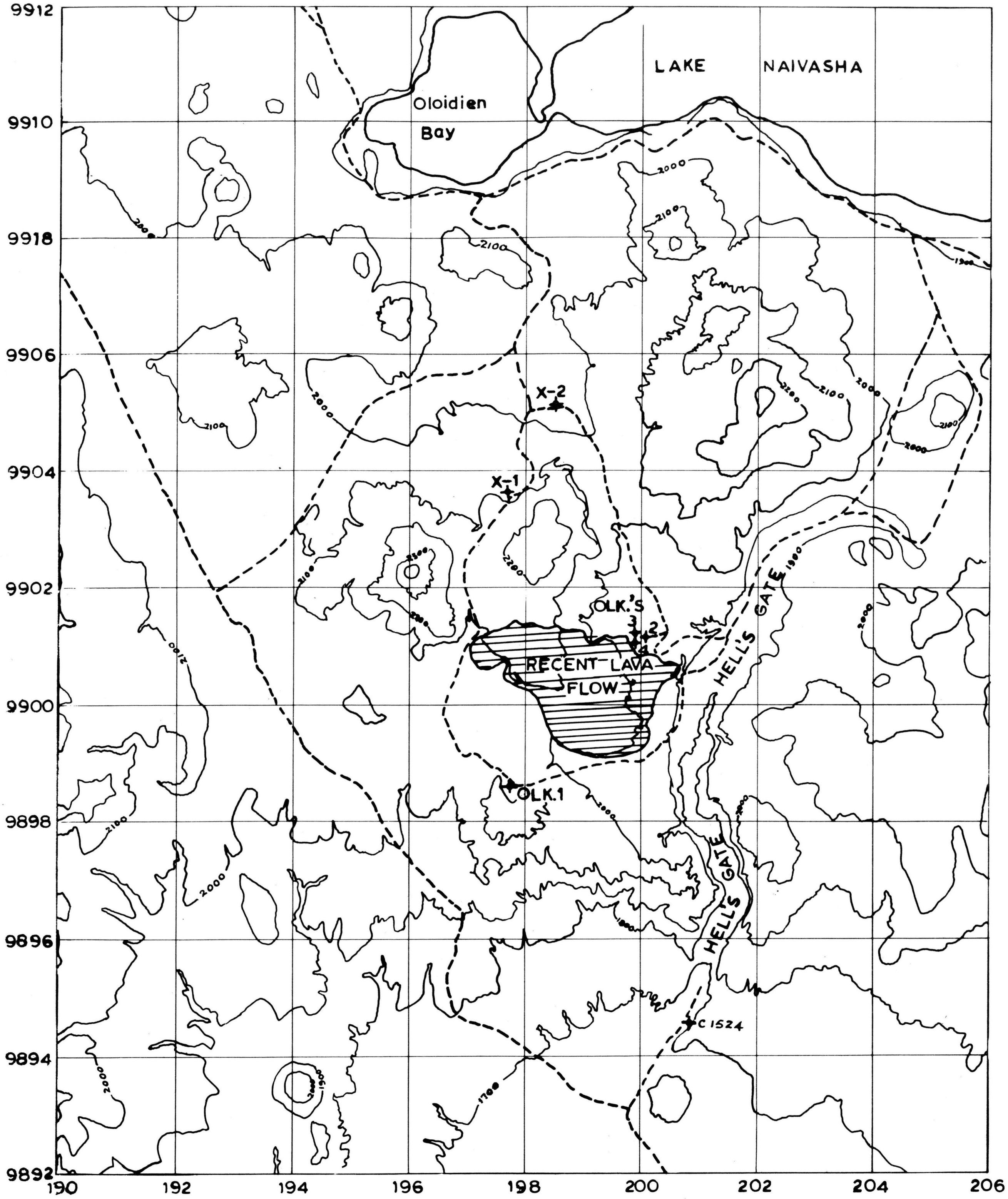

Figure 2. Map of Olkaria area.

loss of circulation, caving formations, and drilling mishaps. Frequently drilling was delayed by lack of water which had to be pumped through a 2-1/2 in. line some 6 km long with a total lift of just over 200 m to the drill site. On a number of occasions dry steam at low pressure blew from the hole, notably at 380 m, but this was then cased off.

Three strings of casing, 12-1/4, 8-5/8, and 6 in. were run into the hole. At a depth of 380 m, below the 6 in. casing, drilling continued at 5-1/8 in. diam with a rotary rig. Temperatures recorded during the percussion drilling reached 120°C at 370 m, but were less than this during the rotary drilling. Hole X-1 was eventually abandoned at a depth of 502 m in January 1958. Before this, however, work with the percussion rig had started in August 1957 on a second hole, designated X-2, some 2 km north of X-1 at an elevation of 1975 m, and drilling was generally more rapid than at

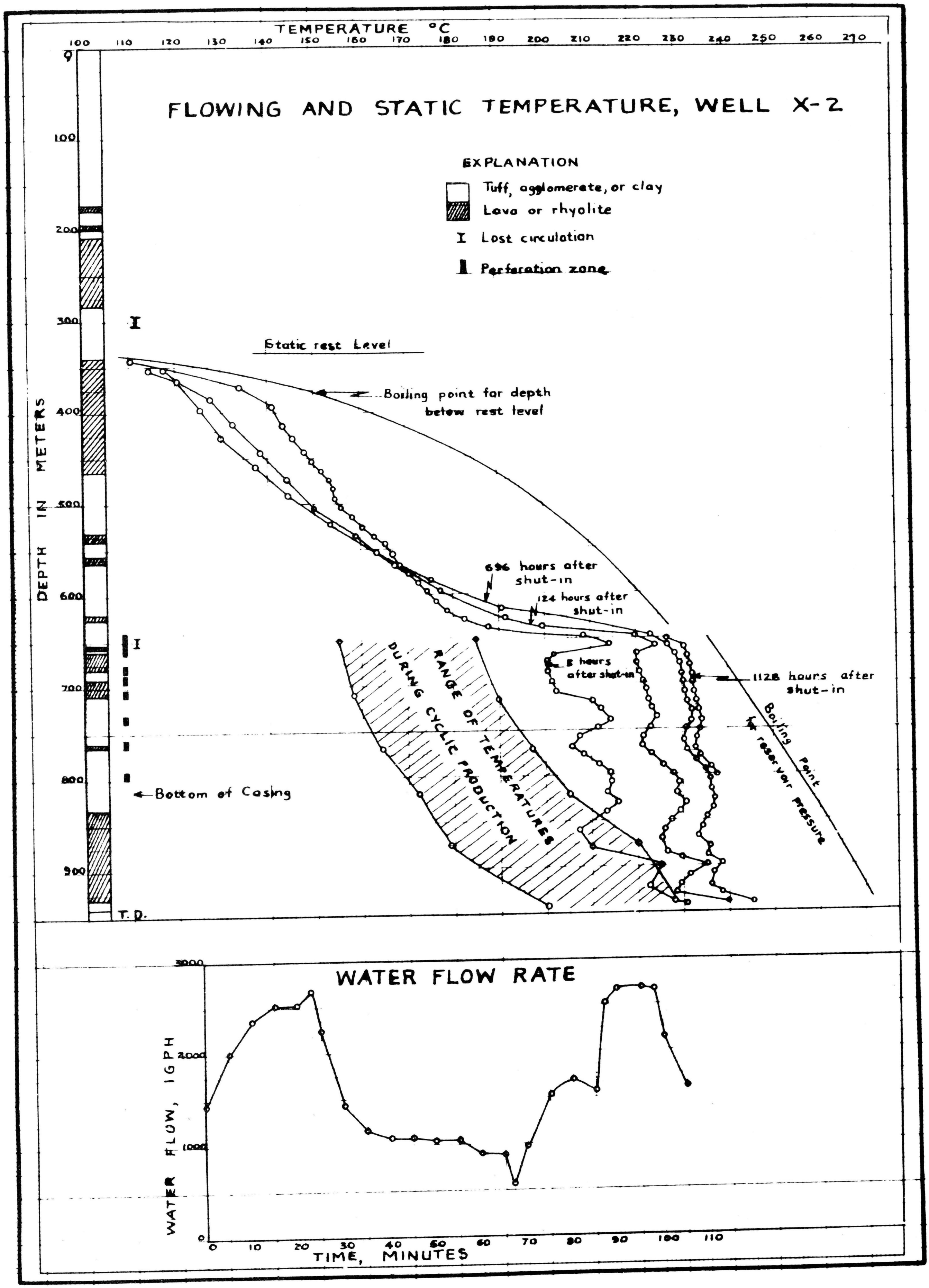

Figure 3. Flowing and static temperature, Well X-2.

X-1. Rotary drilling started after a 12 in. casing was set to 54 m and an 8-3/4 in. casing to 200 m. Progress was delayed again due to loss of circulation and various drilling mishaps, but a depth of 942 m was reached in July 1958. A perched water zone between 55 m and 170 m was cased off but it was thought the cementing of the casing here was poor and that there was a continual leakage of cold water down the annulus between hole and casing into the much hotter zone lower down, where there is a second water reservoir with a rest level of 342 m. After X-2 had been drilled to 942 m, several attempts to bring it into production by air-lifting were made. None of these efforts were successful, however, and work was eventually stopped in March 1959. Details of X-2 and temperatures measured much later are shown in Figure 3.

FURTHER EXPLORATION

Following the abandonment of X-2, interest in further geothermal exploration work during the early 1960s was very low and plans were made to harness the Tana River for hydropower. However, in view of the very high capital costs involved, interest was revived in further geothermal work, and in 1967 a Wenner configuration resistivity survey was carried out in the Rift Valley between Lake Hannington in the north and Olkaria in the south. This survey showed a number of resistivity anomalies and recommended exploration drilling. Eventually a request was made in 1969 by the Kenya government to the United Nations for assistance in financing a much larger exploration program. It was originally intended that work should be concentrated in the Lake Hannington area, but it was later decided to include all three geothermal areas, Olkaria, Eburru, and Lake Hannington.

A project to be jointly financed by the UNDP and the EAPL (which were acting as the Kenya government's agents) was agreed upon, in which the United Nations undertook to supply experts in various specialized fields, and the EAPL provided local counterpart staff to be trained during the course of the project. The UN also financed contracts involving "offshore" expenditure while the EAPL provided all local support staff and the necessary services. At the end of 1970, a start was made and field work was carried out during 1971 and 1972. Drilling of four exploration holes began in the second half of 1973 and was completed at the end of 1974.

GEOTHERMAL EXPLORATION PROGRAM

The following work was proposed for the new project:

1. Preparation of good quality topographical maps.
2. A comprehensive geological survey of the geothermal areas.
3. An infrared imagery survey of three prospects, together with one meter depth ground temperature measurements.
4. Comprehensive resistivity surveys of the three areas.
5. Investigations of gravity anomalies.
6. A microearthquake survey.
7. Hydrogeologic and geochemical surveys.
8. Further work on the two original exploration wells X-1 and X-2.
9. Drilling of four deep exploration holes to be sited after detailed consideration of the work carried out during the first half of the project.
10. A feasibility study giving an accurate assessment of reservoir potential and outline design and cost of an initial geothermal power plant.

Geological Surveys

Detailed geological mapping was carried out in the three areas. The aims were to (1) locate geological formations, structures, and fault patterns which control the occurrence of geothermal reservoirs; and (2) identify potential reservoir formations.

Mapping was initially done by studying air-photographs (1:25 000) and marking on them all the determinable geologic structures such as faults, volcanic cones, young lava flows, explosion craters, steaming, or altered areas. These were later confirmed by field mapping. About 50 field days were spent mapping an area of about 560 sq km around Lake Hannington between April 1971 and the second week of July 1971. For Olkaria and Eburru an area of 800 sq km was covered within about 100 field days between August 1971 and the middle of March 1972 (Naylor, 1971; 1972, unpub. data).

Lake Hannington. The Hannington area is mainly covered by intermediate to basic lavas with associated sediments and pyroclastics of Tertiary to Quarternary periods. The oldest, the Samburu basalts of Miocene age (K-Ar dating gives 14 to 23 million years), are believed to have possible aquifers where they are faulted and fractured. These are uncomformably overlain by Rimuruti phonolites. Late outpourings were mainly trachytes and trachyphonolites. These rocks occur on both sides of the scarp and give an accurate measure of the displacement, some 700 to 800 m during the main period of faulting which followed their eruption.

Geothermal activity is represented by steam jets and boiling springs centered in the southeastern corner of the lake and on the peninsula, boiling springs along the southern end of the western lake shore, and scattered warm springs.

Eburru. In the Eburru areas, the oldest rocks are the Gilgil trachytes of lower middle Pleistocene which outcrop south of Gilgil in the north-south faults. These were followed by centers of trachytic volcanism composed of pumice and welded tuffs. These have been correlated with the pumiceous pyroclastics of the Waterloo ridge on the eastern side of Eburru.

The small ridges of coalescing pumice cones south of Eburru and the vents of obsidian flows on the summit and northern flanks of the Eburru area are a result of the north-south faulting/fracturing system. Related to this late upsurge of magma is a phase of phreatic explosive activity centered on the summit and northern slopes, leaving a complex of craters over the area. Young basaltic flows to the north of Eburru show no faulting, indicating the decline of tectonic activity. During this time, the youngest obsidian flows on the south of the Eburru mountain were extruded and although they are along the faults and fractures, they are not faulted. The Eburru fracture zone shows the greatest faulting and associated geothermal phenomena in the area. The hydrothermal activity is situated on the west of the main fracture in a graben within which the craters are aligned on east-west lineations. At Olkaria, the activity is on the east of the main fracture. Geothermal activity in the Eburru area consists of fumaroles and other steaming grounds.

Olkaria. Early eruptions in the Olkaria area are composed of vent comenditic flows followed by large quantities of pumiceous pyroclastics exposed in Ol Njorowa Gorge as flat bedded tuffs. The same tuffs are found on the southwest part of the area and on the Mau escarpment. These were later cut by the north-south fracture zone along which pumice cones and interbedded lavas erupted.

Extrusion of rhyolitic domes, comenditic flows in north Hell's Gate, and emplacement of dikes in Hell's Gate-Ol Njorowa Gorge are related to this phase of fracturing. However, flows of pumiceous obsidians from Olkaria and other nearby centers cover the faults and are thus younger.

The latest volcanicity is along the north-south Ololbutot fracture. During this phase, white ash and pumice erupted, followed by an upsurge of a magma body, forming a line of phreatic explosion vents along the fracture. The final eruption of this was the recent Ololbutot flow of pumiceous obsidian.

It was, however, difficult to distinguish marker horizons in the Eburru-Olkaria areas and thus stratigraphic correlation was not easy. Consequently, it was not possible to draw geologic sections for these two areas except the geologic logs of the four Olkaria series wells (Figs. 4, 5, 6, 7, and 8). These are general in that only a binocular microscope was used to identify the cuttings.

Geothermal manifestations in Olkaria are predominantly in the form of fumaroles and steam vents except for two warm springs in the upper part of Ol Njorowa Gorge. They are in linear pattern following the fracture fault lines.

Infrared Survey

Early in the project a survey was carried out using aerial infrared imagery, the purpose of which was to locate hot spots on the ground whose existence may not previously have been known due to difficulties of rough terrain and poor access. At Lake Hannington the infrared survey confirmed the location of hot springs which were already known from field mapping, while at Eburru and Olkaria, the IR survey was successful in locating hot ground areas, many of which were formerly unknown. Some of these were later surveyed on the ground by measuring their ground temperatures, and there was over 90% success that hot grounds shown in IR photos had ground temperatures above ambient (Figs. 9 and 10). At Olkaria, the hot ground areas correlated well with the main north-south fault system and the phreatic

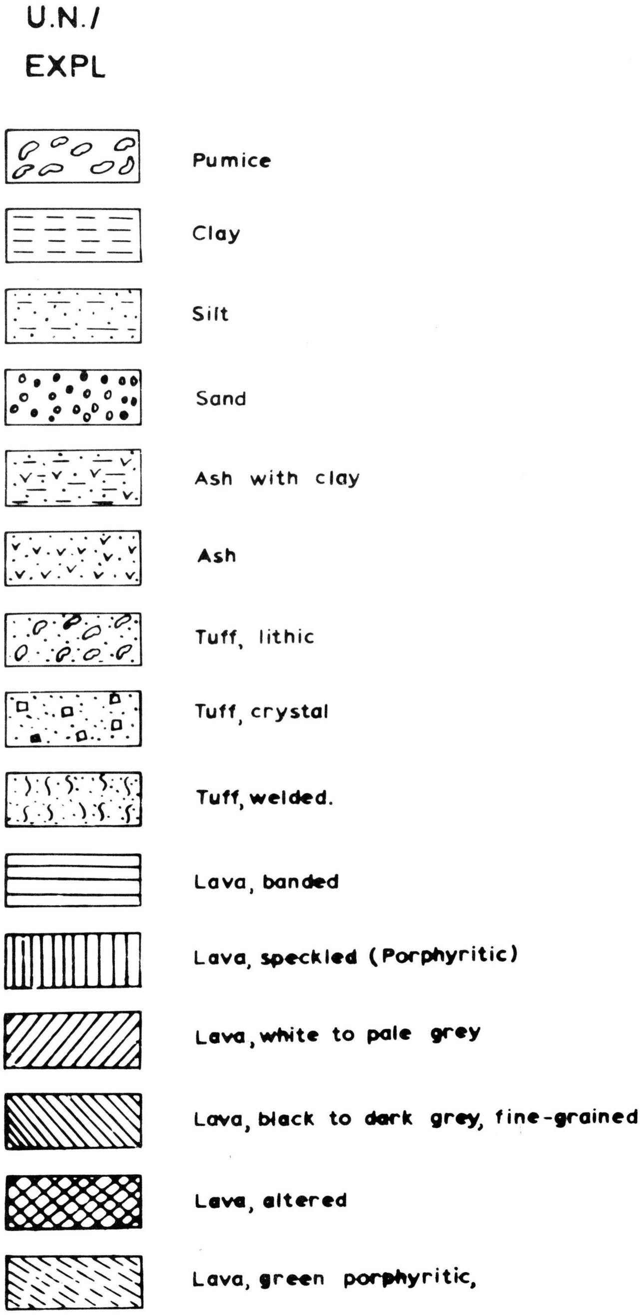

Figure 4. UN/E.A. Power & Lighting geothermal project, explanation for geologic column for Olkaria well series.

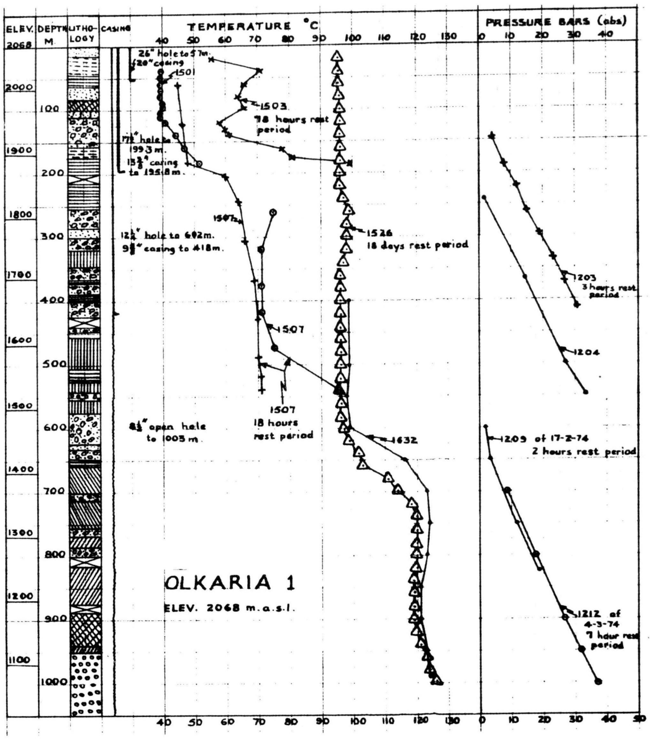

Figure 5. Olkaria 1: Downhole measurements plot.

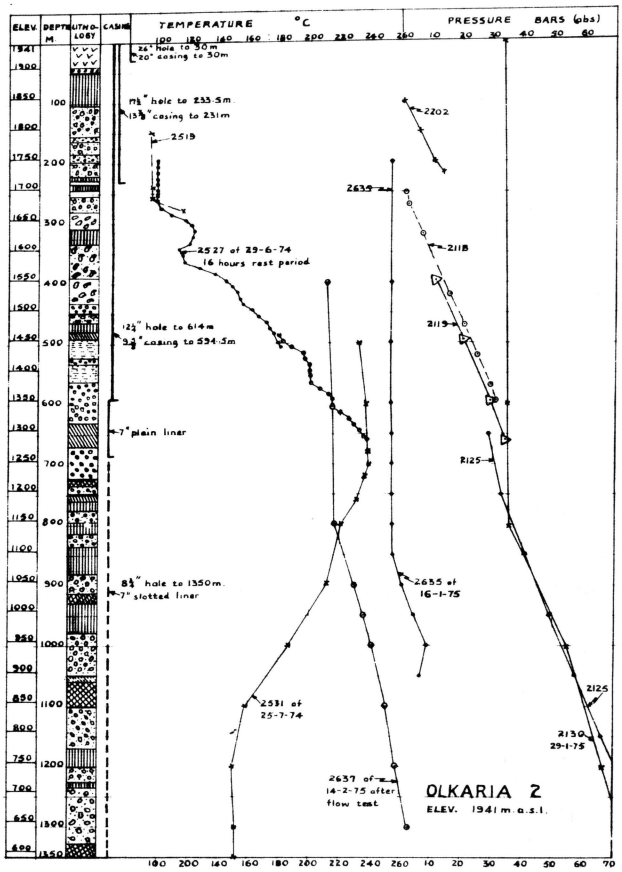

Figure 6. Olkaria 2: Downhole measurements plot.

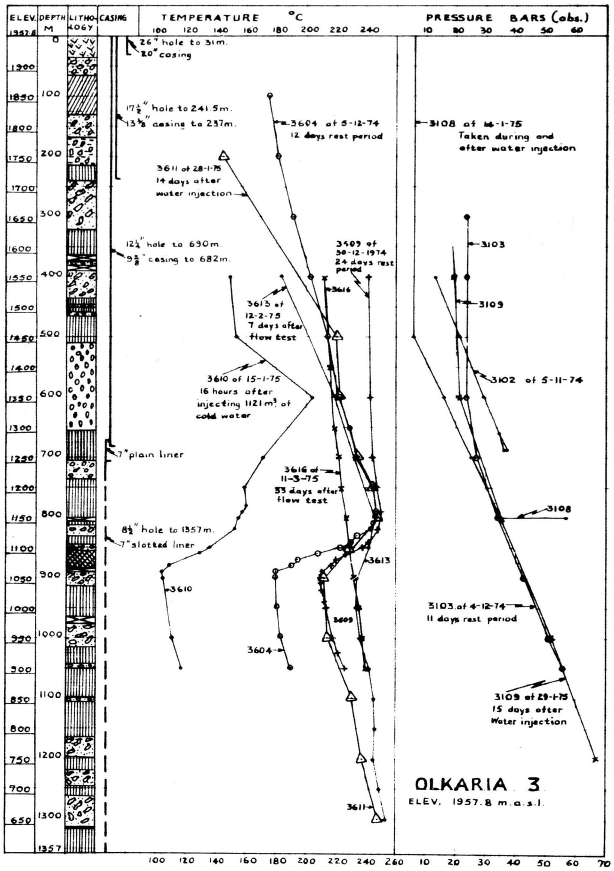

Figure 7. Olkaria 3: Downhole measurements plot.

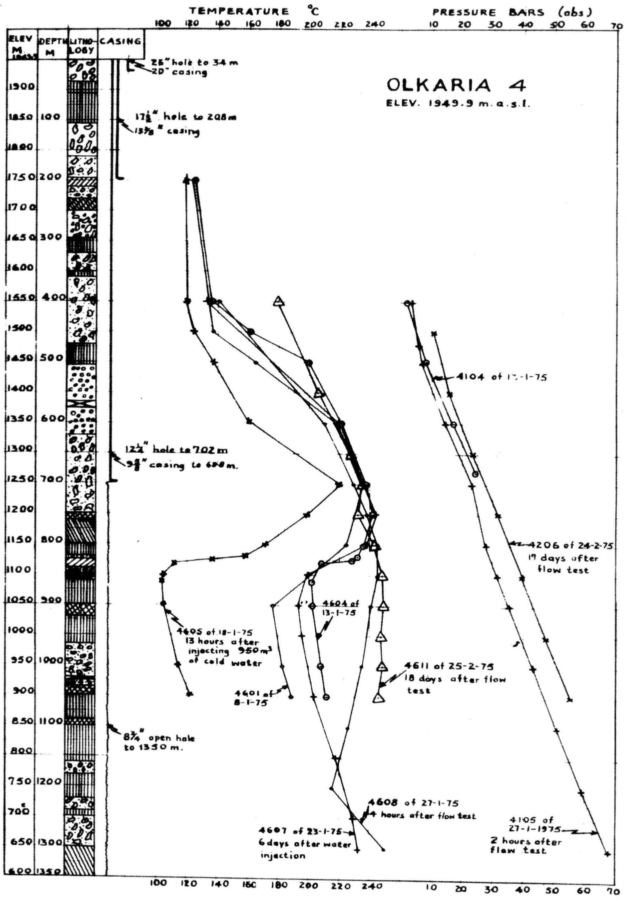

Figure 8. Olkaria 4: Downhole measurements plot.

explosion craters mentioned above. It is believed that this trend reflects a fault along which steam issues.

Ground temperature survey. The 1 m depth temperature surveys were conducted at Lake Hannington and at Olkaria (Fig. 11). In addition, lake bottom temperatures were measured at Lake Hannington. The 1 m depth temperatures were taken on the western side of the lake around the Kiboriit hot springs area. Temperature highs, as expected, were found around the springs, but also a linear pattern parallel to the main structural trend was discovered. The northern one correlates well with the main northward projection of a west-facing normal fault cutting outcropping lavas about 500 m to the south. The lake bottom temperature anomalies also correspond to the discharge areas from the known hot springs of Mwanasis Peninsula.

At Olkaria, the 1 m depth temperature survey reveals north-south-trending hot areas intersected to the south and north of Ololbutot recent lava flow by northwest-southeast-trending lines. These confirm, perhaps more than the geology, the faulting systems in these directions. It is on the basis of this survey, chemistry, and the axial dipole survey that most of the Olkaria series wells have been sited.

Resistivity Surveys

A direct current dipole resistivity survey was performed by Group Seven, Inc. of the USA with the aim of detecting low resistivity vertical boundaries which are likely to mark

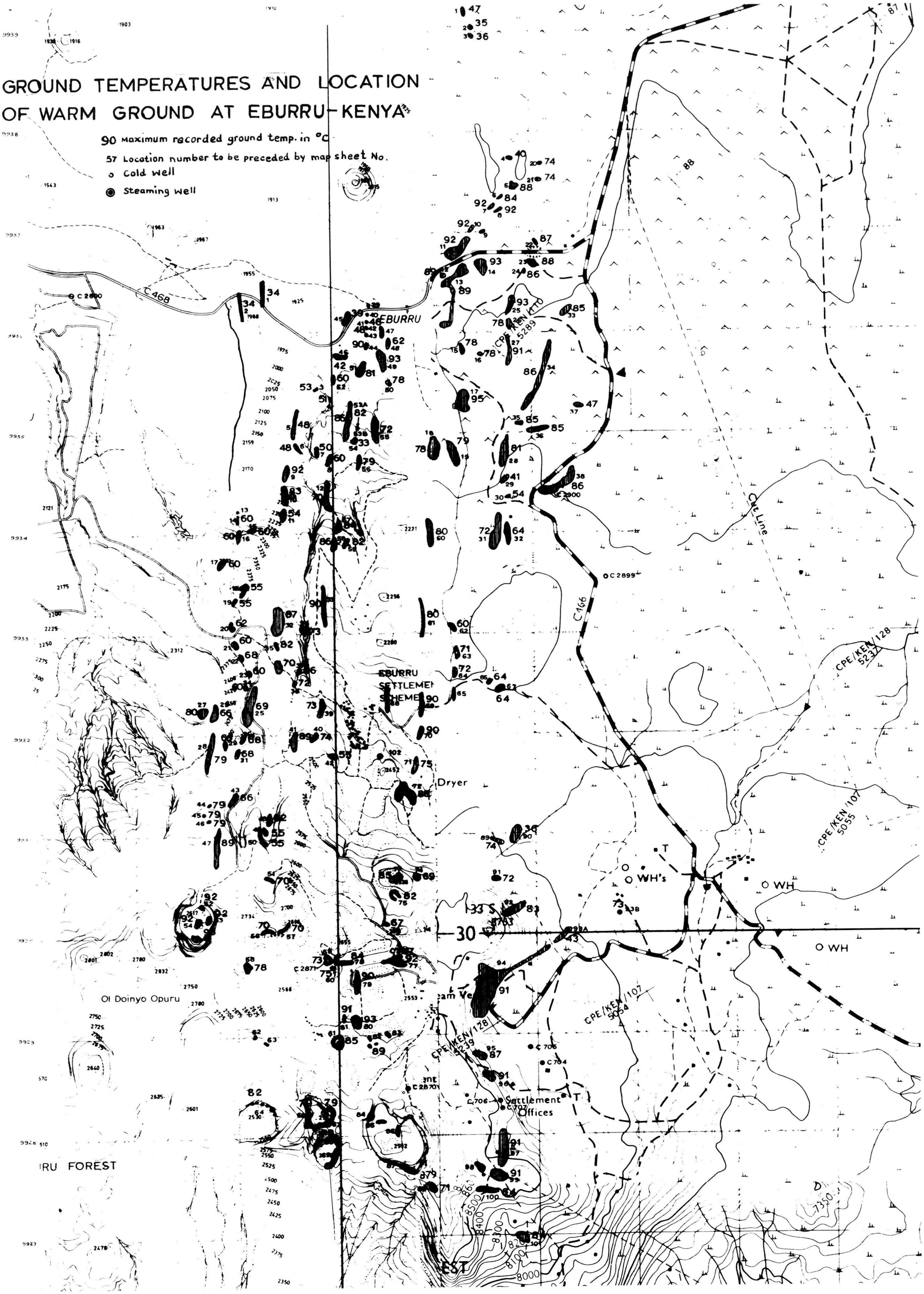

Figure 9. Ground temperatures and location of warm ground at Eburru, Kenya.

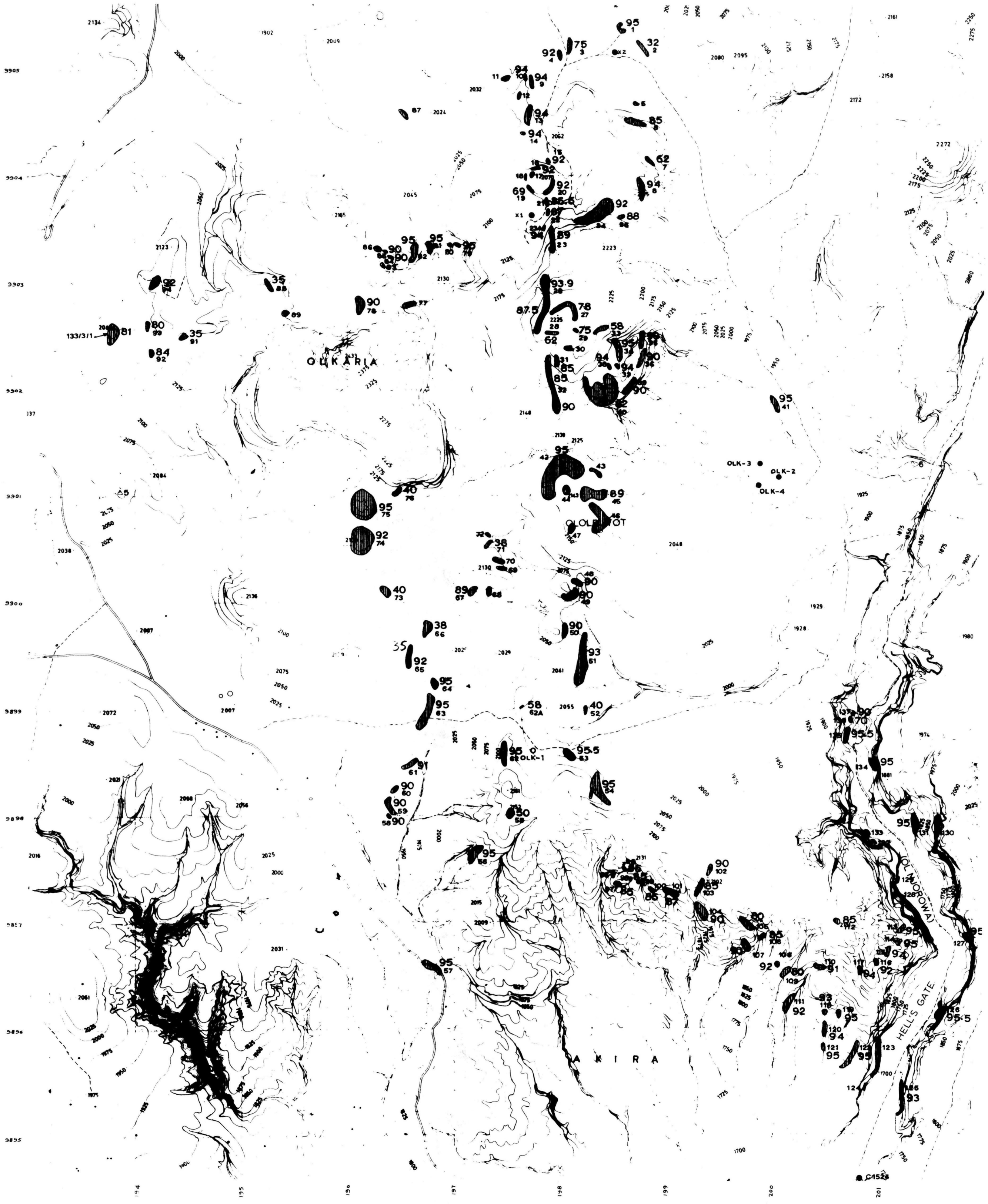

Figure 10. Ground temperatures and location of warm ground at Olkaria.

the lateral boundaries of geothermal reservoirs. Since this method does not show the variation of resistivity with depth, it was augmented by DC Schlumberger soundings and electromagnetic (EM) soundings.

The dipole mapping involved developing a current field in the earth by passing about 30 A of current between two electrode contacts separated by about 2 km. The voltage drop is measured between closely spaced pairs of electrodes at distances up to 10 km from the dipole sources. Eight dipole sources were used to map the three prospect areas,

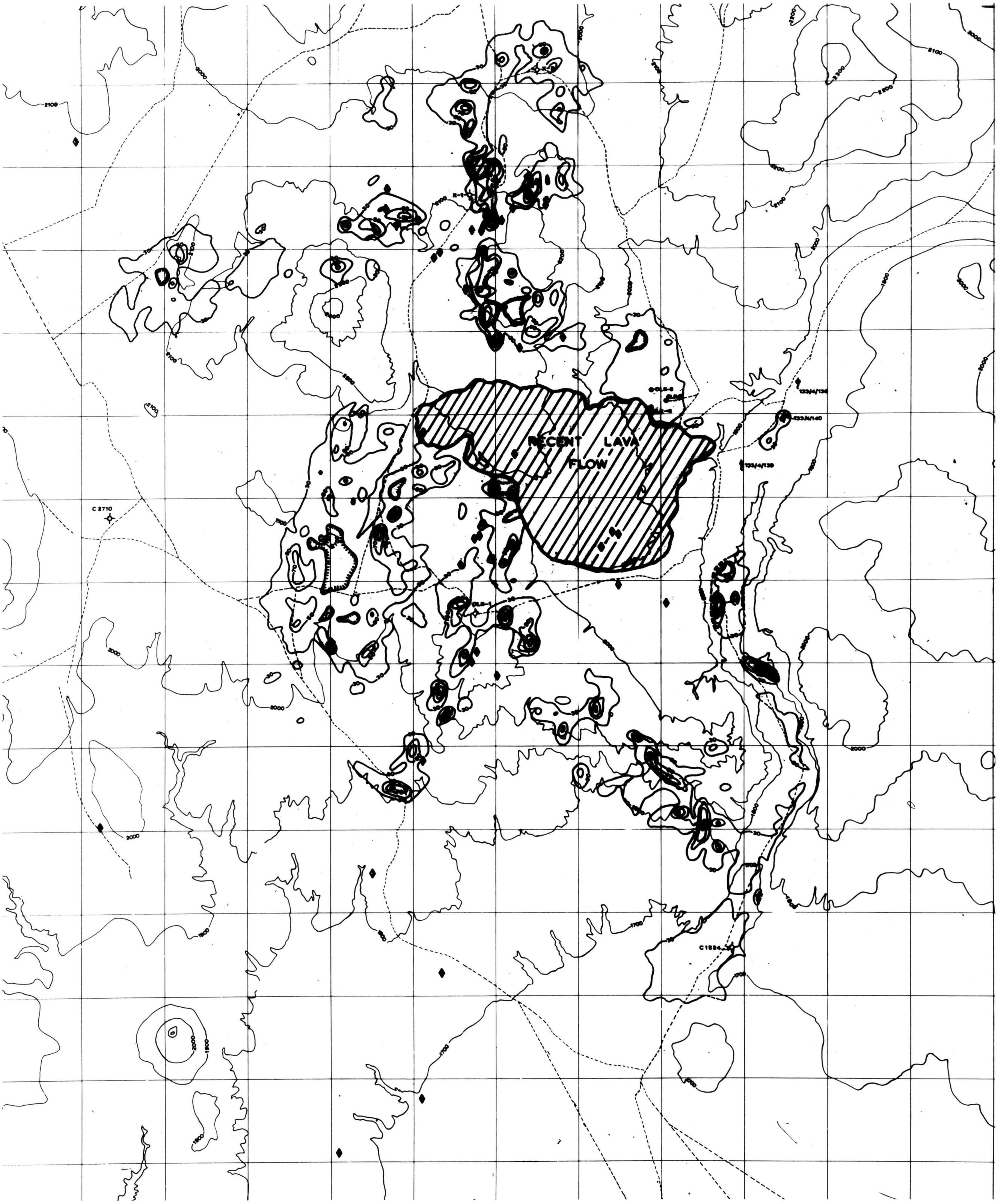

Figure 11. Olkaria ground temperatures at 1 m depth and microearthquake locations.

three each at Hannington and Olkaria and two at Eburru.

Interpretation of the results presented some difficulties. However, at Hannington, the survey showed an area of high conductance, 2500 mhos over about 5 sq km in the center of the lake. High resistivity anomalies were found on the east and west of the lake in areas of surface thermal activity. Schlumberger depth soundings corroborated the above results.

At Eburru and Olkaria, the survey discovered high conductance areas north of Eburru and toward the Mau escarpment while high resistivities were obtained in the known hot ground areas. Low resistivities on the margins of the known geothermal field have been interpreted as being due to lateral lithologic changes. The high resistivity in the hot areas could be due to dry steam saturating the strata to great depths. However, this has not been corroborated by axial dipole surveys in the Olkaria area although Group Seven's EM and Schlumberger depth soundings conformed with their dipole survey. On the whole, difficulties in interpreting dipole results did not render it as useful as it was originally hoped.

Schlumberger traverses were conducted in the three areas with half-current electrode separation of up to 2.7 km $\left(\frac{AB}{2} = 2700 \text{ m}\right)$. The aim was to detect low resistivity horizons with depth and lateral changes in the resistivity as a check on the dipole survey results.

Perhaps the most useful geophysical method so far used has been the axial dipole survey suggested by T. Meidav. This has been conducted at Olkaria and 24 traverse lines have been measured. From the resistivity measurements, a map of resistivity values at depths between 800 m and 1000 m has been constructed (Fig. 12). Five large low resistivity areas (less than 20 ohm · m) have been mapped with three others of less significance. The largest of these is about 12 sq km and runs across the eastern half of Ololbutot lava flow, within which three wells (Olk. 2, 3, and 4) have been drilled. About 3 km north of this, there are two north-trending, banana-shaped low resistivity areas, one of which just borders X-2. The other one seems to be narrowing toward Eburru and further lines are planned to check this.

The western side low resistivity area seems to coincide with some of the explosion craters and steaming ground

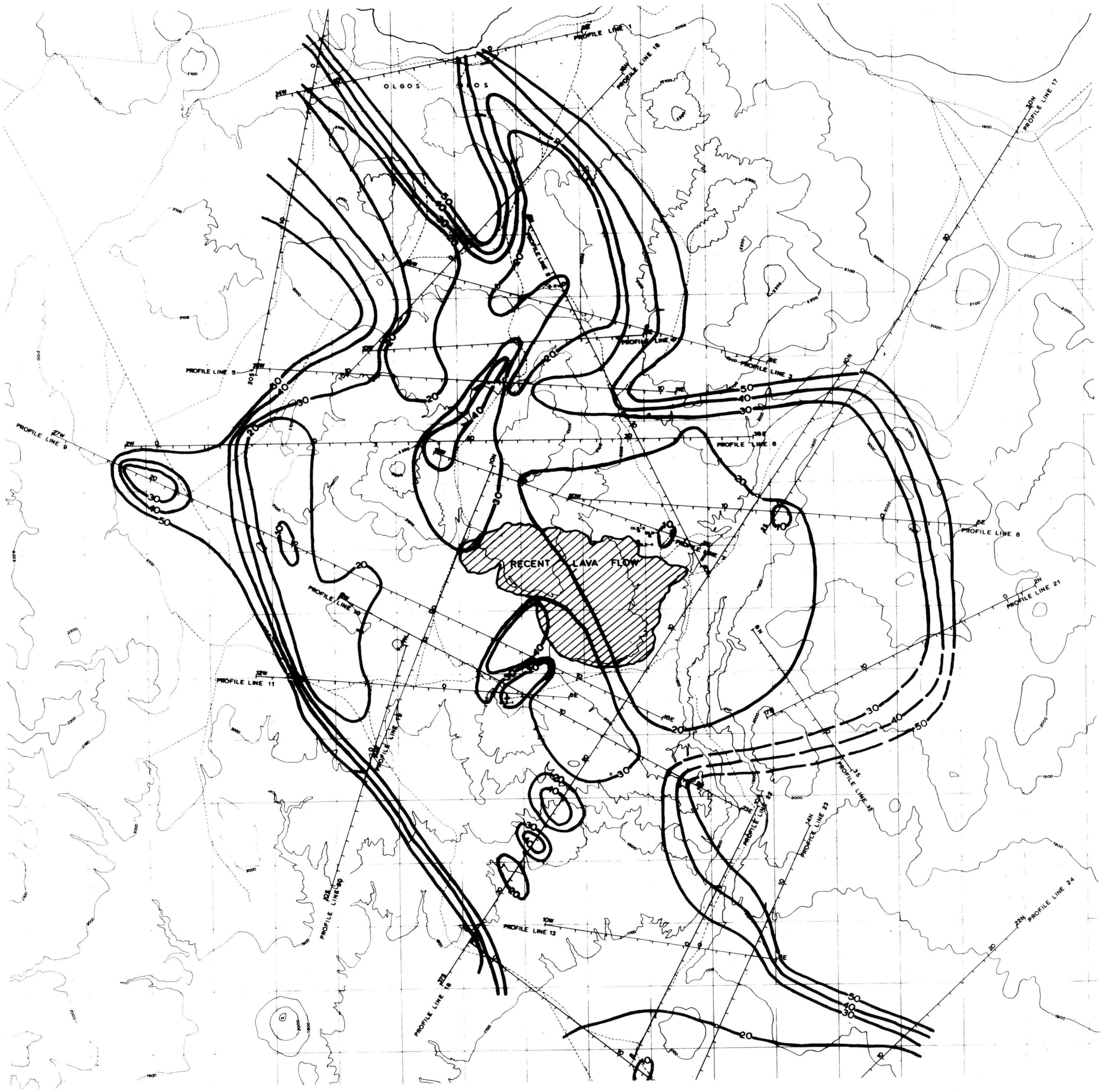

Figure 12. Resistivity map of Olkaria.

there but its significance as a possible production area has yet to be proved by drilling. Another wide low resistivity area is found to the south of the plains leading toward Mt. Suswa where a shallow borehole drilled by a farmer produces substantial amounts of steam which he condenses for drinking water. Further axial dipole resistivity surveys are planned for this area to try and delineate its boundary.

Gravity Survey

The Bouguer anomaly gravity surveys were carried out at the three prospect areas. At Lake Hannington, a negative gravity anomaly of 1.5 mgal, centered on the southern shore of the lake, was mapped. This represents a mass deficiency of about 44 million metric tons according to the calculations by Meidav.

At Eburru, the gravity lows correlate well with the north-south-trending explosion craters and fracture zone. This also coincides with the same axis of graben mentioned under geologic mapping above. No specific geologic correlation could be made from the gravity map of Olkaria except that there is a westward gravity dropoff. This could be a regional trend.

Microearthquake Survey

Another geophysical work performed was the measurement of microearthquake activity in the three areas. Lake Hannington area had the most pronounced and frequent microearthquake events, but many were deep and not connected to known geological and geothermal activity. An exception to this is Mwanasis peninsula where the events occur in the area with surface hydrothermal manifestations.

Earthquake distribution in the Eburru area was very low and the cluster is under the mountain crest at the crossing of the north-south fracture zone. In Olkaria, 49 microearthquake locations were recorded. The earthquake activity in this area is probably connected to the regional tectonic stress responsible for the Rift Valley formation. Most of the epicenters trend north-south parallel to the main fault zone and explosion craters, and the tension axis is in east-west direction. Another microearthquake lineation cuts the north-south one almost at 90° and passes just south of X-1 along an east-west fault. On the whole, the microearthquake activity in Olkaria area shows quite a good correlation with the fault systems of the area and the steaming ground, but evidence concerning the direction of the dip of the main fault was not conclusive.

Hydrogeologic and Geochemical Surveys

A regional hydrogeologic survey was conducted within the Rift Valley from Mt. Suswa in the south to Lake Hannington in the north. The purpose was to give information on the possible connection between shallow ground waters and geothermal reservoirs, to assess the recharge areas and ground water movement, and to calculate water balance, safe yield, and other reservoir characteristic parameters. Approximately 500 water wells were surveyed, with measurements taken of water rest level and temperature, well discharge rates, and chemical composition. In addition, an extensive sampling program of waters from rivers, springs, and lakes in the Rift Valley was also carried out. The results were interpreted by a consulting hydrogeologist (McCann, 1974, unpub. data).

Several hydrogeological maps were plotted from these data and correlated with information from geochemical, isotopic, and geological surveys. The ground water piezometric map revealed two ground water catchment areas with the divide running east-west over the Eburru ridge. The piezometric contours closely follow the topography. The southern drainage area suggests subsurface outflow from the southern end of Lake Naivasha through the Olkaria field, perhaps toward Lake Magadi. The northern one is more conspicuous and passes through Lakes Elmentaita and Nakuru and flattens out around Lake Hannington, perhaps discharging through the springs around the lake. Recharge areas for these drainage areas seem to be the escarpments bounding the Rift Valley and Lake Naivasha. The pattern of these ground water contours ties in well with other hydrochemical and isotopic results.

Ground water balance calculations were made from pumping tests, rainfall, and surface water data for the geothermal areas. Transmissivity values for most of the wells are within 3 to 30 sq m/day, while specific capacities range from 0.1 to around 0.4 liters per second per meter (lps/m). This suggests low permeabilities of the aquifers and the same trend has been observed in the deep geothermal wells. Water balance calculations show that about 250 million cu m of the annual precipitation recharge ground water reservoirs in the Naivasha catchment while about 20 million cu m recharge the Lake Hannington reservoirs. From these figures, it is estimated that more than 150 and 13 million cu m annually recharge the geothermal reservoirs in the Lake Naivasha and Lake Hannington catchments, respectively.

Chemical analyses were conducted on all the waters from wells, springs, lakes, and rivers, in addition to analyses of gases from hot springs and fumaroles in the prospect areas. The chemistry of the shallow and surface waters was used in the regional hydrogeologic studies. Na/K ratio and silica concentrations from hot water wells and springs have been used to calculate reservoir temperatures. Temperature calculations based on concentrations of carbon (C^{13}) isotopes and $\frac{CH_4}{CO_2}$ ratio in gases from steam discharges in the three areas gave reservoir temperatures of over 300°C (Glover, 1972, unpub. data). Temperatures over 270°C have been measured in three of the Olkaria wells.

Work on Well X-2

In the middle of 1971 various attempts were made to bring one of the original wells, X-2, into production. First the hole was pressurized to 800 psi followed by sudden release; although the hole produced a mixture of steam and water for some hours, the flow eventually stopped. After this, the hole was cleaned out to the bottom. Surveys carried out indicated a bottom hole temperature of 235°C, after which efforts were made to bring the well into production by swabbing, but production was not sustained. Temperature profiles of the hole indicated a very rapid rise just below 640 m, and it was significant that between there and the bottom of the hole, 58% of the potential producing zone had been cased off. Also it was considered that the large quantities of bentonite which had been used during the drilling would have effectively formed a sealing cake around the hole, thus preventing water and steam entering.

A program of casing perforation by blasting with shaped charges placed opposite loss of circulation zones was therefore carried out, after which the water rest level rose from 342 to 335 m. Early in 1972 a small percussion rig was used for further swabbing of the well, and by careful adjustment of the wellhead valve a continuous flow of steam and water was achieved. The well was discharged through a 3-1/2 in. flow line, giving a cyclic flow pattern with an 80 minute period. Wellhead pressure varied between 11 and 30 psig, and water flow between 40 and 202 l/min (Fig. 3).

With the successful attempts to bring X-2 in production, the well could correctly be described as a significant discovery and this had a considerable influence on the remainder of the project.

Exploration Drilling

The final phase of the geothermal exploration project which started at the end of 1970 was the drilling of four holes with a maximum depth of 1350 m. At the end of 1972 results of all the field surveys completed during the previous two years in the three prospects were reviewed and it was decided to concentrate drilling work in the Olkaria area largely due to the positive results which had been obtained from hole X-2. (Insufficient funds were available to explore more than one prospect area.)

In preparing the drilling program, the advantages of drilling 8-3/4 in. final diameter hole over a slim hole were considered worthwhile, in spite of the extra expense, so that there would be a minimum of delay in exploiting any significant discovery of steam. It was also decided that in view of the very low water rest levels which were likely to be found, and to prevent the possibility of well damage due to mud caking, it would be advisable to drill in the reservoir with foam. The information available about foam drilling in geothermal reservoirs was, however, rather sparse. It was therefore decided that, as a safeguard, it would be advisable to provide sufficient water at each site to be able to drill with water should the need arise. For the first drill site (Olkaria 1), therefore, it was necessary to construct a 6 in. pipeline from Lake Naivasha some 12 km long and rising to a height of over 250 m above the lake level. This water was pumped in three stages to a 500 000 gallon reservoir after which there was a gravity feed to the drill site.

A modified T12S drilling rig was mobilized to Olkaria in August 1973 and drilling started on Olkaria 1 on 12th October, 1973.

Olkaria 1. Olkaria 1 was sited at the intersection of the well-defined north-south fault through the prospect with a secondary east-west fault. The purpose of this was to give maximum possibility of drilling through a zone of good permeability. There are a number of fumaroles close to the site of Olkaria 1 and there is also some microearthquake activity in the area.

The drilling program called for 20 in. casing to be set at 30 m, 13-3/8 in. casing at about 200 m, and 9-5/8 in. casing when the reservoir was reached at an anticipated depth of 600 m. The fluid used down to 602 m was conventional bentonite mud and the early stages of drilling were notable for frequent loss of circulation zones and low hydrostatic pressure. Below 602 m stiff foam was used and penetration rates were good but it was found that the standard roller bearing tricone rock bits suffered excessive rapid wear of the bearings, due probably to poor lubrication and cooling.

The formation drilled consisted mainly of tuffs and lavas with a number of sedimentary lake beds. It was apparent that the hole intersected two aquifers, the upper one between 140 m and 400 m, which was cased out, and the lower one from 618 m to the bottom of the hole. Downhole temperatures were very low and the maximum recorded was 126°C at 1000 m depth (Fig. 5). A number of attempts were made to air lift the hole into production by pumping compressed air through a 2 in. tube to a depth of 970 m, but none of these were successful and the hole was eventually abandoned at a depth of 1003 m in the middle of March 1974. Eruption was not achieved due to low permeability and low temperature.

After failing to obtain high enough temperatures in Olkaria 1, a cold water step-injection test was conducted to try to determine some of the reservoir characteristics. Injection rates varying from 200 to 1000 l/min were used over a period of about 6 hours and a pressure recorder was placed at 698.5 m to measure pressure changes during and after the injection. A pressure increase of 10.5 bars was recorded during the test, suggesting low permeability and large drawdown. Further calculations showed that the well had a transmissivity value of 4 sq m/day, specific capacity of 2.4 to 4.8 lpm/m and permeability of 34 millidarcies (md). These figures are below those obtained from X-2.

Olkaria 2. Following an analysis of the cause of failure at Olkaria 1 it was decided to move toward the northeast of the prospect (Fig. 2) for drilling Olkaria 2. The chemical data obtained from fumaroles in this area gave indications of high temperatures, and resistivity surveys were also favorable, although there was no obvious geological fault close by. It was also thought the water rest level would be shallower. Drilling started on April 13, 1974, with a 26 in. hole using mud to a depth of 40 m when 20 in. casing was cemented, after which drilling continued with foam at 17-1/2 in. diameter to a depth of 230 m, where 13-3/8 in. casing was set. Because the hole was drilled with foam, and circulation zones were not sealed with cement plugs, it was not known whether a good cement bond was achieved with the 13-3/8 in. casing. Drilling then continued at 12-1/4 in. diameter with foam to around 590 m where it became apparent that either the hole was caving or the foam had insufficient lifting capacity to bring cuttings up to the surface. Casing at 9-5/8 in. diameter was therefore set to 595 m and drilling continued at 8-3/4 in. diameter with foam. Weak formations were again encountered below 600 m and some cement plugs were set to stabilize the hole. Below 600 m aerated mud was used as a fluid, which improved the return of cuttings to the surface, but around 650 m there was some evidence of dry steam production. It was considered that if drilling continued with mud, this could effectively seal the formation so an aerated water/foam mixture was used as drilling fluid and circulation return with cuttings was satisfactory. As the hole was drilled deeper than 1000 m, however, re-establishment of circulation after a rock bit change became more and more difficult and sometimes it was difficult to regain circulation even after adding a drill pipe. This problem was partly overcome by the use of jet subs in the drill string and the hole was drilled to a depth of 1350 m, when a 7 in. slotted liner was run in from 600 m to the bottom of the hole. Details of Olkaria 2 are shown in Figure 6.

Downhole pressure and temperature measurements in Olkaria 2 were taken during and after drilling, some of which are shown in Figure 11. The most stable temperature run indicates that temperatures at the bottom of the hole could be near 280°C. The hole was originally thought to penetrate a dry steam zone, in which case near-constant temperature with depth and pressures close to 32 bars (abs) would be expected. This does not seem to be the case, and after several flow tests and downhole measurements, the hole was found to produce a mixture of steam and water although the dryness factor is much higher than other known wet wells (about 60% steam).

Flow tests have been conducted using lip-pressure pipes with different diameters to obtain flow characteristics. Initially, when operating at a wellhead pressure of 6 bars (abs), the well produced about 50 tonnes per hour of steam which is equivalent to about 5 MW. But later tests show long-term steam production of nearer 30 tonnes per hour.

The McKinley plot of wellhead pressure build-up against time on log-log paper, also a semilog plot of pressure build-up against the ratio of total flow time plus recovery time divided by recovery time $\left(\dfrac{t + \Delta t}{\Delta t}\right)$ shows that Olkaria 2 produces from a fracture or fractures with limited lateral extent, (Figs. 13 and 14). These plots, however, do not reveal the existence of more than one aquifer, which is interpreted to mean that even if the well produces from several fractures they must all have hydrostatic connection. Nevertheless, the transmissivity values obtained are low, less than 4 m^2/day, which is the same value for Olk. 1 and very close to the transmissivity values of most shallow ground water wells in the Rift Valley. Wellhead pressure for 1 min and water flow readings over a 2-hr period are plotted in Figure 5, and show fluctuation in the flow pattern of this hole, using a 5 in. flow test pipe. However, four weeks continuous flow test through 5 in. pipe showed the disappearance of the fluctuation and stable wellhead pressures of 6.0 bars.

The geologic column encountered in the hole is shown in Figure 6. The lithology is predominantly a succession of lava (rhyolitic at the top and trachytic near the bottom) with tuff and a thick section of sediments above the 9-5/8 in. casing shoe. Below the production casing shoe, the hole penetrates more tuffs than lavas (about 55%) and it is inferred that the aquifer horizons are at the contacts between lava and tuffs. Hydrothermal alteration in the form of occurrence of pyrite and kaolinized rocks starts as high as around 200 m and persists to the bottom. Below 1000 m chlorite, sulfur, and magnetite begin to appear. The lithologic column in Olkaria 2 bears some correlation to those of Olkaria 3 and 4.

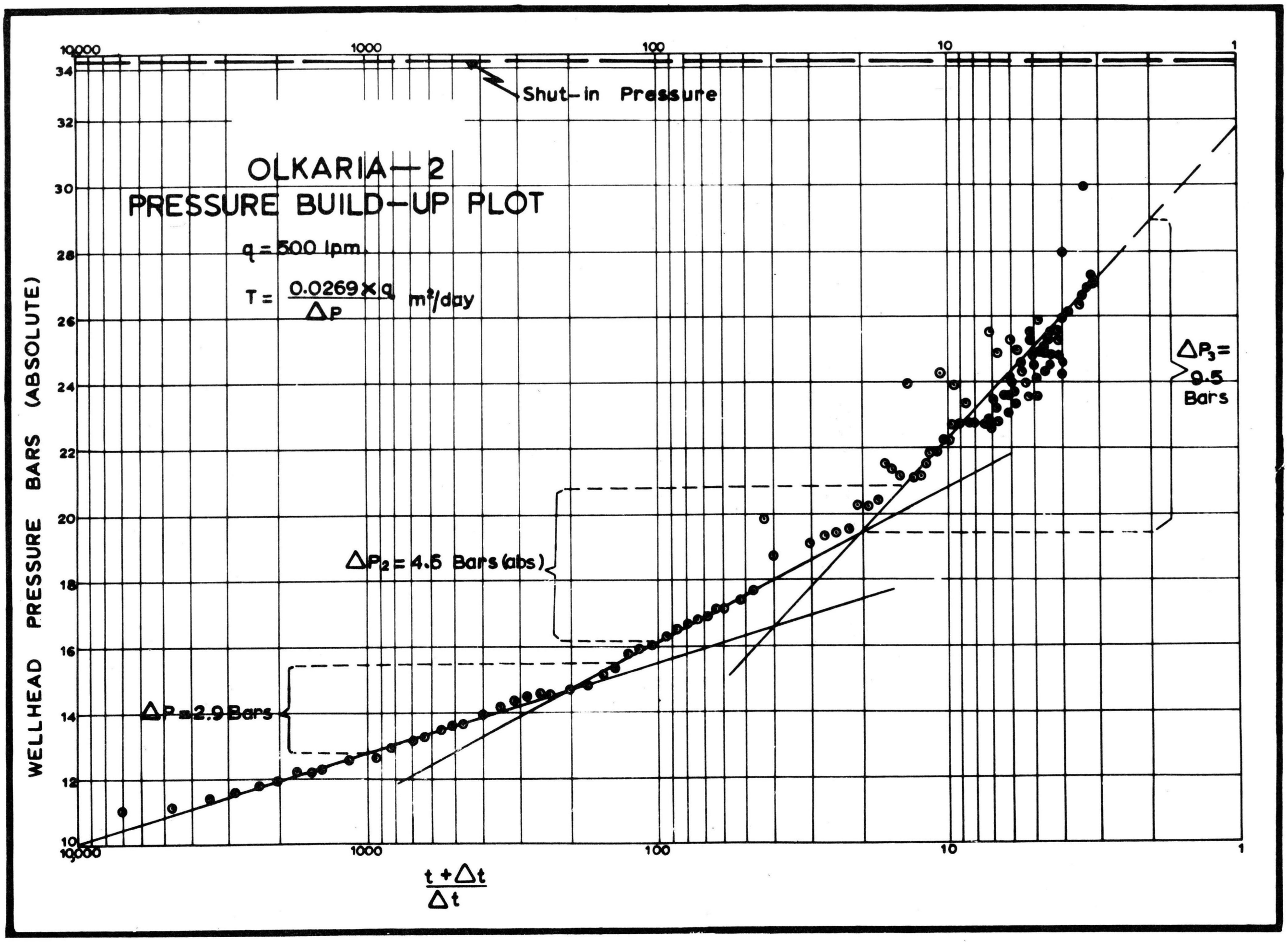

Figure 13. Olkaria 2: Pressure build-up plot.

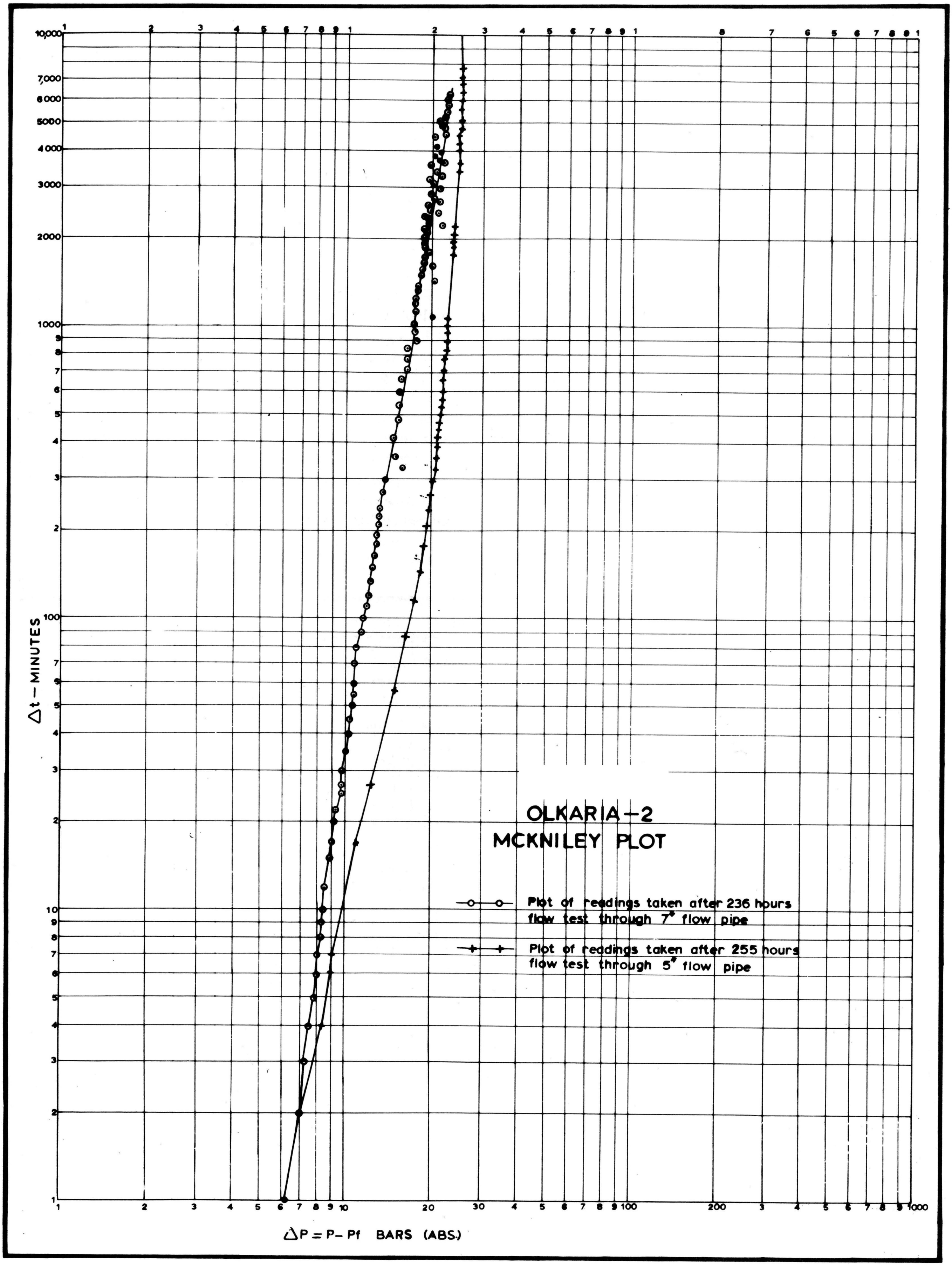

Figure 14. Olkaria 2: McKinley plot.

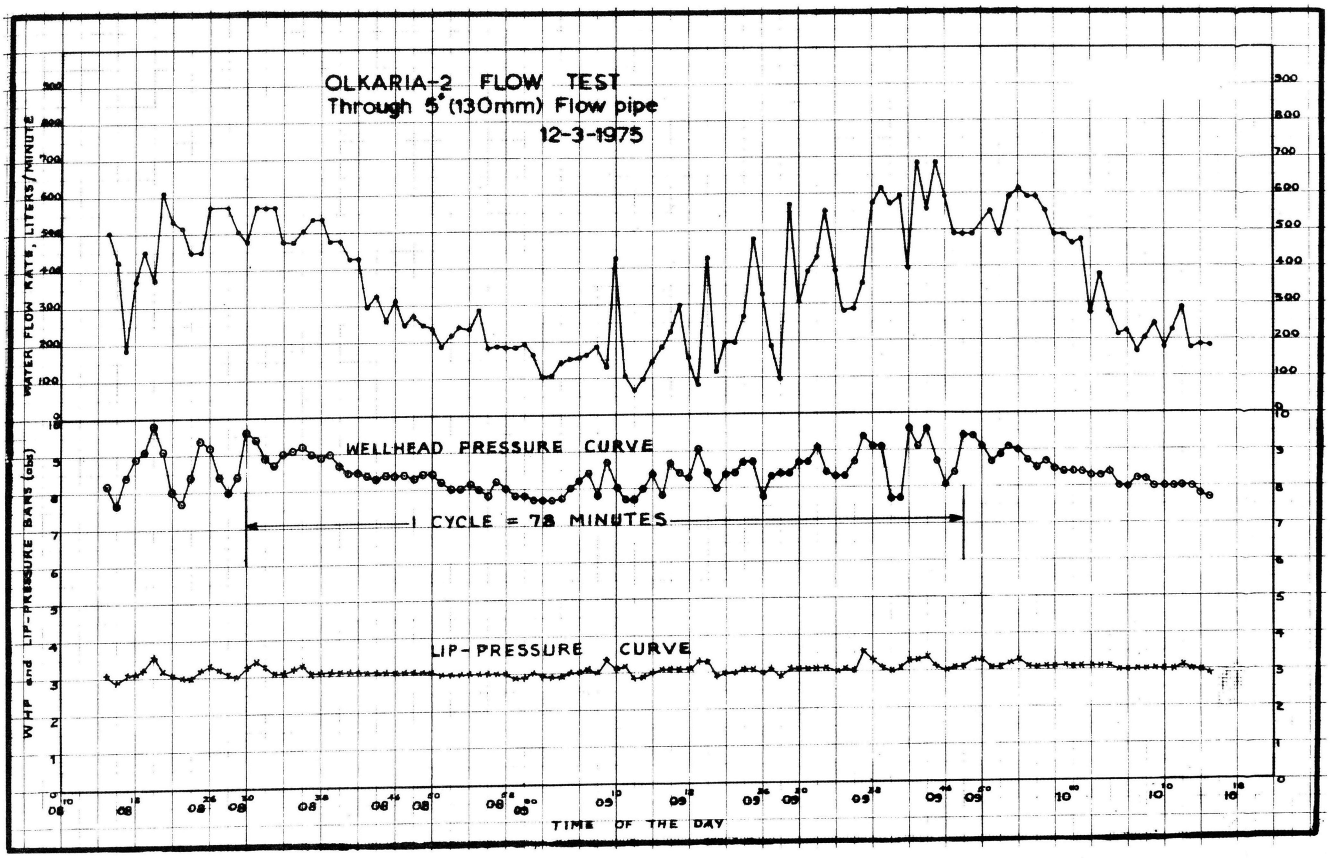

Figure 15. Olkaria 2 flow test through 5 in. (130 mm) flow pipe.

Olkaria 3 and 4. With indications of good output from Olkaria 2, it was decided to drill two more holes as offsets, so that the three well locations were at the corners of a triangle with sides of about 200 m. Both these holes were drilled with little trouble, Olkaria 4 taking only one month from start to finish. The 26 in. hole was drilled with mud, after which foam was used for the 17-1/2 in., 12-1/2 in., and 8-3/8 in. hole, and it was found from experience that a mixture of foam and water gave the best results for lifting cuttings to the surface, although difficulties were frequently experienced in establishing circulation after rock bit changes. Well details from Olkaria 3 and 4 are shown in Figures 8 and 13, and it will be noticed that the 9-5/8 in. casing was set at 700 m in both cases. A 7 in. slotted liner was run into Olkaria 3 from 690 m to the bottom of the hole but Olkaria 4 was completed without a liner so that it could be determined if the hole would produce satisfactorily unlined.

After completion of both Olkaria 3 and 4 the wells were shut in for several days to allow heating of the formation, after which they were blown vertically through 6 in. flow test pipes. Flow rates and wellhead pressures were both very low, in sharp contrast to the results which had been obtained from Olkaria 2 less than 200 m away. As the drilling contract was complete and the crew had left the site it was not possible to carry out remedial work with the drilling rig immediately, and it was therefore decided to carry out a water injection program in both wells to open existing fractures and to create new ones.

Olkaria 3 and 4 wells were drilled to 1357 and 1350 m, respectively, and have similar geologic formations. As in Olkaria 2 the sediments occur mainly above 700 m and have thus been cased out. Below the production casings, tuffs form about 40% and 35% in Olkaria 3 and 4, respectively, while the rest are lavas. Most of the lava within this lower zone is trachyte and all is altered to some extent. Pyrites begin to appear from 250 m. While sulfur starts to appear from 670 m, magnetite is not seen until after 1200 m. The contacts of lavas and tuffs display thin (2 m) horizons of brick red (perhaps steam baked tuffaceous material and the drilling crew noticed fluid inflow and pressure rise whenever these layers were encountered.

Temperature inversions and maximum cooling zones during water injection seem to coincide with the contact zones between lavas and tuffs (Figs. 7 and 8, run nos. 3604, 3609 to 3611, and 4601, 4606, and 4607). It is inferred from this that the contact interfaces may be the permeable zones available in this area and such thin brick-red zones (called old land surfaces in Kenya geological literature) are known to be the aquifers for many shallow water wells in the Rift Valley.

Downhole temperature and pressure profiles shown in Figures 7 and 8 pose several interpretative possibilities. Run nos. 3604, 3609, 4601, and 4604, taken before the wells were flow tested, show a heating rate of about 3°C per day, temperature inversions at about 1050 m above sea level, and temperature maxima at around 1158 to 1100 m above sea level. Both occur either within tuff or at the contacts between altered lava and relatively fresh lava. Run nos. 3610 and 4605, taken some hours after water injection, show maximum cooling of the wells below 700 m with Olkaria 4 showing a maximum temperature drop at 850 m (1100 m above sea level). The heating rate after the injection test as shown by Run nos. 3611 and 4607 averages about 7°C per day, being double the rate before injection. Wellhead pressure in Olkaria 3 also improved after this. Run nos. 3616, 4608, and 4611, taken after flow tests, show the disappearance of the temperature inversions indicated in the earlier runs. However, a later run in Olkaria 3 shows a slight inversion at 900 m and a temperature of 271°C at 1050 m, and Olkaria 4 shows no inversion and 286°C at 1300 m. The Olkaria 4 temperature plot follows theoretical boiling temperature curve from 500 m downward.

CONCLUSION

It is clear that a large geothermal power potential exists in the Olkaria area, particularly in view of the high temperatures and wellhead pressures which have been recorded; but in view of the poor results which have been achieved with Olkaria 3 and 4, output will be restricted by poor permeability. Plans are in hand to deepen Olkaria 4 from 1350 m to 1750 m in the hope of increasing output and, if this is successful, further holes will be drilled to this depth. It has also been suggested that a dry steam zone exists below 600 m and that this zone has been partly cased out by setting the 9-$^5/_8$ in. casing to 700 m in Olkaria 3 and 4 whereas the 9-$^5/_8$ in. casing shoe in Olkaria 2 is at 596 m. Olkaria 3 was perforated between 609 m and 701 m but no significant output increase was achieved. Further drilling locations and the casing programs for more holes are dependent upon the results obtained from these workover operations.

However, in view of the very high cost of operating an oil-fired plant at Mombasa, there is a very strong incentive to continue geothermal exploration in Kenya. In the event of the area around Olkaria 2, 3 and 4 proving uneconomical, further holes will be drilled elsewhere in Olkaria in order to obtain further information about the extent of the reservoir. An idea of the size of the field can be gauged from the fact that a downhole temperature of 246°C has been measured in hole X-2 which is 5 km away from Olkaria 2. It is also possible that exploration may be continued at Lake Hannington and Eburru if overall results at Olkaria are poor.

Calculations show that even if a well has an output equivalent to only 1.8 or 2 MW (electrical) it would still compare favorably with other sources of electrical generation in Kenya, and it is confidently expected that with drilling and testing of Olkaria 3 and 4, this output can be achieved. Meanwhile, preliminary inquiries are being made about the possibility of installing a small atmospheric exhaust turbine generator which could supply the local 11 kV electrical distribution system and which would involve minimum expenditure and allow an early return on the capital so far invested in the geothermal program.

It would be fair to say in conclusion that although results so far have been disappointing, there is justification for optimism that further work will demonstrate the feasibility of economic large scale power generation which will be of considerable long-term benefit to the developing country of Kenya.