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SUBSURFACE STRATIGRAPHY AND HYDROTHERMAL ALTERATION OF THE EASTERN SECTION OF THE OLKARIA GEOTHERMAL FIELD, KENYA

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ABSTRACT

Petrological examination of cuttings from Well numbers 2,3,5,6,8,9,10,11,12 and 13 show that the rocks comprising the drilled eastern part of the Olkaria reservoir below about 150m consist of subhorizontal intercalated rhyolite, trachyte and basalt lavas plus occasional thin pyroclastic beds of similar compositions. Cuttings of microgabbro were also recovered from some wells; these probably derive from dykes or sills too thin to be other than local ephemeral heat sources. There is no evidence that faults with significant vertical displacement occur within the area drilled.

Many of the cuttings, especially those deriving from below 550m, show the effects of complete or partial fluid/rock interactions which have produced a suite of hydrothermal minerals including quartz, hematite, albite, adularia, chlorite, illite, pyrite and calcium bearing phases such as calcite, montmorillonite, wairakite, epidote, sphene, fluorite, mordenite, prehnite and anhydrite. The identity and distribution of the minerals have been used to reach the following conclusions about prc-drilling conditions prevailing in the Olkaria reservoir.

Rocks down to a depth of about 550m are nearly impermeable, but there is poor to good lateral permeability in most rocks occurring below this depth; there is not a close correlation between rock type and permeability, but generally the thin pyroclastic beds have the highest permeability and a sequence of widespread basalt lava flows occurring between 500 and 650m usually, but not invariably, also have relatively good permeability. None of the penetrated dykes or sills of microgabbro serve as channels for thermal fluids, nor is there any evidence of significant vertical permeability in this part of the field. Fluids probably move laterally along very narrow, interconnected joint channels, contacts between lava flows or boundaries between separated blocks within brecciated lavas; it is probable that thermal fluids do not pervade, or perhaps even fully saturate, all the rocks in the reservoir.

The altering thermal fluids are deduced to be near-neutral alkali chloride water of slightly varying salinity and generally saturated with respect to CaF_2; at 2600 these have values for CO_2, $a_{Ca^{2+}}/a^2_{H^+}$, a_{K^+}/a_{H^+} and a_{Na^+}/a_{H^+} of 0.01 mole, $10^{8.6}$, $10^{4.5}$ and $10^{5.8}$ respectively; the fugacities of gases dissolved in this fluid at 260-300° are $fO_2 = 10^{-28}$, $f_{S_2} = 10^{-8}$, $f_{H_2S} = 10^{-2.5}$ and $f_{H_2} = 10^{-3}$ bars. There is no evidence, from the alteration, for the presence of either vapour only or condensate zones except very close to the surface; however, two-phase conditions prevail between about 550 and 700m depth.

Before drilling there was a fairly steep thermal gradient, locally at boiling temperature, down to about 500-700m; below this the alteration shows that the temperature reversals measured in some wells predate their being drilled. Temperatures in deeper parts of the reservoir are between 250 and 2700 but the predrilling 250° isotherm is closest to the surface in the northwest part of the area drilled and near to Well 2.

The distribution of calcite and other hydrothermal minerals is consistent with a model whereby water of near-neutral pH, hotter than 270° and containing 0.01 moles of dissolved CO_2, ascends a zone located somewhere northwest or west of the area; this water flows laterally, mostly at depths between 500 and 800m, across the field, gently losing carbon dioxide as it does so.

INTRODUCTION

The Olkaria geothermal field is located in the floor of the Eastern Rift Valley of Kenya (figure 1), on the southeastern shores of Lake Naivasha and 80km from Nairobi. The field is presently (1984) producing 30MW electrical, but its potential output is probably much greater than this.

The surface geology in the vicinity of the geothermal field consists of young alkaline rhyolites overlying thin lacustrine sediments (Naylor, 1972; O. Odongo pers. comm.). However, this paper describes sub-surface stratigraphy and hydrothermal alteration of cuttings recovered from 10 wells (2, 3, 5, 6, 8, 9, 10, 11, 12, 13) drilled to depths between 901 and 1685m. About 300 thin sections of cutting chips were examined and these observations were occasionally supplemented by X-ray Diffraction results; however, more work, for example, fluid inclusion geothermometry and clay mineralogy, still remains to be undertaken on these samples.

STRATIGRAPHY

The stratigraphy of the eastern section of the Olkaria geothermal field is summarised in Figures 2 & 3; formation boundaries are mostly located from the lithlogical logs of S.B. Bwire-Ojiambo and O. Odongo of the Kenya Power Company. Because many cutting samples are fine-grained and/or hydrothermally altered, a very simple nomenclature system is used: pyroclastic rocks are named following Browne (1971); rhyolites in this paper refer to extrusive rocks containing phenocrysts of primary quartz and usually sodic plagioclase and/or primary K-feldspar; trachytes are here categorised as extrusive rocks containing phenocrysts of K-feldspar and/or sodic plagioclase, but without phenocrysts of primary quartz. Other rocks are named following convention.

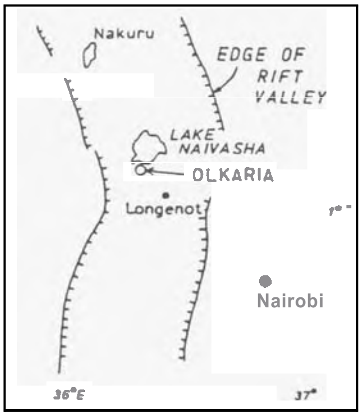

FIGURE 1: Location of Olkaria Geothermal Field.

Examination of cuttings (figures 2 & 3) shows that:

1. The field is predominantly composed of lavas (basalt, trachyte and rhyolite), with their pyroclastic equivalents comprising less than 10% of this volume.

2. Except for the microgabbro the rocks were deposited subaerially; there are no marine, nor significant amounts of lacustrine, sediments occurring below about 200m depth.

3. There are marked variations in the thickness and distribution of the subsurface formations; the cross-sections (figures 2 and 3) are the simplest that could be drawn, and the reality is probably much more complicated; it is likely that successive lavas flowed onto a terrain which was very irregular. Nevertheless, correlation between drillholes is possible, and several units can be recognised in more than one drillhole. Down to a depth of about 500m rhyolite and trachyte lavas predominate, but below this, to about 700m, rocks of basaltic composition (pyroclastics, intrusives, but mostly lavas) are more common and widespread. Below about 700m trachyte predominates with subordinate basalt and rhyolite lavas; however, the lateral distribution of all three types varies considerably.

   Several of the pyroclastic units occur in close proximity to effusive rocks of the same composition; for example, scoria overlies, underlies or is interbedded with basalt lava in several drillholes. This suggests that the two rock types are genetically associated and perhaps even derive from the same vent; the same relationship is probably also true for some rhyolitic and trachyte rocks.

4. The microgabbro, possibly genetically related to the youngest basalt flow, was encountered in some wells, but simple calculation shows that this cannot be a significant heat source for the Olkaria system. Distribution of the microgabbro is undoubtedly more complex than that indicated in figures 2 and 3 where it is shown to form sills and dykes.

Marker Units

No ideal (i.e. widespread and distinctive) marker units were recognised. Several potentially useful units, such as scoria, occur but were not encountered in all wells; nor were pyroclastic rocks erupted onto flat surfaces. Lavas, which are more widely distributed, are seldom sufficiently distinctive to allow close or confident correlations to be made between drillholes. This problem is also compounded by the homogenising effects of hydrothermal alteration, a process which, for example, readily destroyed the potentially diagnostic ferromagesian minerals. Nevertheless, despite these limitations, correlation between drillholes are attempted (figures 2 and 3), and the following units are the most easily recognised.

Spherulitic Rhyolite Lava

This lava occurs in several drillholes and samples examined include, for example, cuttings from wells 2(52-88m), 3(68-70m), 5(72-79m) and 6(96-198m). The rock is typically white to pale grey in colour but mottled; it is spherulitic or microspherulitic and locally flow-banded with a low phenocryst content (0-10%). Embayed quartz forms small phenocrysts together with rarer K-feldspar, including anorthoclase. Where fresh the groundmass contains small needles or riebeckite, hornblende and aegirine-augite, aenigmatite and also quartz and albite-oligoclase.

Trachyte Lava

This unit occurs in several drillholes, for example cuttings from well 2(222-242m), 3(236-238m), 5(197-206m), 6(248-250m), 8(250-252m), 10(258-269m), 11(236-260m), 12(194-260m), 17(238-280m). It is a grey to brown porphyritic rock that is commonly vesicular; euhedral to rubhedral, but in places embayed phenocrysts of K-feldspar (including sanidine and anorthoclase) vary in abundance (1-5%) and size (up to 4mm long). Less abundant are phenocrysts of dusty albite-oligoclase which occur in a fine-grained (60 μ or smaller), uniformly crystalline groundmass consisting of euhedral laths of feldspar, interstitial quartz and, where fresh, clinopyroxene and occasionally very rare olivine.

Chemical analysis (table 1) shows that a core of this unit from well 17(238-240m) is much more iron-rich but contains less magnesium and calcium than that of an average trachyte but alteration and oxidation have caused some elements in this rock to exchange partly with those in the circulating fluids.

Basalt Scoria and Vesicular Basalt Lava

At least two thin but distinctive units of these lithologies were encountered by several drillholes (e.g. cuttings from 2(642-644m), 8(500-502 and 624-626m), 9(468-470m), 11(510-512m and 564-566m), 12(476-478m), 13(590-592m)). Both units are characterised by different sized vesicles that vary greatly in abundance. Rocks are typically grey to brown and contain euhedral phenocrysts of calcic plagioclase, up to 4mm long, but in places these are so small as to be indistinguishable from crystals that form the groundmass; in some samples, however, the matrix is opaque in thin section.

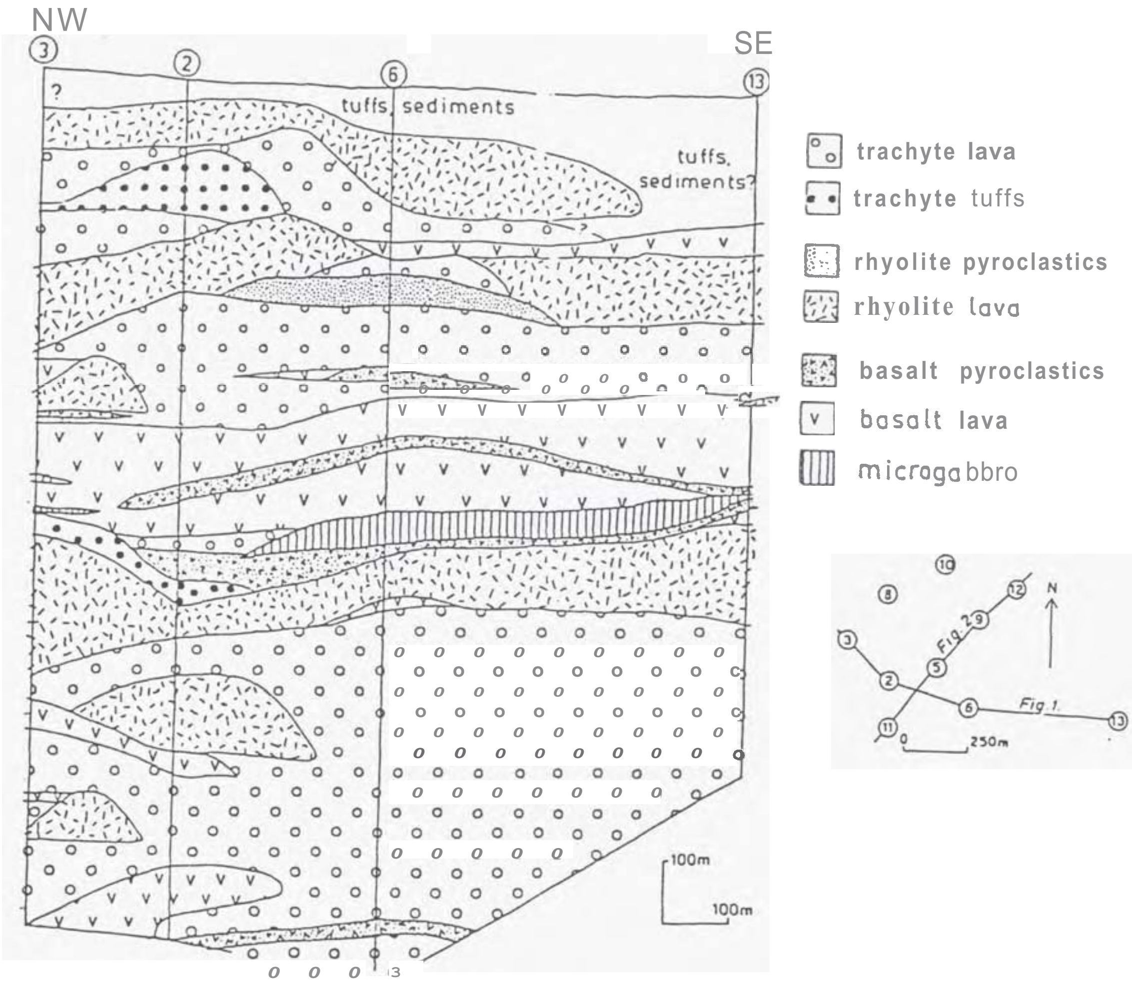

FIGURE 2: *Summary* Stratigraphy of NW-SE section of Olkaria Geothermal Field based upon cuttings.

Micronabbro

Easily recognised in thin section from its coarsely crystalline character; unfortunately this unit is of little help in correlating between drillholes because of its intrusive nature.

Basalt Lava

This unit occurs in all drillholes and is .probably composed of several flovs vhich together have an average thickness of about 150m. The lavas vary in colour from black to grey-green, depending on their degree of alteration, and include both porphyritic and non-porphyritic types. Euhedral phenocrysts of andesine-labradorite occur in many samples and these are occasionally aligned in subparallel fashion; typical plagioclase phenocrysts are less than 1mm long but very rarely some exceed 3mm. Clinopyroxene commonly occurs in these rocks, mainly in small grains interstitial to plagioclase in the groundmass; ferroaugite also forms small interstitial grains in places and is a late crystallisation product. Hovever, orthopyroxene and olivine are now much rarer as both altered readily; nor were they ever abundant in the fresh rocks. The groundmass of this unit differs' considerably in crystallinity vith ophitic and subophitic textures developed.

Rhyolite Lava

This is another widespread unit; it was encountered in all ten drillholes although it is notably thinner in well 8. In most places rhyolites underlie the basalt lava flovs but are locally also interbedded with them. This lava consists of several flovs, possibly even deriving from different vents, but most have feu phenocrysts (10% at most); vhere present, these include embayed to euhedral quartz crystals, mostly about 0.8mm diameter, but occasionally as large as 2mm. Euhedral laths of K-feldspar (3.6 x 1mm) occur in places, and several samples contain intergrown crystals of optically continous quartz and sodic plagioclase; very rarely K-feldspar and plagioclase also form intergrown grains. The groundmass is mostly homogenous, although locally microspherulitic, and contains microcrystalline anhedral

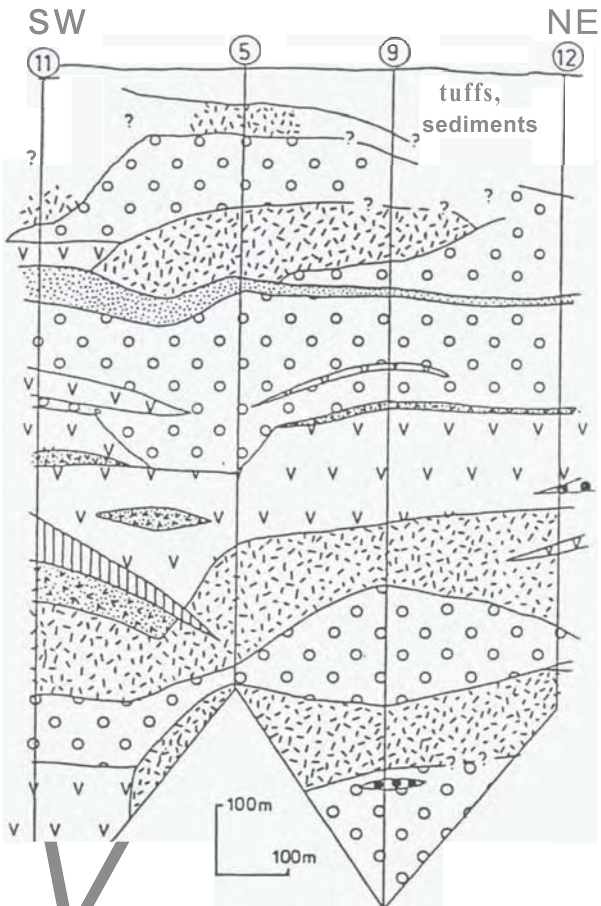

FIGURE 3: Summary Stratigraphy of SW-NE section of Olkaria Geothermal Field based upon cuttinqr: key and section line as in Figure 2.

quartz. Core correlated with this lava from well 16 (736-738m) (table 1) has SiO_2 in excess of 75% but little MgO, TiO_2, or CaO; the analysis shovs that plagioclase in this sample must be sodic albite but K-feldspar is about five times more abundant than plagioclase.

Deeper Trachyte Lava

A series of trachyte lavas of greatly different thickness were encountered near the bottom of most drillholes (figures 2 and 3). Chips vary in both their textures and phenocrysts: the former are, in places, flow-banded, brecciated or vesicular. The groundmass is occasionally heavily opacitised but is usually trachytic, fine-grained, quartzose and of homogeneous appearance. Phenocrysts of K-feldspar (anorthoclase or orthoclase where fresh) and sodic plagioclase comprise up to 15% of the rock, and crystals range in size from about 0.5 to 3 mm but most are about 2.5 mm long; they are typically euhedral but occasional K-feldspar phenocrysts are embayed. Very rarely (e.g. well 13, 1046m), quartz occurs as xenocrysts with strongly developed embaymcnts. Chemical analysis (table 1) of two cores (16, 1178-80m and 17, 1234-37m) shows that MnO, MgO and CaO are uniformly low but these samples have been hydrothermally altered.

Structure

The lavas and pyroclastic rocks which comprise some of the reservoir rocks of the Olkaria field have been subjected to neither tilting nor folding. Nor is there any evidence, from the cuttings, that faulting has occurred; however, this is not to say that faulting has not taken place: for example, the offset of several units (fig. 3) below 600m depth, between wells 11 and 12, may be due to displacement along a fault whose last significant movement predated the eruption of the overlying, apparently undisturbed, rhyolite lavas and pyroclastics. Cuttings from several locations show evidence of having been brecciated but this may have resulted from flow rather than faulting.

HYDROTHERMAL ALTERATION

Introduction

Many of the cuttings from the Olkaria drillholes show the effects of fluid and rock interaction; this process has produced not only a variety of hydrothermal minerals but has also changed the chemistry of the reservoir rocks themselves. These hydrothermal minerals are generally the same as those which occur in many of the world's geothermal fields (Browne, 1984) and for this reason it is appropriate to interpret the observed alteration of the Olkaria samples in the light of experience gained elsewhere in relating mineralogy to measurable reservoir parameters.

Alteration of Primary Minerals

The unaltered trachytic 8nd rhyolitic rocks encountered by the Olkaria drillholes have a fairly simple mineralogy; in response to fluid/rock interaction the decreasing stability of the primary phases seems *to* be: quartz, iron-titanium oxides, IC-feldspar, plagioclase, sodic amphibole, pyroxene and volcanic glass. Plagioclase and iron-titanium oxides are the most stable minerals in rocks of basaltic composition, followed by clinopyroxene and then orthopyroxene/olivine; basaltic glass is their least stable phase.

The Hydrothermal Minerals

Hydrothermal minerals present in the cuttings from Olkaria include abundant and widespread quartz, hematite and chlorite. Calcite is also common but is mainly present in distinct zones; other calcium-bearing phases include minor to rare wairakite, prehnite, laumontite, mordenite, epidote, sphene, Ca-montmotillonite and fluorite plus very rare gypsum and anhydrite. Both albite and adularia occur as hydrothermal minerals, but illite and limited interlayered illite-montmorillonite are the only other significant alkali-containing secondary phases, and both are much less abundant than they are in fields such as Broadlands and Wairakei. Pyrite is also rarer at Olkaria, and pyrrhotite was not seen; by contrast, hematite is much more videspread and abundant than it is in New Zealand, Philippine and Indonesian geothermal fields.

Most hydrothermal minerals form veins and vugs, but some, commonly albite, quartz, calcite and chlorite, also replace primary minerals and glass.

TABLE 1

COMPOSITION OF CORE SAMPLES

Drillhole No:	16	16	17	17	17
Depth (m):	736-38	1178-80	238-40	550-52	1234-37
SiO_2	75.73	67.10	62.70	54.95	64.04
TiO_2	0.33	0.72	0.62	0.42	0.80
Al_2O_3	9.26	13.26	14.76	15.44	11.41
Fe_2O_3	2.38	5.52	6.63	5.16	6.19
FeO	2.87 (in)	1.22	1.37	4.17 (in)	4.63
MnO	0.16	0.23	0.31	0.21	0.40
MgO	0.10	0.19	0.13	2.07	0.57
CaO	0.11	0.76	0.85	4.77	0.52
Na_2O	1.03	3.88	4.55	4.49	3.39
K_2O	5.64	5.45	5.65	3.05	3.76
P_2O_5	0.02	0.07	0.06	0.34	0.09
H_2O^- (110°)	0.19	0.37	0.84	1.02	0.51
$H_2O^+ + CO_2$ (850°)	1.67	0.64	1.29	2.35	2.63
	99.49	99.41	99.76	98.44	98.94

(in): incomplete acid digestion

Major elements were analysed using X-Ray Fluorescence by Dr R. Parker; FeO, H_2O^- and H_2O^+ + CO_2 were determined using wet chemistry by Miss Vicki Lockhart; both of the Geology Department, University of Auckland.

16/736-38 m. Rhyolite lava. Porphyritic and containing embayed to euhedral-shaped phenocrysts of quartz and euhedral laths (3.6 x 1 mm) of dusty K-feldspar: also present are crystals of intergrown quartz and sodic albite plus rare intergrown Na and K-feldspar. The groundmass consists of microcrystalline anhedral quartz; minor Fe-chlorite present.

16/1178-80 a. Trachyte lava. Contains euhedral phenocrysts of feldspar (adularia and calcic albite) up to 2.5 mm long and comprising about 15% of the rock in a fine-grained, quartzose and oxidised matrix: minor Fe-chlorite present.

17/238-40 a. Trachyte lava. Porphyritic vith euhedral to subhedral phenocrysts Of primary K-feldspar (including sanidine) up to 4 mm long, and mostly part oxidised (5%); plus less obvious dusty albite occur in a fine-grained matrix of uniform crystallinity (about 60u); this consists of euhedral laths of feldspar (analysis sucjqests calcic albite) with interstitial quartz. No primary pyroxenes or amphiboles remain but hydrothermal chlorite is present.

17/550-52 m. Basalt Lava. A porphyritic rock containing euhedral phenocrysts of partly altered plagioclase up to 4 mm long (5%) and xenocrysts of quartz with pronounced reaction rims occur in a groundmass of plagioclase and mostly oxidised ferromagnesian minerals, including pyroxene. Plagioclase has partly altered to prehnite, rare anhedral sphene and chlorite. Veins consist of quartz, abundant prehnite, rare epidote and K-feldspar.

17/1234-37 m. Trachyte Lava. Altered and silicified vith both potassic and iodic feldspar: veins of quartz and adularia plus minor chlorite are present.

Adularia occasionally forms veins but mainly replaces either plagioclase or primary K-feldspar; in the latter case there is a near isochemical transformation of orthclase, sanidine or anorthoclase to an optically and structurally different phase (adularia).

The extent of fluid/rock interaction in this part of the Olkaria field is much less than that of most New Zealand systems, but the intensity of alteration is similar to that of Kavah Kamojang, Indonesia.

Subsurface Permeability Estimates

Estimates of subsurface permeability (ffgures 3 and 4) are based SOLELY upon the identify and occurrence of the hydrothermal minerals (especially the feldspars) which occur in the cuttings; they result from past experience with rocks from geothermal fields where the observed alteration mineralogy can be related to measured well and reservoir permeability (Reyes and Tolentino, 1982; Elders 1977; Browne 1984).

The estimates do not take into account information or data from other sources such as the drilling records or well tests. The permeability numbers assigned in the figures are fairly subjective and the boundaries rather vague, being a balance between the intensity and rank of alteration. Nor is the eleven point scale (0 - 10 in table 2) linear as a score of 8, for example, generally means that the rocks from their indicated depth will be more than twice as permeable as those from a depth with a score of only 4. In other words these numbers are only guides to relative permeability.

TABLE 2: RELATIONSHIP BETWEEN HYDROTHERMAL MINERALOGY AND DEDUCED PERMEABILITY FOR BASALTIC AND RHYOLITIC ROCKS OF EASTERN OLKARIA

Deduced Permeability Score (arbitrary units)	Usual Mineralogy
0	no hydrothermal minerals
1	traces of calcite, montmorillonite, pyrite, quartz.
2	primary feldspars fresh; ferromagnesian minerals partly altered
3	primary feldspars fresh; ferromagnesians completely altered
4	primary feldspars partly altered; ferromagnesians completely altered
5	primary feldspars completely altered; minor hydrothermal albite
6	abundant hydrothermal albite; matrix consists of hydrothermal minerals
7	abundant hydrothermal albite plus less adularia
8	adularia with less albite
9	adularia is the only feldspar present
10	adularia occurs throughout the rock in the matrix and as phenocrysts

This scheme is modified to assign numerical permeabilities to trachytic rocks which often contain appreciable amounts of primary K-feldspar. Although primary K-feldspar (anorthoclase, orthoclase, or sanidine) recrystallises to adularia as a result of fluid/rock interaction, this process requires only minor and local addition of potassium with much less water through flow, i.e. lower permeability than is needed for adularia to form, for example, in less potassic rocks such as basalts. For this reason in assigning permeabilities of trachytes I used the formula 1/2 ('score' from table 2) + 1. I think that this admittedly arbitrary process allows for more realistic comparison between the permeabilities of different rock types within the reservoir.

The observed hydrothermal alteration suggests the following with respect to permeability prevailing within the Olkaria reservoir at the time(s) the minerals formed.

1. The drillholes penetrate fairly similar alteration sequences, but with some variations (figures 4 and 5). This means that permeability, within the area drilled, is dominantly a lateral feature for there is no evidence that steep faults or other vertical, or near-vertical, features with good permeability occur here; fluids thus ascend in zone(s) located outside the area enclosed by these wells - an interpretation consistent with that of Grant and Whittome (1981).

2. There are marked differences in alteration of many lava chips, especially basalt labelled as coming from the same locations; some cuttings are intensively altered but others are almost fresh. Even allowing for some of the problems inherent in using cuttings this implies that within zones of higher lateral permeability, fluids must move via very narrow channels and do not pervade, nor perhaps everywhere even fully saturate, the reservoir rocks. This interpretation is also consistent with the presence of numerous narrow veins (typically 1-2 mm vide), although perhaps wider ones would not be represented in the cuttings. The genesis of such channels is uncertain but they may be cooling joints, the very irregular open boundaries between separated blocks in flow breccias, contacts between lava flows, or combinations of all three. Vesicles in some of the basalt flows also form permeable channels where they are connected, but many porous rocks have low permeability.

3. None of the drillholes encountered very high, widespread permeability, such as that which occurs in the best bores in New Zealand or the Philippines. Very impermeable rocks occur down to a depth of about 550m (figures 4 and 5); only very locally (e.g. in Wells 2 and 6) above this depth is there even slight permeability. Consequently, in my opinion, no useful production has been lost by installing production casing in any of these wells to a depth of 550m.

   However, except in only a few places, most rocks occurring below about 550m have allowed at least some fluid to flow through them (figures 4 and 5). Comparison of these figures with those showing the stratigraphy (figures 2 and 3) suggests that there is not a very strong correlation between rock type and permeability although in most drillholes the pyroclastic units are the most permeable; unfortunately these are mainly thin and probably not able to provide sustained production. The basalt lava flows occurring between about 500 and 650m usually also have good permeability but some must also locally, at least, inhibit movement of thermal fluids. The deeper lava flows have varying, but at best only moderate, permeability, and some of the rhyolites are indicated to be tight.

Pre-Drilling Temperatures

Many cuttings do not contain minerals which can be used to deduce prevailing or past thermal conditions, although the observed general hydrothermal alteration clearly shows that the circulating fluids were hotter than

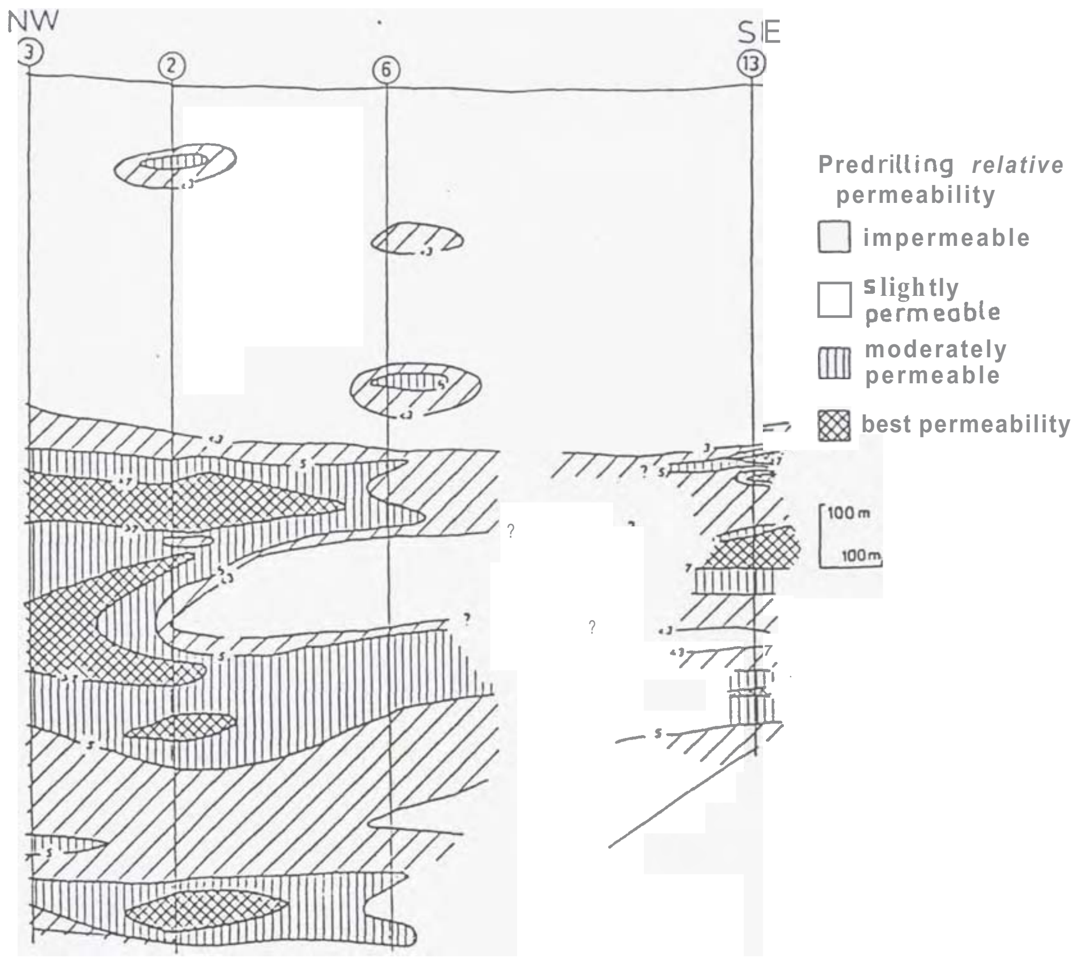

FIGURE 4: Subsurface permeability of a NW-SE section through Olkaria Geothermal Field based upon observed hydrothermal alteration of cuttings: section line shown in Figure 2.

the rocks with which they came into contact. It is especially difficult to estimate the pre-drilling temperatures in the shallowest 600m or so of the Olkaria reservoir, although in places zeolite and some clay minerals occur. Hany cuttings below this depth contain hydrated hydrothermal minerals (vairakite, epidote, prchnite, illite) that can be used to deduce their formation temperatures.

In most wells, downhole alteration indicates that there is a fairly steep geothermal gradient down to about 700m, below which depth there is either only a slight temperature increase to well bottom or one, and perhaps even more, temperature reversal(s). Epidote vas First recognised in the cuttings from ten wells at the following depths: Well 2, 638m; Well 3 693m; Well 5, 676m; Well 6, 680m; Well 8, 500m; Well 10, 594m; Well 11, 1014m; Well 12, 590m; and Well 13, 1050m. This indicates the approximate location of the pre-drilling 250° isotherm (figure 6), but since epidote (and calcite) are absent in many deeper cuttings, it is likely 'that thermal reversals were (are) typical features of this part of the Olkaria reservoir. This interpretation is consistent with the earlier expressed opinion that fluid here moves laterally.

The distribution of epidote (figure 6), however, suggests that the hottest part of the field is its northwest sector and in the vicinity of Well 2; the coldest Indicated temperatures occur to the southeast, in the direction of Well 13.

Fluid Composition

The hydrothermal minerals present in the cuttings show that:

1. The altering fluid is (or was) near neutral alkali chloride water; only very locally (e.g. well 12, 594m) was there sufficient SO_4^{2-} for

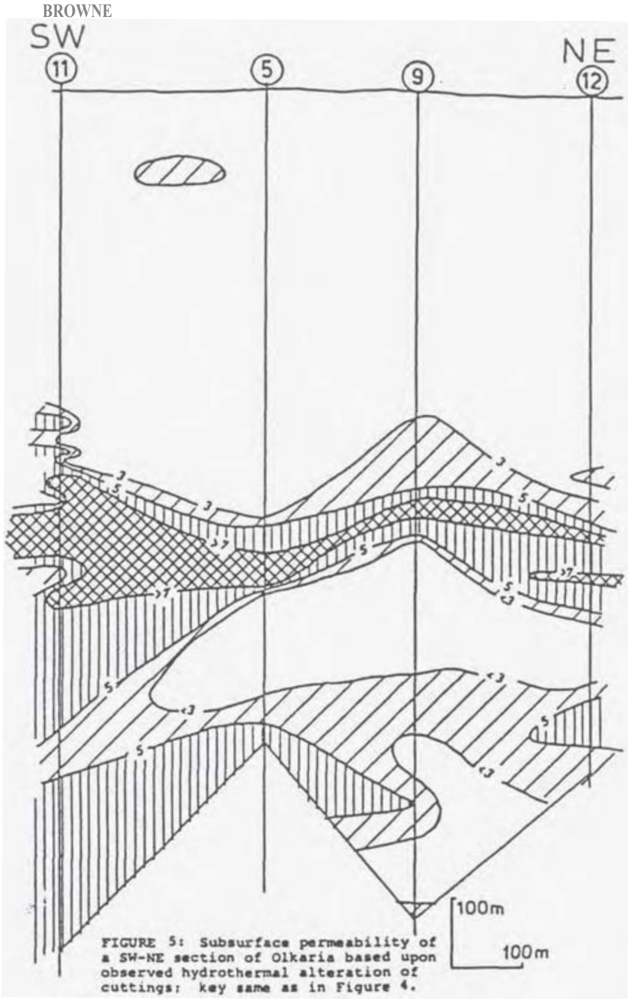

FIGURE 5: Subsurface permeability of a SW-NE section of Olkaria based upon observed hydrothermal alteration of cuttings: key same as in Figure 4.

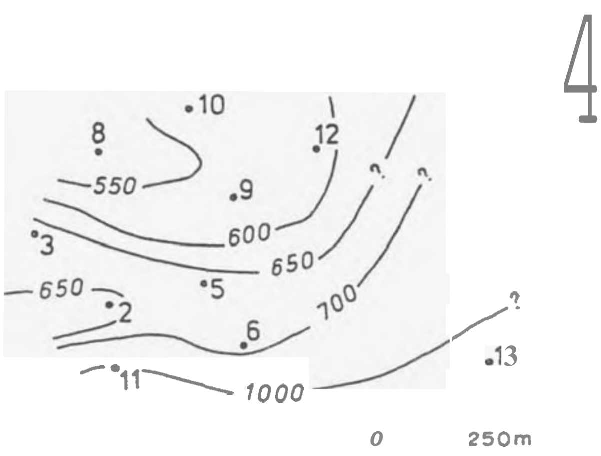

Figure 6: Depth to the shallowest occurrences of epidote in Olkaria well cuttings (note: samples from Well 4 were not examined). Contours in metres.

sulphate minerals to deposit. There is no mineralogical evidence for the presence of either a vapour only or a condensate tone, except at the very shallowest depths. However, boiling and two phase conditions probably occur where calcite is most abundant; (see next section). The irregular distribution of minor fluorite may be due to mixing of fluids with different salinities (including descending rain water) (Richardson & Holland, 1979). In places, however, the vaters are locally saturated, or oversaturated, vith respect to CaF_2. The concentration of calcium in solution is also affected, or controlled, by the presence of other calcium phases of which there are many in the Olkaria cuttings. By considering the system $CaO-Al_2O_3-SiO_2-K_2O-H_2O$ at, say 2600 (Figure 7) it is possible to estimate the activities of the Ca^{++} and K^+ ions, vith respect to pH, present in the altering fluid; thus the $a_{Ca^{2+}}/a_{H^+}$ is about $10^{8.6}$ and the a_{K^+}/a_{H^+} is about $10^{4.5}$. In a similar way, from figure 7b, the a_{Na^+}/a_{H^+} of the fluid is $10^{5.8}$.

Approximate calculations by Mr I Bogie (pers comm) based upon reported chemical analyses for Na, K and Ca in the Olkaria waters and using measured discharge enthalpies, show that the deep water has a pH of 5.8 ± 0.5 (i.e. very close to neutral at 2600); where boiling takes places the fluid vould, of course, become more alkaline due to loss of carbon dioxide.

2a. The concentration of carbon dioxide dissolved in the deep Olkaria fluid is very low, perhaps only about, or even less than, 0.01 moles; this' is indicated by the presence of calc-silicate minerals such as epidote, sphene, laumontite, wairakite and prehnite, plus the almost complete absence of calcite in cuttings recovered from below a depth of about 850m. However, calcite occurs in many shallower samples, mostly in one, or two distinct zones across the field (≃250-400 and 480-680m): The tone is thinnest in the northwest (about 150m) and widest towards the northvest (250m). Calcite may precipitate either where thermal fluids are heated or else lose CO_2; since both non-corroded primary and hydrothermal quartz also occur in the calcite zones, it is likely that fluids here are cooling rather than heating, so it is CO_2 loss which causes calcite to precipitate. Therefore the calcite horizons are interpreted as zones where two phase conditions prevail, and here CO_2 gently separates from south east moving fluids.

2b. Pyrite occurs in very small amounts (<<1%) in many Olkaria cuttings, but the mineral is neither abundant nor widespread compared vith its occurrence In many geothermal fields, for example Wairakei and Broadlands; by contrast, iron oxides are very abundant at Olkaria although they are uncommon in active NZ geothermal fields. The apparent stability of primary magnetite and the widespread distri-butiou of secondary hematite and iron alumi-nium silicates allows estimates of the concen-trations of some dissolved gases in the deep thermal fluid using the stability diagrams of, €or example, Ciggenbach (1980) and McKibben (1979). Thus, the oxygen fugacity at 300° of the Olkaria fluid, deduced from the alteration mineralogy, is about 10^{-28} bar and its sulphur fugacity 10^{-8} bar.

At a slightly lower temperature (260°) the deduced concentrations of dissolved H_2S and H_2 in the Olkaria waters are about $10^{-2.5}$ and 10^{-3} bars respectively, i.e. well below mineralogical-based predictions for their values in the New Zealand fields (H_2S, $10^{-0.8}$; H_2, 0.1 bars).

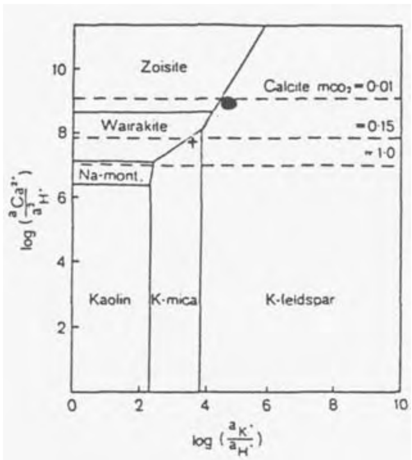

Figure 7a: Phase diagram for potassium and calcium minerals in terms of ion activity at 2600 with quartz present; m = moles. Circle plots location of deep Olkaria waters estimated from the hydrothermal minerals observed in the cuttings; the location of Broadlands waters (+) is shown for comparison.

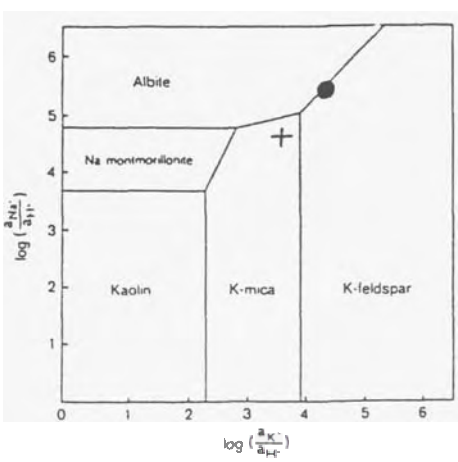

Figure 7b: Phase diagram for sodium and potassium under the same conditions as those shown in Figure ?a.

Temporal Changes vithin the Olkaria Reservoir

The age of the geothermal field at Olkaria is not known but there is evidence that, during its life, the thermal activity has changed both in location and character. Evidence €or this includes:

(a) The occurrence of secondary quartz and other hydrothermal minerals which line joints in dykes exposed within nearby Ol' Njorowa (Hell's Gate) Gorge; at some time in the past these dykes clearly served as fluid channels. Intuitively one would also expect that the intrusion and eruption of Holocene lavas (such as Olobutot) would induce

(b) Several cutting chips contain hydrothermal minerals zoned within veins and vugs whose textures are due to physical changes within the reservoir although when these changes took place is not known. For example, in some places a low temperature zeolite (mordenite) is preserved, in what are now much hotter zones, by having become encased within calcite deposited at a later time.

(c) Inspection of the temperature profiles of some wells shows, for example, that the alteration deduced temperature (T.alt) at 640m in Well 2 is 30° hotter than that measured (T.meas). In Well 6 at 680m, T.meas was 2350, and at 980m, 265°, compared with a T.alt of 250° at both depths; there is also a big difference between T.alt of 2650 and T.meas of 2260 at 668m in Well 8. By contrast, comparison at T.alt and T.meas for Well 9, 3 and perhaps also 5, suggests that rocks encountered in these wells are thermally stable although T.alt is slightly hotter than T.meas at the deeper levels in Well 10.

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