

## THE ROLE OF 'STEAMING GROUND' OVER HIGH TEMPERATURE SYSTEMS IN THE KENYA RIFT

M.P.Hochstein <sup>1)</sup> and D.Kagiri <sup>2)</sup>

1) Geothermal Institute, The University of Auckland, New Zealand  
 2) The Kenya Power Co. Ltd, Nairobi, Kenya

### ABSTRACT

several types of geothermal systems occur in the Kenya Rift; the most common type is hosted by young volcanic complexes where almost all discharged heat is derived from shallow vapour with very little liquid discharge. Fumaroles and 'steaming ground' are the prominent manifestations although most (60%) of the heat discharged at Olkaria involves conductive transfer. Linear proportionality between various types of thermal ground exists and allows assessment of the Olkaria heat loss ( $445 \pm 70$  MW) to be based on a detailed study of a sub-area. A poorly understood quasi-conductive mechanism controls the heat transfer of steaming ground which accounts for c. 30% of the Olkaria natural losses. Extending the proportionality concept to other prospects it was found that the heat loss of the Eburru prospect is of the order of  $160 \pm 50$  MW. The output of all systems characterised by steaming ground is of the order of 1200 MW; the natural heat output of Olkaria is by far the largest of all geothermal systems in the Kenya Rift.

### INTRODUCTION

Reconnaissance studies of geothermal prospects in the Kenya Rift Valley were started by the Kenyan Government over 40 yr ago. They attracted sponsorship of international (UNDP) and bilateral aid programmes. After completion of a 15 MW pilot plant at Olkaria, reconnaissance studies were continued by the Kenya Power Co. (KPC). Other reconnaissance studies were undertaken as separate aid projects and results were documented mainly as unpublished project reports. None of these allows a clear ranking of prospects. The first comparable studies became available in 1990 when teams of the British Geological Survey (BGS), in collaboration with the Kenyan Ministry of Energy and a second UNDP geothermal project, published their surveys of the southern Rift Valley sector (Clarke et al., 1990). The report also contains data which had been collected

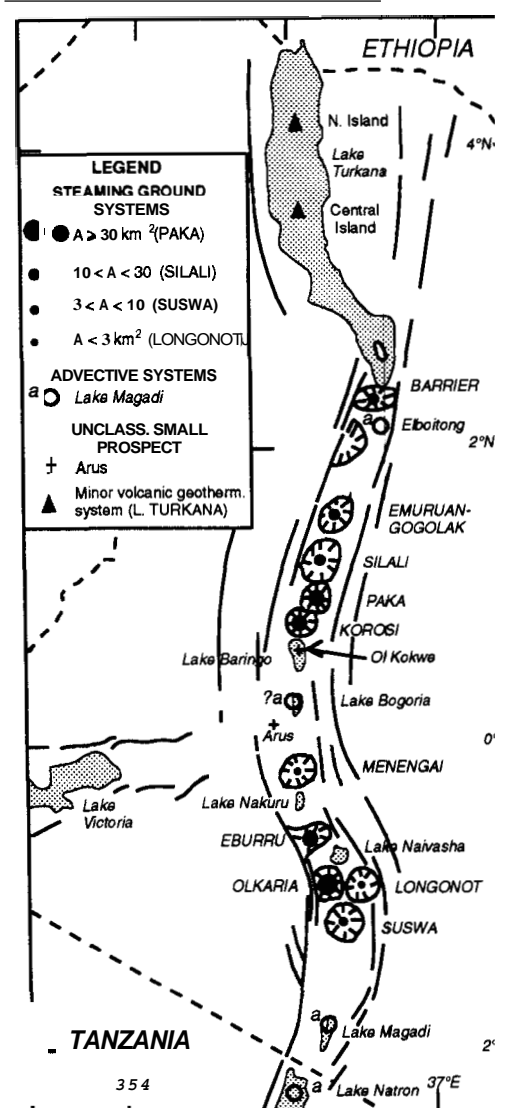


Fig.1 Location of geothermal prospects in the Kenya Rift Valley.

y KPC staff. Similar studies of the poorly known northern sector of the Rift (Dunkley et al., 1993) contain a tentative ranking of 9 geothermal prospects, based on the extent of mapped thermal ground.

Important geothermal prospects in the Rift Valley known from reconnaissance studies are shown in Fig. 1. The figure does not include smaller prospects which discharge little (< 1 MW) heat. Several groups of prospects can be recognised. The largest group contains at least 9 prospects which are all associated with young volcanoes and volcanic complexes and are characterised by significant steam discharge at the surface but practically no discharge of thermal water on the flanks or in valleys. Because of their association with steaming ground, these systems are called here "steaming ground systems"; Olkaria is the most important prospect in this group. Another group contains advective flow systems where only hot water is discharged in natural sinks (lakes). There are also a few other prospects in Fig. 1 which belong to neither group. Only prospects belonging to the large group of steaming ground systems are discussed in this paper.

Mapping of geothermal prospects with thermal methods has been widely used in Kenya. Airborne infra-red (IR) surveys were already used in the early 1970's to delineate thermal ground at Olkaria and Eburru (Glover, 1972). A second UN-sponsored IR survey was made in 1973/4 covering the S part of the Rift. Only results from the Magadi sector have been published (Crane, 1981). LANDSAT thematic mapper images were used by BGS teams during their reconnaissance of N Rift prospects (Dunkley et al., 1993).

Detailed ground temperature surveys were undertaken at Olkaria and Eburru where temperatures (T) at 1 m depth (T(1.0)) were measured. The extent of IR-anomalies was verified at Olkaria, Eburru, Lake Magadi and over the N Rift prospects by near surface spot T readings.

When we looked for criteria to rank the Kenyan geothermal prospects in the early 1990's, we found almost no data which could be used for such ranking. Natural heat loss is one of the parameters which allows ranking but no reliable heat loss data were available. The detailed ground surveys of Olkaria and Eburru had not been analysed and the T-survey of the S part of the Olkaria prospect (E.Domes area in Fig. 2) was still incomplete. A follow-up survey was undertaken in 1993 which covered the E.Domes area and provided important information about T at shallow levels (T at 0, 0.15, 0.5 and 1.0 m depth). The first detailed heat loss study of the S.Olkaria-E.Domes area was completed by Kagiri (1994). Whether these data can be used to assess the losses of other Olkaria sectors will be discussed in this paper.

## THERMAL GROUND AT OLKARIA AND EBURRU

The first information about the extent of thermal ground over both prospects came from IR-data. Maps showing the area of each IR-anomaly, verified by spot readings at 0.15 m depth (T(0.15)), are still available. The Olkaria anomalies cover a total area of c. 0.85 sqkm, areas with spot data of T(0.15) > 70 °C cover 0.77 sqkm (see Table 1). At Eburru, with colder ambient air T, the IR anomalies cover areas of 0.75 and 0.66 sqkm respectively. A map which shows the IR anomalies over Olkaria can be found in Clarke et al. (1990). All areas with intense steaming ground and fumaroles coincide with an IR anomaly. Using empirical data for steaming ground from a NZ study (Dawson, 1964), the likely surface heat discharge was assessed in 1972 pointing to c. 375 and 130 MW for Olkaria and Eburru respectively (Glover, 1972). We know now that these estimates contain systematic, although partially compensating errors since the area of thermal ground was underestimated in 1972 and the data of Dawson overestimated losses. However, the first study indicated that there is about 3 times more heat discharged at Olkaria than at Eburru.

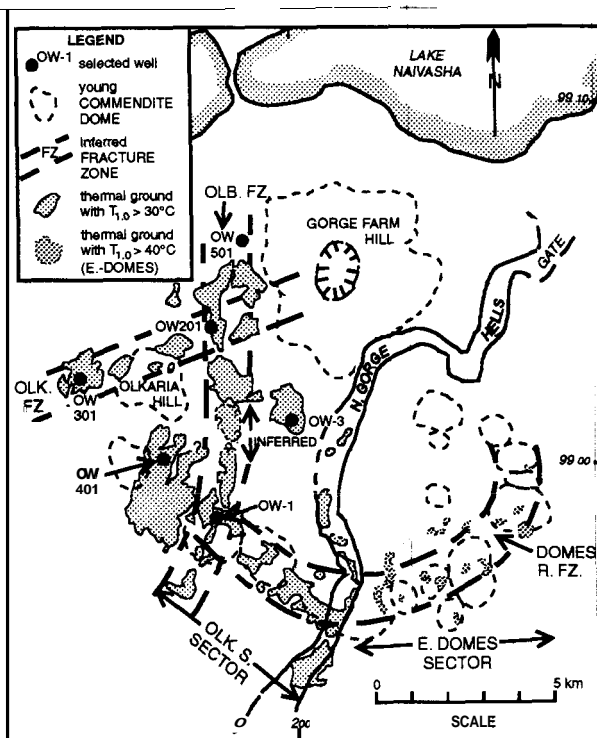


Fig. 2. Olkaria Geothermal Field: Extent of thermal ground with temperatures at 1 m > 30 °C. (OLK.FZ.=Olkaria Fracture zone; OLB.FZ.= Olbutot Fracture Zone; DOMES R.FZ.= Domes Ring Fracture Zone)

TABLE 1: EXTENT OF THERMAL GROUND IN SECTORS OF OLKARIA AND EBURRU

Sector	Area (km <sup>2</sup> ) with T (1.0) > 30 °C	Area (km <sup>2</sup> ) with T (1.0) > 50 °C	Area (km <sup>2</sup> ) with T (1.0) > 70 °C	Area (km <sup>2</sup> ) IR - Anomalies
W. - Olkaria	5.45	0.69	0.10?	0.17
C.+N.-Olkaria	3.7	0.58	0.18	0.35
S.-Olkaria	3.45	0.48	0.13 1)	0.25
E.-Domes	2.0	0.30	0.07 1)	
N.-Eburru	3.2	0.32	0.11	0.32
C.-Eburru	1.35	0.11	0.03	0.13
S.-Eburru	1.55	0.15	0.05	0.20

1) Area of steaming ground with  $\Delta T/\Delta z > 50 \text{ }^\circ\text{C/m}$  at 0.15 m covers c. 0.30 (km<sup>2</sup>) (1993 survey).

A better picture of the extent of thermal ground at Olkaria was obtained by the 1 m T-survey, partially completed in the late 1970's (see Fig.2). The first survey did not extend beyond the Njorowa Gorge since minor thermal ground in the E.Domes sector was not thought to be connected with the Olkaria system. The 1993 survey covered the E.Domes area and also included the S.Olkaria sector for comparison. A similar detailed 1 m T-survey was undertaken at Eburru as part of a Kenya-Japan bilateral project (JICA, 1983). All data together allow a subdivision of thermal ground into 'weak thermal ground ( $30 < T(1.0) < 50 \text{ }^\circ\text{C}$ ), 'intermediate' ground ( $50 < T(1.0) < 70 \text{ }^\circ\text{C}$ ), and 'hot' ground with  $T(1.0) > 70 \text{ }^\circ\text{C}$ . Only the outer contour of 'weak' thermal ground at Olkaria is shown in Fig.2 to avoid crowding. The 1993 survey showed that the extent of 'hot' ground in the original T(1.0) survey was underestimated in the S.Olkaria sector and that 'steaming ground' which shows up with elevated T(0) values occurs already where T(1.0) is  $> 60 \text{ }^\circ\text{C}$ . To overcome this, heat transfer of steaming ground was later assessed from T(0.15) data (see Table 1).

The term "steaming ground" was introduced in the literature by earlier NZ studies when it was thought that a thin layer of steam visible over the surface of some very hot ground was derived from a direct transfer of steam from a shallow soil layer to the air. Our studies have shown that such transfer seldom occurs. However, all "steaming ground" is characterised by elevated surface temperatures T(0) which can be recognised in IR-data. With reference to elevated ground temperatures the term has a clear heat transfer connotation and will be used here in that sense.

To check whether there is any relationship between the areas of various types of thermal ground, one can plot the area enclosed by  $30 < T(1.0) < 50 \text{ }^\circ\text{C}$  contours versus the area with  $50 < T(1.0) < 70 \text{ }^\circ\text{C}$  for various sectors of the Olkaria and the Eburru prospect using data from Table 1. The plot in Fig.3 shows a

clear linear relationship although the proportion of 'intermediate T' ground at Eburru is significantly smaller. A larger scatter is indicated if one plots the area with  $T(1.0) > 70 \text{ }^\circ\text{C}$  versus the area with IR anomalies, although some proportionality still exists. Since the first area contains a large uncertainty, we used the proportionality of the IR - anomalies together with our own T(0.15) data to assess the areas of steaming ground at Olkaria

There is no linear proportionality between the areas of IR anomalies over Olkaria and Eburru and the areas with conductive heat transfer. This probably reflects different threshold levels in the IR data since the ambient air T at Eburru and its ground emissivity

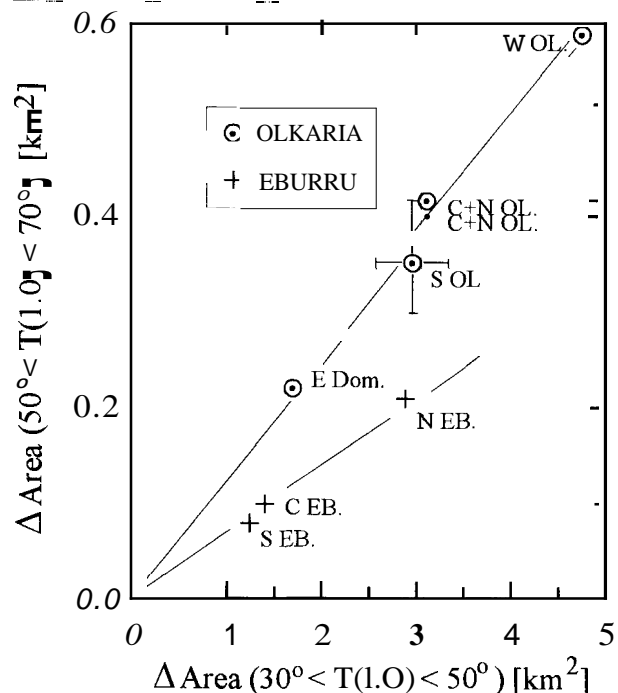


Fig.3. Area of two types of thermal ground for sectors of the Olkaria and Eburru Fields.

(dominantly agricultural land) differ from those at Olkaria (2.5 °C higher ambient air T and dominant natural park land).

**CONDUCTIVE AND QUASI-CONDUCTIVE HEAT TRANSFER IN THERMAL GROUND**

Temperature data from the 1993 survey were analysed to separate ground with conductive heat transfer from "steaming ground" with a different transfer mechanism. The T data were not reduced for daily T (mean amplitude ± 5 °C) and annual T (c.± 2 °C) variations since no long term recording base was used. This causes some scatter of the data ( up to ± 1.2 °C for T (1.0) and ± 1.8 °C for T (0.15)). The scatter of T(0) over cold ground is significantly greater but daily variations are attenuated over steaming ground once T(0) is > 10 °C above ambient.

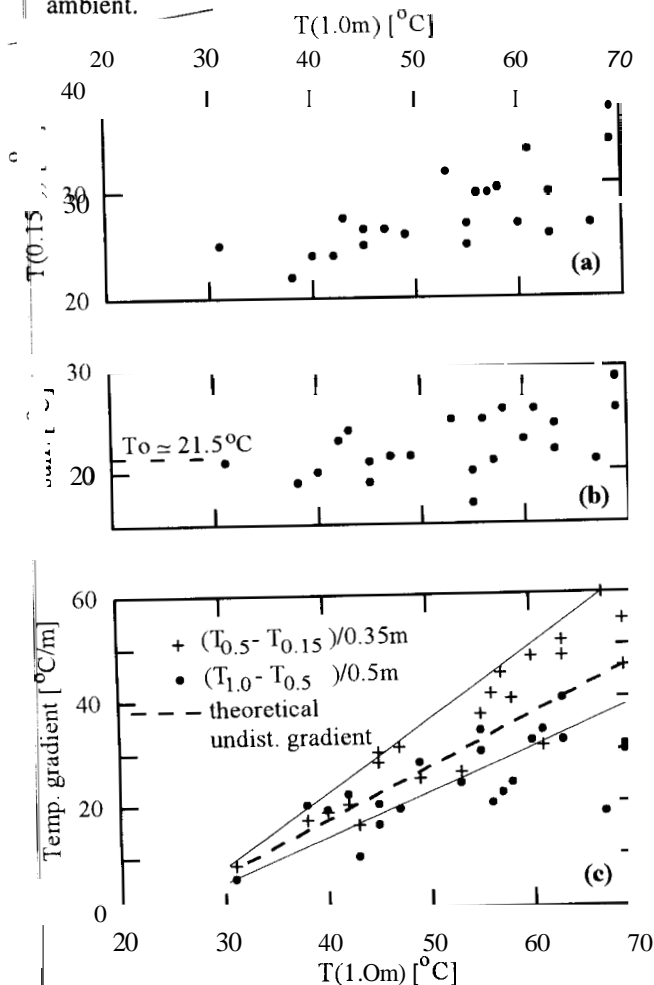


Fig.4. Conductive heat transfer: 1 m temperature (T (1.0)) versus T at 0.15 m (a), T at the surface (b), and two temperature gradients (c) (for depth interval of 0.5 to 0.15 m and 1.0 to 0.5 m respectively), S.Olkaria-E.Domes area.

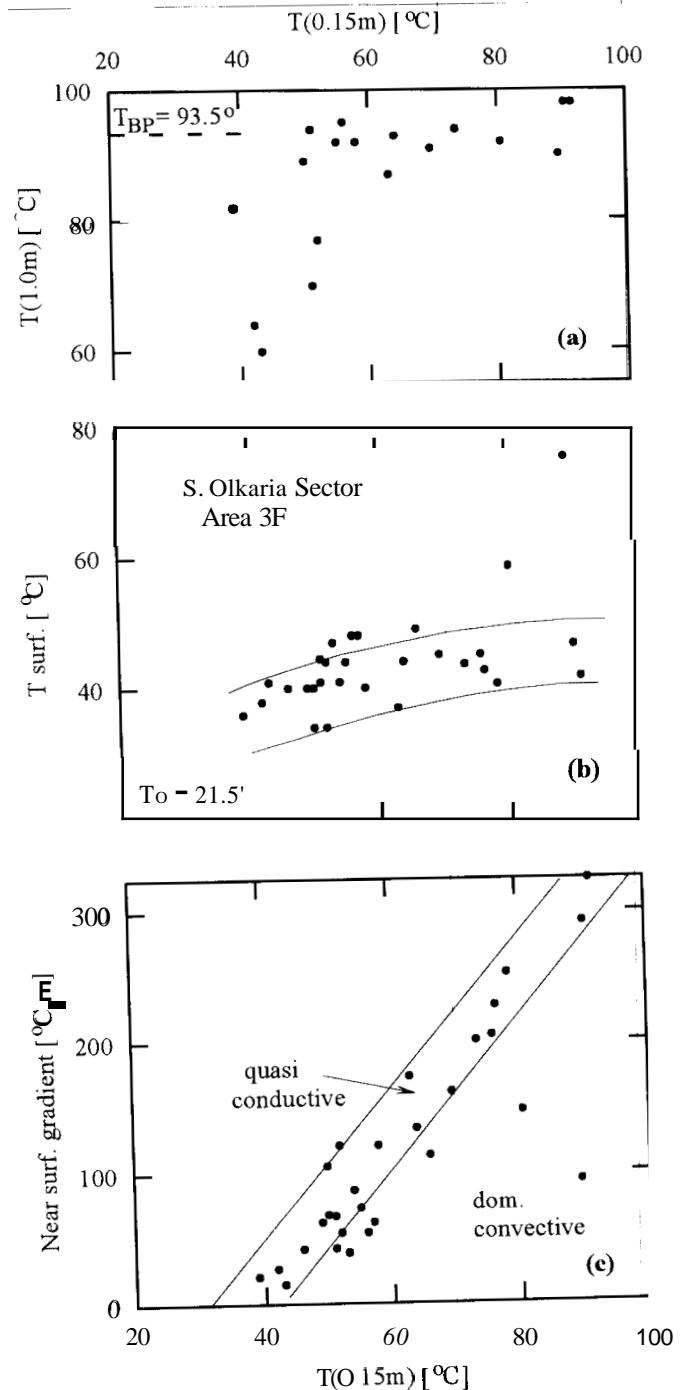


Fig.5. Quasi-conductive heat transfer: 0.15 m temperature (T(0.15)) versus T at 1.0 m (a), T at the surface (b) and the near-surface temperature gradient (c), from steaming ground in S.Olkaria.

Conductive transfer is clearly indicated for stations in the S.Olkaria-E.Domes sector where  $T(1.0)$  is  $< 70$  °C. The temperature gradients between 0.5 and 1.0 m depth (grad (0.5-0.15)) and 1.0 and 0.5 m (grad (1.0-0.5)) have been plotted versus  $T(1.0)$  in Fig.4c. For undisturbed conditions and constant thermal conductivity both values should coincide. The plot shows that there is a significant scatter with grad (0.5-0.15) values being somewhat greater which can be explained by inhomogeneity in thermal conductivity or minor convective transfer, especially for  $T(1.0) > 60$  °C when surface T values ( $T(0)$ ) start to increase. The plot indicates that the mean gradient in the upper 0.5 m (at  $T(1.0) = 40$  °C) is  $18.5 \pm 4$  °C/m; it increases to  $40 \pm 10$  °C/m for  $T(1.0) = 60$  °C. These values are close to predicted gradients with respect to  $T(0) = 21.5$  °C, the mean annual T at Olkaria.

A different near-surface temperature field occurs beneath steaming ground where temperature gradients below 0.5 m attain rather small values and where the near-surface gradient (grad (0.15-0)) tends to increase almost linearly with  $T(0.15)$  once  $T(0.15)$  is  $> 40$  °C. The trend is shown in Fig.5c based on results of a T- survey of steaming ground in the S.Olkaria sector associated with the Olbutot Fracture Zone (Fig.2). The pattern points to a quasi-conductive heat transfer near the surface and a small convective component (dQ) to maintain the surface at elevated temperature (see Fig.5b). A similar behaviour has been observed over the steaming Hipaua ground in NZ (Severne and Hochstein, 1994) where the slope of the linear band enclosing grad (0.15-0) values is similar to that observed at S.Olkaria (c. 5.5/m) and in the E.Domes area (slope of c. 4/m). The finding that the near-surface T gradient increases quasi-linearly with  $T(0.15)$  temperatures casts doubt on an earlier interpretation of NZ data by Dawson (1964) who inferred that heat transfer at the surface of steaming ground was controlled by a power ( $T^4$ ) relationship. Fig.5 also shows that once  $T(1.0)$  approaches local boiling point (BP) temperatures (93.5 °C at Olkaria, elevation c. 2000 m), with  $T(0.15) > 50$  °C, minor convection of steam occurs beneath a few stations as indicated by lower grad (0.15-0) and anomalous  $T(0)$  values. The same phenomenon has also been observed over steaming ground at Hipaua in NZ.

Some condensation of steam is always associated with steaming ground. The areas with elevated  $T(0)$  values have usually a 'moist' appearance and coincide with reduced or even absent vegetation. Studies in NZ (Hipaua) have shown that saturation (S) can reach a maximum ( $0.5 < S < 1$ ) below 0.2 m depth; at shallower level, values of  $0.3 < S < 0.5$  seem to prevail. Assuming that a similar setting occurs at Olkaria, one can postulate that most of the steam

rising from below, say, 1 m depth would condense in a shallow saturated layer, presumably with intense thermal alteration. Since no condensates are discharged in sinks at the surface, all liquid drains downwards. This setting has affinity with that of a "heat pipe" described, for example, by McGuiness (1988). Heat transfer at the top of the shallow condensate layer would then be a dominantly conductive transfer controlled by the T at the top of that layer.

The thermal conductivity k of partially saturated soils (saturation S) with porosity  $\phi$  and matrix conductivity  $k_p$  can be estimated from:

$$k = b k_p (1 - \phi)^m + S \phi k_f$$

where b and m are empirical constants (b=1 and m=2 are used here as suggested by Hochstein and Soengkono, 1994) and  $k_f$  is the conductivity of condensates ( $0.6 \text{ W/m}^\circ\text{C}$ ).

Very few porosity data are known for the pyroclastic surface layer at Olkaria; again we have to resort to data from steaming ground studies at Hipaua where  $\phi$  of thermally altered ground is in the range of  $0.3 < \phi < 0.4$ . For rhyolitic pyroclastics the matrix conductivity is  $2 < k_p < 2.5 \text{ W/m}^\circ\text{C}$ . Assuming that similar constants apply to steaming ground at Olkaria, the near-surface layer of steaming ground would have an average conductivity k of  $1.05 \pm 0.25 \text{ W/m}^\circ\text{C}$  for  $0.3 < S < 0.5$ .

The layer with dominantly conductive heat transfer of ground surrounding steaming ground at Olkaria is dry. The porosity of dry, thermally unaltered pyroclastics falls in the range of  $0.3 < \phi < 0.5$ . For such a dry cover a conductivity of  $0.85 \pm 0.35 \text{ W/m}^\circ\text{C}$  can be inferred.

#### NATURAL HEAT LOSS OF THE OLKARIA FIELD

The surface heat transfer occurring in the S.Olkaria-E.Domes area can now be assessed. The various loss components are listed in Table 2. Conductive losses are dominant and amount for that sector to about 100 MW. The quasi-conductive losses associated with steaming ground were assessed from several sub-area vs. temperature gradient plots pointing to a transfer of  $c. 47 \pm 23 \text{ MW}$ .

The heat discharged by fumaroles was assessed from steam volume flow rates using both a VENTURI meter and a PITOT tube. There was some discrepancy between the results and a separate estimate was made using proportionality between steam cloud volumes with reference to a calibrated discharge feature. The total discharge was found to be  $12 \pm 5 \text{ MW}$ . Minor discharge of hot water in the Gorge accounts for about 1MW.

TABLE 2: ASSESSMENT OF HEAT LOSS COMPONENTS FOR GREATER OLKARIA FIELD

Component	Area or Feature	S.-Olkaria and E.Domes (MW)	C. + N.-Olkaria (MW)	W.-Olkaria (MW)	Subtotal (MW)
Conduct.	30<T(1.0)<50	73.5±34	49±23	75±35	197.5±54
Conduct.	50<T(1.0)<70	24.5± 8.5	17± 6	25± 8.5	66.5
IQ corr.	60<T(1.0)<70	2?	1.5?	2?	5.5
quasi-cond.	steaming grd	47 ± 23	45 - 75	20 - 40	c.137 ±?
steam	fumaroles	12 ± 5	17 ± ?	8 ± ?	c. 37 ± ?
hot water	hot springs	1.0	0	0	1.0

The total natural heat discharge of the Olkaria-E.Domes area is therefore  $160 \pm 42$  MW. Using a slightly different weighting for sub-areas of steaming ground and using a constant thermal conductivity  $k$  of  $1.3 \text{ W/m } ^\circ\text{C}$ , Kagiri (1994) obtained a total of 187 MW with no error estimate.

The assessment was extended to the other sectors of the Olkaria Field. The conductive losses can readily be assessed (see Table 2) and since there is no liquid natural discharge, that component could be neglected. However, there was a problem in assessing the losses of steaming ground. Proportionality between intense steaming ground and areas with  $T(1.0) > 70^\circ\text{C}$  is poor. Extreme values and sector proportionality between IR anomalies were then used to obtain an upper and a lower estimate for the losses with reference to losses in the S.Olkaria sector. No error estimate can be given; it is likely that in the W.Olkaria area losses are between 20 and 40 MW and over the Central and North Olkaria area, where intense steaming ground is associated with the Olbutot fault zone, these losses are in the range of 45 to 75 MW. The total natural heat discharged by all mapped thermal ground is therefore of the order of  $445 \pm 70$  MW, a huge heat discharge which is similar to that associated with the largest liquid dominated systems in NZ.

The estimate given here is still conservative since conductive losses of warm ground in the outer west of Fig.2 have not been included. In addition, there is still a large area of minor thermal ground with  $22 < T(1.0) < 30^\circ\text{C}$ ; extrapolation of data from Fig.3 indicates an area of 40-50 sqkm for this ground. With an anomalous heat flux of  $1 - 3 \text{ W/sqm}$  it is possible that another  $100 \pm 50$  MW of heat is transferred through that ground. Thermal ground at Olkaria might therefore cover a total area of 55 to 65 sqkm.

#### INFERRED LOSSES OF OTHER STEAMING GROUND SYSTEMS IN THE RIFT

Using the same assessment as shown in Table 2, the likely heat loss of the Eburru prospect was estimated using data in Table 1 and assuming that there is close affinity between the mechanisms of heat transfer at Olkaria and Eburru. Proportionality of ground with  $T(1.0) > 70^\circ\text{C}$  was used at Eburru to assess both steaming ground and fumarole discharges with reference to the respective S.Olkaria components. Since no condensates and diluted deeper liquids are discharged at Eburru, losses by discharge of thermal water could be neglected. It was found that the likely heat discharge at Eburru is of the order of  $160 \pm 50$  MW of which 70% are transferred by conduction in ground with  $T(1.0) < 70^\circ\text{C}$ . The ratio of heat discharged at Olkaria and Eburru based on detailed ground surveys is almost the same as that inferred 25 years ago from IR- anomalies and spot temperature readings, namely 2.8 (in 1996) versus 2.9 (in 1972). This indicates that for the steaming ground systems in the Kenya Rift relative (but not absolute) heat losses can be estimated from IR-data.

Using published maps and copies of field notes of the BGS team (kindly made available in 1995 by P.Dunkley) a recent study at Auckland by Ndolo (1996) showed that a quasi-linear proportionality between various types of thermal ground also exists between systems in the N part of the Rift which exhibit significant hot and steaming ground (Dunkley et al., 1993). There is a very close relationship between the Eburru and the Korosi systems where in each case steaming ground is aligned for c. 9 km in NNE direction with an average width of c. 3.5 km between the outer segments. With this link, which still has to be substantiated by ground studies, an

order of magnitude estimate can be given for the losses of the N prospects. It was found that there is close affinity between the systems at Eburru, Korosi, and Silali which together discharge probably about as much heat in the natural state as Olkaria.

The total heat transferred by all steaming ground systems shown in Fig. 1 is of the order of 1200 MW, again a conservative estimate. Almost 40% of that heat is discharged by one prospect: Olkaria.

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