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THE TONGARIRO GEOTHERMAL SYSTEM (NZ): REVIEW OF GEOPHYSICAL DATA

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SUMMARY - A review of geophysical data collected over the Tongariro geothermal prospect since 1974 is presented. Interpretation shows that the resistivity structure and hydrological setting of the Tongariro geothermal system have close affinity to those of a vapourdominated system. Its vapourdominated reservoir is capped by a coherent, c. 200 to 300 m thick condensate layer containing altered rocks with low resistivity. All active manifestations are confined to a c. 10 km^2 large area underlain by the high standing part of this layer. The heat discharged by all manifestations amounts to c. 58 MW of which most (c. 44 MW) is released by the Ketetahi fumarole field. Four earthquake swarms since 1985 had epicentres close to the Te Mari Craters, where volcanic activity occurred last century. The isotopic characteristics of discharged steam and the recent history of volcanic eruptions can be used to classify the Tongariro prospect as a volcanic geothermal system.

1. INTRODUCTION

The Tongariro geothexmal system in the North Island of New Zealand occurs beneath the high-standing young volcanic massif of Mt Tongariro. Its reservoir has been directly affected by recent volcanic activity since magma discharged fiom the Upper Te Mari Crater and Red Crater (Fig.1) last century (D.R. Gregg, in Wilson, 1960) must have ascended through the geothermal reservoir. The structure of the Tongariro geothermal system, as it is presently known, can only be inferred from the interpretation of geophysical and geochemical data.

Major active Surface manifestations occur at Ketetahi with minor steam discharges at Red- , Central - , and the Te Mari Craters (Fig.1). Previous reconnaissance studies include chemical and isotopic analyses of condensates and steam samples fiom Ketetahi and Red Crater (Lyon and Stewart, 1985, and Giggenbach, 1996). The heat discharged at Ketetahi in 1936/37 was assessed by Wilson (1960); results of a repeat survey in 1973/74 are listed in Hochstein and Bromley (1979) and for the Red Crater and Te Mari Crater manifestations in Hochstein (1985). Other published geophysical studies include DC-resistivity and MT surveys (Hochstein and Bromley, 1979).

Surface manifestations and Surface alteration outside the Ketetahi area were studied recently by Walsh (1997); this study also includes an analysis of local seismicity and a compilation of all resistivity data, including additional MT soundings made recently. Results of the study and a review of heat loss studies of the Ketetahi fumarole field are summarised here.

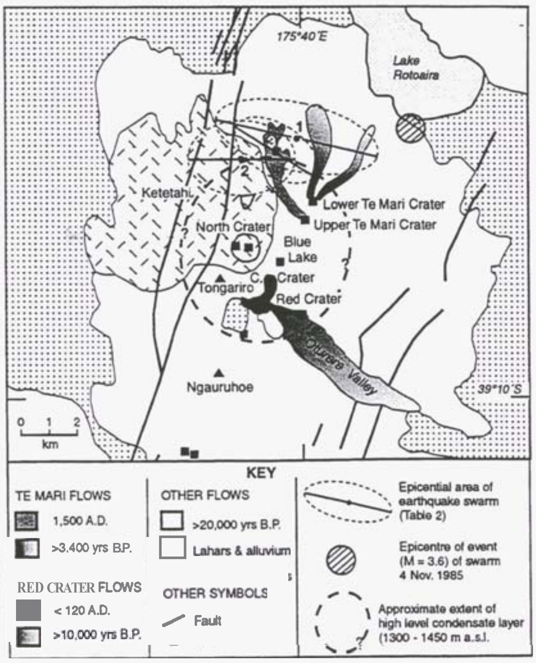

Fig.1: Geological map of the Tongariro area showing the extent of young lava flows (Cole, 1978); epicentral areas of earthquake swarms between 1985 and 1995 are also shown.

2. GEOLOGICAL SETTING

The Tongariro geothermal system is hosted by Quaternary volcanic rocks of the Tongariro Massif, comprising calc-alkaline basaltic andesites, andesites and minor dacites. Radiometric ages of these rocks reveal alternating periods of dynamic cone growth and quiescence (Hobden et al., 1996).

All presently active thermal areas are confined to deposits and flows which are less than 15 ka old (Fig.1).

The Tongariro Massif is dissected by numerous NNE trending, young normal faults with a significant strike slip component. Most of these faults dip towards eruptive centres (Cole, 1990). The young volcanic vents of Red Crater and the Te Mari Craters occur over a concealed fracture zone with the same (i.e., NNE) regional tectonic trend (Fig.1). The inferred, thick condensate layer capping the geothermal reservoir appears to be centred on the North Crater of the flat topped Mt Tongariro.

3. HEAT LOSS ESTIMATES

A heat loss survey conducted in 1996 covered areas with Surface manifestations at Central Crater, Red Crater and the Te Mari Craters. The Ketetahi area could not be re-surveyed because access was denied. In assessing the heat discharged at each area, their discharge features were grouped into:

(1) steaming ground with temperatures at 0.2 m depth ($T_{0.2}$) > 85 °C;
(2) warm ground with $T_{0.2}$ < 85 "C;
(3) thermally *(steam)* altered but now inactive cold ground;
(4) direct discharges of *steam* and gas (fumaroles and *steam* vents) as well as diffusive *steam* discharges (confined to fractured andesite lava flows).

Steaming and warm ground in all three areas listed in Table 1 covers a total of c. 50,000 m^2 with $T_{0.2}$>15°C, including 6500 m^2 with $T_{0.2}$ > 80°C. The latter ground is thermally altered. Dominantly conductive heat transfer is indicated for this ground by plotting $T_{0.2}$ versus the temperature gradient in the top 0.2 m thick layer (Fig.2). A slope of about 4 m^{-1} is indicated. Only for $T_{0.2}$ > 85 °C, the data change rapidly, pointing to some convective heat transfer by ascending steam. The plot is similar to that obtained by Severne and Hochstein (1994) for the Hipaua steaming ground area within the Tokaanu-Waihi prospect which lies c. 20 km NNE of the Tongariro system. Using the Same constants and pro-portionality for conductive and convective transfer as used to analyse the Hipaua data, partial heat losses for the three thermal areas were obtained which are listed in the second and third rows of Table 1. The area with warm ground (class II) is only poorly known and values in the third row are uncertain.

Heat transfer by *steam* discharged from fumaroles and *steaming* vents was assessed from mass flow

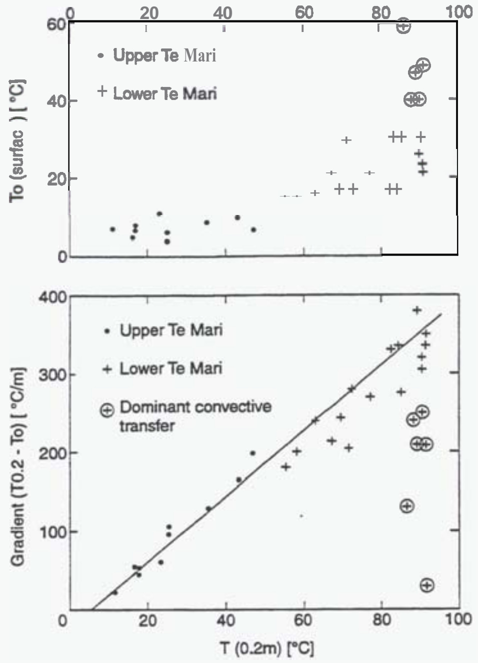

Fig. 2: Temperatures at 0.2 m depth versus temperature gradient between 0.2 m and surface (Tongariro *steaming* ground areas-except Ketetahi)

estimates and *steam* enthalpy. The mass flow rate, in turn, was estimated by using vent size, sound pitch of discharging *steam,* height and shape of *steam* plumes. Direct losses by *steam* are shown in the first row of Table 1. Steam losses fiom Red Crater are c. half an order of magnitude lower than those cited in Hochstein (1985); the old values had been overestimated whereas the losses from steaming ground cited in 1985 had been underestimated *(see* Appendix). The total heat losses fiom the three areas listed in the first three rows of Table 1 are only c. 30% of the 44 MW discharged by the Ketetahi fumarole field (see Appendix). The actual losses from the whole Tongariro geothermal system, however, are greater than the *sum* of the losses from these active areas. Conductive losses from the high standing layer of hot condensates extending beneath the Tongariro Massif have to be considered as well as possible losses caused by lateral, concealed outflows of condensates. These components will be assessed after the likely reservoir structure based on resistivity surveys has been introduced.

4. MICRO-EARTHQUAKE ACTIVITY

Earthquake swarm activity beneath the nearby geothermal system of Tokaanu-Waihi is characterised by aligned epicentres (Hochstein et al. 1995). To check whether a similar pattern occurs beneath the Tongariro geothermal system, seismic data recorded by a local network during 1986 to 1995 were analysed. Swarm activity in the area shown in Fig.1 was cited by Sherburn (1992) who observed a *swarm* on 4. Nov 1985. Only the epicentre of the largest event of this swarm could be determined with accuracy; it lies near the S shore of Lake Rotoaira (Fig. 1).

Further analysis showed that between 1988 and 1994 three more swarms had occurred close to, but to the N of the highstanding condensate cap of Tongariro. The characteristics of the swarms are listed in Table 2; the approximate spread of associated epicentres was assessed by best fit ellipses which are shown in Fig. 1; the epicentral areas lie between 11 km^2 (*swarm* 88 Dec 25) and 6.5 km^2 (swarm 94 Jan 30). The focal depth of all events was assumed to be < 5 km. Minor, *swarm*-like events occurred on 94 Feb 08, 94 Mar 28, and 95 Jun 18 whose epicentral areas (0.5 to 2 km^2) lie within those of the major swarm events listed in Table 2.

Differences between the swarm activity beneath Tongariro and Tokaanu-Waihi are:
1. Almost all epicentres of the Tongariro swarms lie outside the area with an inferred high level cap of condensates whereas at Tokaanu-Waihi almost all epicentres lie close to the centre of the geothermal reservoir.
2. The epicentral area enclosing the Tongariro swarm events is larger than that at Tokaanu whose epicentres are more clearly aligned.

The only swarm at Tongariro with aligned epicentres is that of 88 Dec 25 (see Fig.1). The major WNW trending axis (ellipse) of its epicentral area intersects at right angles the presently active NNE trending faults. Almost all Tokaanu swarms show alignment in the same direction (i.e., WNW). Since the epicentral *areas* (Fig.1) are close to the historically active Te Mari Craters (last activity between 1869 to 1896) it is possible that magma injection in basement fractures is still occurring.

The spatial distribution of seismic energy from all seismic events between 1986 and 1995 was also studied. This showed that most of the energy was associated with the swarm events. If swarm activity is eliminated from the data set, the plot of the residual seismic energy shows a random spatial distribution forthe whole area shown in Fig.1 with little seismic activity beneath the Tongariro geothermal system.

5. RESISTIVITY STRUCTURE OF THE TONGARIRO GEOTHERMAL SYSTEM

The first resistivity studies (DC- and MT soundings) were made between 1975 and 1978 (Hochstein and Bromley, 1979). A follow-up survey was *started* in 1996 and results from two additional MT-soundings are listed in Walsh (1997), together with the interpretation of a few additional DC-soundings from the 1975/78 *survey* which were only analysed recently. The location of all sounding stations is shown in Fig. 3. Most of the stations (10 out of 14) lie along a N-S profile (A to C in Fig. 3). The interpreted 1-D sections along profile AC are shown in Fig. 4.

Since only a few additional stations have been occupied since 1978, the overall resistivity structure in Fig.4 is similar to that shown by Hochstein and Bromley (1979). The following features *can* be recognised:
1. A low resistivity layer (3 to 10 ohm-m) occurs beneath the whole NS section at depths between c. 300 to 500 m; beneath the Oturere Valley this layer might exhibit slightly greater resistivities (up to 20 ohm-m). It is overlain by rocks with resistivities > 150 ohm-m. The layer is close to the surface (within 40 m) in the Ketetahi area where thermally altered rocks are exposed at the surface.
2. Some of the soundings show that the low resistivity layer is probably limited in thickness to about 200-500 m (allowing for equivalence). Further resistivity work is needed to confirm this.
3. The effect of rocks beneath this layer *can* only be recognised in the MT-soundings, pointing to intermediate values between 30 and 50 ohm-m. Tertiary mudstones, underlying the volcanic rocks to the north, are inferred to produce a layer of similar resistivity (30 ohm-m) near MTB.

These features can still be interpreted in terms of the old (1979) resistivity model where the 200 to 500 m thick, low resistivity layer was thought to represent thermally altered rocks saturated with hot condensates ("condensate layer") which are underlain by less altered rocks of a vapour dominated reservoir. The resistivity structure of the Tongariro reservoir is indeed similar (with respect to each of the three features listed above) to that of the vapourdominated systems of Kamojang and Darajat in Java (Sudarman and Hochstein, 1983). In addition, there are close similarities between their geological and hydrological settings. All three prospects occur beneath high standing young volcanic massifs, exhibit similar fumarole fields and discharge fluids of the same composition.

In 1979 we suggested that the Tongariro geothermal reservoir is probably confined to the area covered by the domed condensate layer (top at levels of c. 1300 to 1450 m a.s.l.), i.e., between Red Crater and the Ketetahi fumarole field shown in Fig. 4. The extent of this updomed layer is also shown in Fig. 1 where it encloses c. 30 km^2 . This interpretation implies that the low resistivity layer outside is caused by alteration from outflow structures of hot condensates. However, no thermal springs, even with diluted condensates, have been found in deep valleys on the flanks of the Tongariro massif. This implies that the outflowing fluids are restricted by overlying aquitards. Developments of the Kamojang and Darajat reservoirs in Java showed that large outflows of condensates do not normally occur. Results of modelling studies (Straus and Schubert, 1981) indicate that for fluid flow stability, these reservoirs have to be surrounded and capped by rocks of low permeability (probably of the order of <<1 milliDarcy) which impedes outflows, although

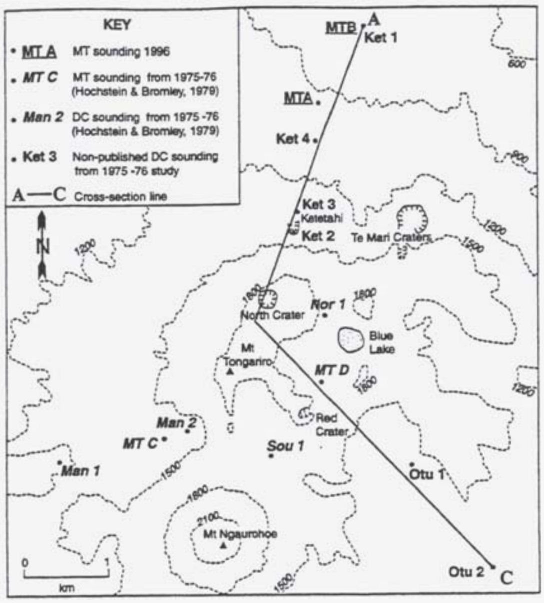

Fig.3: Location of MT- and DC resistivity sounding stations occupied in the Tongariro *area.*

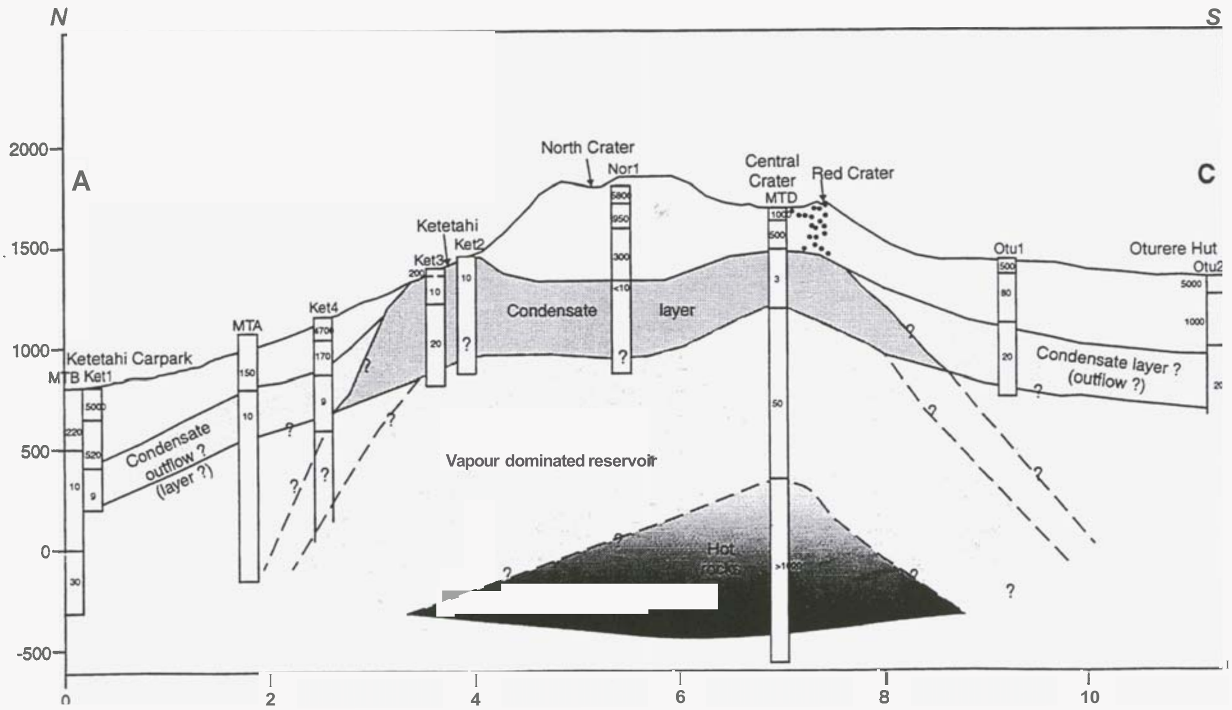

Fig.4: Resistivity cross-section from Ketetahi carpark (A) to Oturere Hut (C); figures in the resistivity column beneath each station refer to true resistivities (assuming a 1D-structure).

the rocks inside the reservoir exhibit high permeabilities (up to 40 milliDarcy). Ongoing MT studies north of the MT B station have recently shown that the low resistivity layer wedges out, probably into Tertiary mudstones.

6. INFERRED HEAT TRANSFER ASSOCIATED WITH THE HOT CONDENSATE LAYER

Well measurements made at Kamojang (Dench, 1980) have shown that this vapour-dominated system is capped by a coherent condensate layer. The temperature at the top of this layer is close to boiling (at p_{atm}). The pressure and, hence, temperature increases linearly with depth with p at the bottom of the layer reaching c. 35 bar (c. 240 °C). Fluids analysed from the Ketetahi fumarole field indicate that vapour separation occurs there at c. 250 °C (Giggenbach, 1996). This implies that this process should occur at the top of the vapour dominated reservoir (i.e., bottom of the condensate layer). Assuming that the thermal regime of the condensate layer covering the Tongariro reservoir is similar to that at Kamojang, the conductive heat losses from the top of the layer can be assessed. Since this layer occurs at depths between c. 300 and 500 m below ground surface along the whole section in Fig.4, and using an average thermal conductivity of, say, 2 W/mK for these cover rocks, a conductive heat transfer of c. 0.5 MW/km^2 is indicated. If the area of the concealed condensate layer is of the order of 30 km^2 (high standing cap), the total conductive losses would be c. 15 MW. If the condensate layer plus outflows are considered, the area could be as large as 60 km^2 (with inferred conductive losses of the order of 30 MW).

There are probably also losses associated with outflows from the high standing condensate layer. Conservation of mass can be used to argue for a radial outflow assuming that all heat transferred by conduction (i.e. c. 0.5 MW/km^2) is replenished by condensation of vapour (at a rate of c. 6.3 kg/s) in the lower part of the layer. Using a pressure gradient value given by the slope of the layer in Fig. 4, and assuming a thickness of c. 250 m for this layer, its (radial) permeability can be assessed for condensates at, say, 170 °C moving downslope. This points to an average value of c. 9 milliDarcy for this layer. To maintain fluid stability, the bottom of the layer requires, however, permeabilities of $\ll$ 1 milliDarcy (Straus and Schubert, 1981). A radial outflow of 6.3 kg/s of condensates would transfer c. 4 MW of heat. If condensation of vapour also takes place beneath the flanks, then the heat transfer by outflows would be greater.

The total heat loss of the Tongariro system is therefore given by the sum of the losses from all Surface manifestations (c. 58 MW), the conductive losses from the top of the condensate layer which, according to its inferred area, are between 15 and 30 MW, and some minor losses (at least 4 MW) from an inferred radial outflow of condensates.

7. DISCUSSION

The Tongariro geothermal is most likely a vapour-dominated system, which is capped by a coherent condensate layer containing intensely thermally altered rocks. Reservoir and condensate layer are hosted by young volcanic rocks of the Tongariro volcanic centre. The resistivity structure of the Tongariro prospect has close similarities to other vapour-dominated systems in a similar setting in Java (Kamojang and Darajat). The reservoir and its condensate layer have been pierced by magma, feeding minor flank eruptions at the Red - and Te Mari Craters during the last century. Steam discharged today by these craters and the Ketetahi fumarole field have essentially the same chemical and isotopic signatures indicating that between 30 and 80% of the steam is of magmatic origin (Giggenbach 1996). The Tongariro system can therefore be classified as a volcanic geothermal system. Earthquake swarm activity with epicentres close to the Te Mari Craters can be interpreted as events due to deep intrusive magma activity.

A re-assessment of the heat output of the Ketetahi fumarole field (c. 44 MW) completes a 60 yr long history of attempts to estimate heat discharge from this field. Earlier attempts were impaired by overestimating direct steam discharges and underestimating losses from steaming ground. The heat discharged by all active surface manifestations of the Tongariro system is c. 58 MW, which is rather low compared to direct discharges from liquid dominated systems in the Taupo Volcanic Zone, but similar to losses from Kamojang and Darajat. The low output reflects, presumably, the effect of mantling low permeability rocks which are required to maintain flow stability within the vapour reservoir. Such a mantle would also impede lateral recharge of colder meteoric fluids. The high proportion of magmatic steam discharged can thus be explained.

The lateral extent of the (low resistivity) condensate layer is still unknown; it may vary between 30 and 60 km^2. Additional MT-soundings over the flanks are required to define its true extent which would allow an assessment of the likely conductive heat losses from its top.

APPENDIX

A. HEAT LOSS ASSESSMENTS OF THE KETETAHI FUMAROLE FIELD (A REVIEW BY M.P.HOCHSTEIN)

The first heat loss assessments of the Ketetahi fumarole field were made in 1936/37 when S.H.Wilson measured the (volume) flow rate of fumaroles using a Pitot tube and assessed the output of other steam vents by comparing steam cloud volumes. This study was the first attempt to measure the heat output of a major geothermal field in New Zealand. A summary of the observations was published much later (Wilson 1960); the survey gave variable results, as indicated by the quoted range of 35 to 155 MW with a median value of c. 65 MW. In addition to losses by steam discharge, minor losses associated with the discharge of hot condensate water were also quoted. No further details of the measurements were given, apart from measurements made in the steam jet of a major fumarole (the "Main Blowhole").

A second assessment of heat discharged by the fumarole field was attempted in 1973/74 when the location of all major discharge features, the extent of thermal and steaming ground together with soil temperatures, and the discharge rate of condensates were mapped and measured by P.R Moore, later published by Moore and Brock (1981). The output of fumaroles was assessed by M.P.Hochstein using the method of Wilson (1960); the output of warm and steaming ground was obtained by using the empirical relations of Dawson (1964). The fumarole studies showed again non-reproducible results. A preliminary assessment of the survey was communicated in 1976 when a range of 100 to 125 MW was cited for the total heat discharge (Hochstein and Moore, 1976).

A1. PROBLEMS WITH ASSESSING FUMAROLE MASS FLOW RATES

When fumarole fields similar to that of Ketetahi were surveyed in Java by M.P.Hochstein after 1975, it was found that the 1973/74 Ketetahi survey contained systematic errors since:

1) anomalously high and non-reproducible volume flow rates can be obtained when the steam flow of a fumarole is measured not inside the vent but at some convenient, short distance above it;

2) stable flow speeds of fumaroles can sometimes be obtained in the centre of the steam jet (v_{max}) but not near the margin; reduction with respect to an average speed ($v_{av} = 0.6 - 0.7\ v_{max}$) is required.

The output of the same large fumarole (Nr.43 in Moore and Brock, 1981) was measured again in June 1979; this time reproducible results were obtained in the vent where v_{max} = 190 m/s with T_{max} = 135 °C. With v_{av} = 115 m/s, a mass flowrate of 1.7 kg/s of steam was obtained (equivalent to a heat discharge rate of 4.5 MW). In 197314 a three times greater, apparent flowrate had been inferred when measurements were made c. 0.5 m above the vent. A similar problem was also encountered in 1936/7, as indicated by Wilson's measurements taken in the largest Ketetahi fumarole, the "Main Blowhole" (Wilson, 1960). Here he observed apparent flow rates between 2.7 and 8 kg/s. The differences can be explained as due to an influx of air which is sucked towards any steam jet discharging with high speed.

Assuming that the output of the large fumarole had not changed significantly between 1973/4 and 1979, as indicated by the rather constant T values measured by Giggenbach inside the vent during the same period ("Main vent" in Giggenbach, 1996), we used the June 1979 data to revise our 1976 estimate. The total output of the Ketetahi field is a reduced value of c. 36 ± 8 MW (see Table 3) which was cited by Hochstein and Bromley (1979). Unfortunately, Moore and Brock (1981) did not notice this revision and listed in their study the 1976 estimate.

A2. PROBLEMS WITH ASSESSING HEAT DISCHARGED BY STEAMING GROUND

Our difficulties in assessing the heat losses at Ketetahi did not end with the revision of the steam discharges. We still had reservations about our 1979 assessment of losses from steaming ground (listed as c. 9.5 MW in Table 3) which had been obtained by using an empirical formula of Dawson (1964) where heat discharged over such ground was assumed to be proportional to the 4th power of the soil temperature at 0.15 m depth.

Flowrate measurements of the acid condensates discharged at the dace had shown rather constant values of c. 8.5 kg/s for the small Ketetahi basin; both Wilson and Moore and Brock had obtained almost the same values in 193617 and 1973/4, respectively. As the local boiling temperature is 95 °C, the flow rates indicate a heat transfer due to condensation of subsurface steam of c. 19 MW (c. 26 MW if 3 kg/s of condensates from the nearby Rangihiroa Valley are included). It was therefore likely that in 1979 we underestimated the heat loss of steaming ground. More detailed studies of heat transfer over "steaming ground" were required.

The first of such studies was made in 1993 when the output of steaming ground of the Hipaua fumarole field (Tokaanu-Waihi system) was assessed (Seveme and Hochstein, 1994). This showed that most of the heat transfer at the dace is by conduction since there is a linear relation between the soil temperature at shallow depth (0.2 m was used) and the near-surface temperature gradient which drives conductive transfer. Similar results were obtained a year later over much larger areas of steaming ground at Olkaria in Kenya (Hochstein and Kagiri, 1997). The results shown in Fig. 2 confirm the linear relationship between heat transfer and shallow subsurface temperatures. Assuming that proportionally heat transfer by steaming ground at Ketetahi is similar to that at Hipaua and Red Crater, the 1979 assessment was revised (*see* Table 3); the losses from *steaming* ground increased from c. 9.5 to c. 17.5 MW which raised the total heat output of Ketetahi to c. 44 MW.

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Table 1: Heat discharge rates (all figures in MW)

Mode	Te Mari Craters	Red Crater	Central Crater	Sub Total
Steam Discharge	0.3 ± 0.06	0.7± 0.1	0.1 ± ?	c. 1
Steaming Ground	0.9 ± 0.2	2.4 ± 0.5	0.1 ± 0.02	c. 3.4
Conductive Losses (class II)	c. 3	c.6	c.0.03	c. 9
Total Losses (Hochstein 1985)	(c. 5)	(c. 11.5)	n.d.	

Table 2: Characteristics of earthquake swarms (1986-1995), Greater Tongariro Area

(Dur = duration of swarm with n events; M_{max} = max. magnitude (from coda); D1 = magnitude difference between largest and second largest event in the swarm; F = area enclosing all epicentres of *swarm.)*

Date	Dur (hr)	n	M_{max}	D1	F (km^2)
85 Nov 04*	85	40	3.6	0.9	?
88 Dec 25 (Nr.1)**	28	14	3.9	0.6	11
91 Dec 25 (Nr.2)**	2.4	18	3.6	0.2	11
94 Jan 30	9	33	1.5	0.1	6.5

* Swarm analysed by Sherburn (1992); ** Number in Fig.1.

Table 3: Heat loss assessments of Ketetahi thermal area
(all values in MW)

Study	Fumaroles	steaming Ground	Evaporat. (Condens.)	Creeks	Total
S.H.Wilson (1936/7)	---------- c. 63 ----------			1.5***	c.65
M.P.Hochstein* (1973/74)	20± 7	9.5 **	c.5	1.7	36 ± 8
This review (197314 data)	20±7	17.5 ± 3**	c.5	1.7	44f 8

* listed in Hochstein and Bromley (1979).
** area with $T_{0.15}$ > 15 °C (at 0.15 m) was c. 100,000 m^2, including c. 10,000 m^2 with $T_{0.15}$ > 75 °C.
*** excluding heated run-off of other nearby warm creeks (i.e., only Mangatipua Stream).