# THERMAL PROPERTIES OF STEAMING GROUND (WAIRAKEI FIELD, NZ)

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**SUMMARY** – Shallow temperature monitoring and soil sampling in areas of steaming ground at Wairakei and Tauhara have revealed that the ***thermal diffusivity*** of these pumice soils averages about 0.4 E-6 $m^2/s$. The ***thermal conductivity*** varies between 0.4 and 1.4 W/mK, in response to variations in moisture content of 100 to 700 $kg/m^3$. Vertical temperature gradients, and therefore conductive heat losses, are linearly related to the temperature above ambient, by a factor that decreases with depth. Convective heat transfer dominates above about 70°C. Twice-daily temperature pulses rising towards the surface are triggered by steam from subsurface boiling caused by periodic pressure waves originating in the upper atmosphere. These merge with downward pulses of diurnal solar heating, complicating the assessment of soil diffusivity.

## 1. INTRODUCTION

The term 'steaming ground' has been used to describe thermal manifestations where vapour from a high temperature geothermal reservoir rises close to the surface. As the vapour condenses at shallow depths, a steep temperature gradient develops between the surface and the level of condensation, transferring heat by conduction through the top layer of soil, which is often hydrothermally altered. If condensation occurs at very shallow depths, minor steam can also be discharged directly through cracks and small vents, thus involving some convective and advective heat transfer.

The first attempt to assess heat transfer fiom steaming ground of some New Zealand geothermal prospects was made more than 40 yrs ago (Benseman, 1959) by using a surface calorimeter which produced a large scatter of heat flux data when plotted versus the soil temperature at a reference level. Later attempts to obtain empirical relationships between anomalous heat flux and soil temperatures at shallow depths were of limited success. An empirical classification of 9 types of steaming ground proposed by Dawson (1964) was reduced to one of 3 types by Allis (1979a). Of these, the lower two represent dominantly conductive heat transfer which prevails, for example, in most (c. 95 %) of the steaming ground in the Karapiti area. Estimates of heat transferred were still subject to large uncertainty caused by the lack of detailed information about the spatial distribution of the in-situ thermal conductivity of steaming ground (Bromley and Hochstein, 2001; Allis et al., 1999).

To obtain representative shallow thermal properties, which allow an improved assessment of the conductive heat losses of steaming ground in the Wairakei-Taupo area, we monitored daily temperature variations at selected sites and assessed near-surface physical properties using cores taken at shallow depths.

## 2. THEORETICAL BACKGROUND

The conductive heat flow **q** at shallow depth **z** in thermal ground is given by:

$$q(z)= (\Delta T/\Delta z)(z)\ \lambda(z) \qquad (1)$$

where $(\Delta T/\Delta z)(z)$ and $\lambda(z)$ denote the temperature gradient [°C/m] and, the thermal conductivity [W/m K], which can both vary with depth. The parameter $\lambda(z)$ is a linear combination of three thermal constants:

$$\lambda(z) = \alpha\ c_{eff}(z)\ \sigma_w(z), \qquad (2)$$

where $a$ is the thermal diffusivity [$m^2/s$], $c_{eff}(z)$ the effective thermal capacity per unit mass [kJ/ kg K], and $\sigma_w(z)$ the bulk (or wet) density [$kg/m^3$] of a soil sample consisting of a mixture of solid particles and the (partially) saturating liquid. The effective heat capacity $c_{eff}$ of a soil sample is:

$$c_{eff} = [\ c_p\,(1\text{-}\Phi)\,\sigma_p + c_f\,\Phi\,S\,\sigma_f\,]/\,\sigma_w, \qquad (3)$$

where $c_p$ is the mean specific heat capacity of the soil particles (c. 0.8 kJ/ kg K for most rock types (Schaerli and Rybach, 2001)), $\Phi$ the porosity of the sample, $\sigma$ the particle density of the soil matrix [$kg/m^3$], $c_f$ the heat capacity of the saturating liquid in the pores (4.18 kJ/ kg K for water), **S** the degree of pore saturation, $\sigma_f$ the fluid density, and $\sigma_w$ the bulk (wet) density of the sample. The fluid parameters $c_f$ and $\sigma_f$ vary slightly with the temperature prevailing at depth z. The density terms in equation (3) are related by:

$$\sigma_w = (1\text{-}\Phi)\,\sigma_p + \Phi\,S\,\sigma_f = \sigma_d + \Theta, \qquad (4)$$

where $\{(1-\Phi)\ \sigma_p\}$ is the *dry* density ($\sigma_d$) and the term ($\Phi\ S\ \sigma_f$) represents the specific moisture (liquid) content $\Theta$ [$kg/m^3$] of the sample. These parameters can be introduced into equation (2) which can be recast in the form:

$$\lambda(z) = a[c_p\,\sigma_d + c_f\Theta]. \qquad (2.1)$$

Normally the first term in equation (2.1) is dominant, but in porous, partially saturated pumice soils, such as at Wairakei, the second **term,** ($c_f\ \Theta$**),** is significant. Hence, the 'in situ' thermal conductivity $\lambda(z)$ and, in **turn,** the heat flux $q(z)$ of steaming ground, are strongly influenced by the specific soil moisture content $\Theta$ at depth z. Since $\Theta$ varies with time, owing to changes in infiltration, transpiration and subsurface condensation, the thermal conductivity of thermal ground also varies with time, i.e. $\lambda(z,t)$.

The thermal diffusivity $a$ of a homogeneous soil layer, initially at constant temperature, can be obtained from the downward propagation of a diurnal, pseudo-harmonic solar heat pulse with amplitude $\Delta T_o$ ("C) and period P (radian frequency $\omega = 2\pi/P$) at the surface. Its attenuated amplitude $\Delta Tz$ at depth z and time t is given, according to Ingersoll et al.(1955), by:

$$\Delta Tz = \Delta T_o \exp[-z\,(\omega/2\alpha)^{0.5}]\cos[\omega t - z\,(\omega/2\alpha)^{0.5}]. \qquad (5)$$

For the maximum of $\Delta Tz$, the **cos** term is unity. Since the 'apparent' period P of a daylight heat pulse cannot easily be measured, one has to solve for the unknown parameters $a$ and $\omega$ of the pulse. For this one can use the expression:

$$(\omega/2\alpha) = [\{\ln(\Delta Tz/\Delta To)\}^2/z^2]. \qquad (6)$$

If one introduces $t_o$ as the time when the pulse at the surface reaches a maximum and the phase lag At = ($t - t_o$) for the time shift affecting the maximum at depth z, one obtains a second equation for $a$ and $\omega$ from the phase lag At since:

$$(\omega/2\alpha) = (\omega\,At)^2/z^2. \qquad (7)$$

Equations (6) and (7) are independent of the actual temperature Tz at depth **z,** and can be used in thermal ground. The two unknown parameters can be obtained using a least squares fit approach.

The actual daily temperature variations contain a sequence of other short and long wave terms, all with different decay characteristics, which can be approximated by a Fourier series. Newson and O'Sullivan (2001) describe the use of Fourier analysis as an alternative means of determining thermal diffusivity from the temperature records described here. The amplitude decay and phase shift with depth, at the dominant frequency (the daily term), are used separately to calculate thermal diffusivity.

## 3. METHODS AND RESULTS

Properties of thermal ground were measured at two localities in the Wairakei-Taupo area between February and April 2001, namely at three sites in the Karapiti Thermal **Area** near the now extinct Karapiti Fumarole (KP1,2,3), at **two** sites (KP4,5) near the northern rim of crater D2 (Bromley and Hochstein, 2000), and at four sites (TH2,3,8,9) along the Tauhara test profile at the eastern **boundary** of the Taupo Golf Course (near 'Green #15'). Ground temperatures had previously been monitored for several days in the Karapiti field by Allis (1979b), and for about 2 years along the Tauhara test profile (Mongillo, 1993).

At the Karapiti sites, soil temperatures were measured with a calibrated thermistor probe at 1, 5, 10, 15, and 20 cm depth and recorded every 5 min. with a Fluke Hydra data logger for periods from **4** to 7 days each. At each site, soil samples were taken at 0-15cm and 15-30cm depth. At the Tauhara test profile, spot temperatures were measured several times at each site at 1, 5, 15 and 30 cm depth. Previous soil temperature monitoring records (Mongillo, 1993) were also used to obtain average near surface temperature gradients.

The pumice soils at the Karapiti sites are thermally altered; the intensity of alteration appeared to be related to the soil temperature at sampling depth. At Tauhara, all pumice soil samples appeared to be fresh and almost unaltered. Two of the Karapiti sites (KP1 and KP4) were on bare steaming ground, the other **three** (KP2,3,5) were covered by stunted prostrate kanuka shrubs. All sites at Tauhara were covered by grass.

Temperature records from the Karapiti sites are shown in Figs 1a to 1d. Infiltrating rainfall, as seen at site KP5 (Fig 1d) causes significant reductions in temperature and disturbs the gradients for several days. The daily temperature maximum shows a normal exponential amplitude decay and a linear phase shift with depth at sites KP2 (Fig.1b) and KP3. However, at sites KP1 and KP4 (Fig-la, 1c), which encountered higher temperatures (**>75°C** at 20 cm), the diurnal pulses propagate only to c.10 cm depth, where they merge with periodic heat pulses rising from below (as evidenced by increasing amplitude and reversed phase shift). These rising temperature pulses are inversely correlated with atmospheric pressure **as** recorded by a "Casella" analogue barograph at the IGNS Wairakei office. The pulses originate from convecting steam rising from an underlying boiling aquifer, which **boils** more vigorously during periods of lower atmospheric pressure. A semi-diurnal (12-hr period) pattern can be detected in both the atmospheric pressure and induced temperature

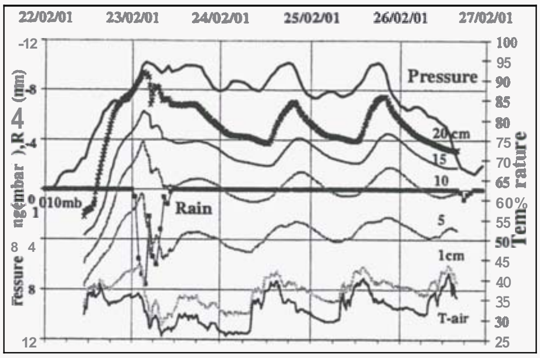

Figure 1a. Site KP1 temperature logs showing inverse correlation with atmospheric pressure changes (rising steam), and with hourly rainfall.

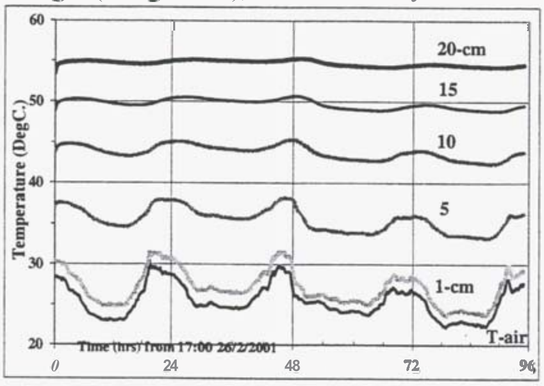

Figure 1b. Site KP2 temperature logs showing normal propagation of diurnal temperature pulse down to 20 cm depth.

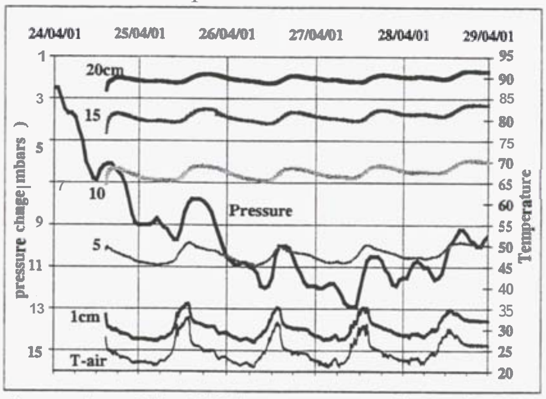

Figure 1c. Site KP4 temperature logs showing inverse correlation with 12-hour pressure changes (-1010 mbars).

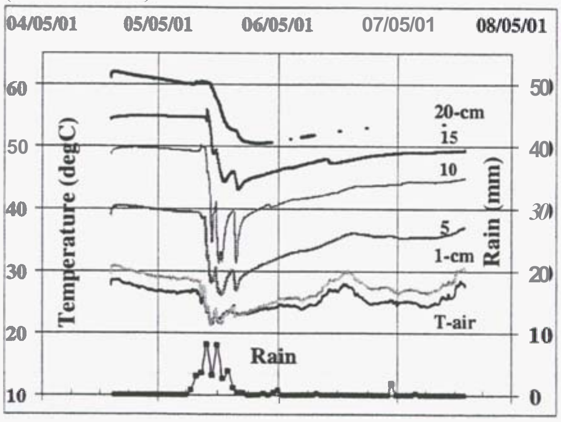

Figure 1d. Site KP5 temperature logs showing the effect of rain.

records. This is not a "lunar-tide" effect but a complex "atmospheric-tide" effect caused by solar heating of the ozone layer and propagation of 12-hr harmonic oscillations, while 24-hr oscillations are trapped (Chapman and Lindzen, 1987). Hence, the late afternoon pressure drop induces an upward heat pulse that merges with the downward midday solar heating pulse. Such sites will produce invalid apparent thermal diffusivities if the two different heat sources are not recognised.

Soil samples were taken using 16-cm long, cylindrical brass tubes (3.8 cm diam.). The cores usually suffered some compression during sampling and sometimes also during core recovery. Using the core length before and after recovery in comparison with the actual penetration depth, a compressibility factor $c_v$ was obtained which is the ratio of the volume of the recovered core to that of the in-situ sample. Each sample tube was sealed in the field to avoid moisture loss. Apparent bulk density ($\sigma_{wa}$) and apparent dry density ($\sigma_{da}$) were measured in the laboratory, the latter after a drying period of > 2 days (at 105 deg C). In situ densities were computed using $c_v$, i.e. $\sigma_w = c_v \sigma_{wa}$. The dried sample was mechanically ground to a fine powder and the particle density $\sigma_p$ was measured with a pycnometer after removing air bubbles under high vacuum. The densities are listed in Table 1.

All $\sigma_p$ values are less than that of pure silicic rocks (c. 2650 kg/m$^3$). The $\sigma_p$ values of samples from the Tauhara sites are between 2250 and 2400 kg/m$^3$ (typical of rhyolitic glass) suggesting that some air-filled pores remained even after grinding. Tests using uncrushed and naturally saturated samples gave apparent $\sigma_p$ values between 1700 and 2000 kg/m$^3$ indicating that up to 30% of all voids in these samples are poorly connected and filled with air in their natural setting. The particle densities of samples fiom the Karapiti sites reflect the intensity of thermal alteration of the soil with the highest $\sigma_p$ values coming from samples which consisted almost entirely of porous kaoline clay.

## 4. INTERPRETATION

The 'in situ' thermal diffusivity *a* of unaltered (non-thermal) pumice soils at Wairakei was studied by Dawson and Fisher (1964) using a simplified harmonic analysis of daily and seasonal temperature variations which had been observed down to 6 m depth for several years. Assuming a period of 24 hrs for the daily pulse, they obtained values of 0.3 E-6 and 0.59 E-6 [m$^2$/s] from the analyses of amplitude decay and time lag respectively. Similar values of 0.23 E-6 and 0.59 E-6 are obtained by Fourier analysis of our site KP2 data (Newson and O'Sullivan, 2001). The difference between the two values indicates that the purely conductive heat transfer model is either inadequate, or(and) the apparent mean period of the dominant pulse was < 24 hrs. We re-analysed the data from the **1960's** using equations **(4.2)** and **(4.3),** retaining the dominant frequency $\omega = 2\pi/P$ as parameter, and obtained a best fit value of **0.41** +/- **0.03** E-6 [$m^2$/s] for the diffisivity $a$ and a mean period of **16.5** hrs for the summer pulses. Our analysis of the annual temperature wave gives a similar average value for $\alpha$ of **0.35** E-6, indicating that the thermal diffusivity of unaltered pumice soils in the Wairakei setting is almost constant to depths of several metres. However a range of 0.25 to **0.45** E-6 for very dry to very wet conditions is likely.

Daily temperature variations at the Karapiti sites and at one Tauhara site **(TH3)** were also analysed using equations (6) and (7); amplitude and phase lag data of our smaller data sets show a greater scatter than those of Dawson and Fisher. This is, in part, due to contamination by the pressure-induced, steam-heating pulses observed at **KP1** and **KP4.** Best fit diffusivity values are in the range **0.3** E-6 < $a$ < 0.5 E-6 $m^2$/s (average **0.4** $m^2$/s) with apparent periods between **13** to 16 **hrs** for the dominant pulses.

Using the density data from the core studies, the effective thermal capacity ($c_{eff}$) can be obtained from equation **(3)** and the 'in situ' thermal conductivity ($\lambda$) determined using equation (2). They are listed in Table **1** and point to an increase of $\lambda$ with depth at sites where cores were taken from different depths. This increase should correspond to an increase in the specific moisture content $\Theta$ according to equation (2.2). A plot of computed thermal conductivity versus $\Theta$ (Fig.2) confirms the inferred relationship. For comparison, an empirical linear function obtained by Evett **(1994)** for non-thermal, silty clay soils in Texas (US) is **also** shown in Fig.2 (for values of $\Theta$ **< 300 kg/** $m^3$).

For an assessment of the heat flu q, the temperature gradient ($\Delta T/\Delta z$) at the mid-point of each core was averaged from periods of stable temperature. For Karapiti sites, these gradients show a decrease with depth (Fig. **3),** reflecting an increase in thermal conductivity. Temperature gradients at the Tauhara sites, at **10, 30** and **75** cm depth, were determined from **1989-1991** averages of pre-dawn **(5** am) data (Fig. **4).** These confirm the decreasing trend with depth at all sites. Some variation in gradient values with time is also observed. During summer months, gradients at 10cm depth are higher than average by about **15%,** and at 30cm depth lower by about **10%**, because of the effect of the seasonal temperature wave.

When the Tauhara average temperature gradients are plotted as a function of average temperature for different depths (the midpoint of the gradient interval), they show (Fig. 5) a striking linearity, with slopes that vary hyperbolically from **31** $m^{-1}$ at

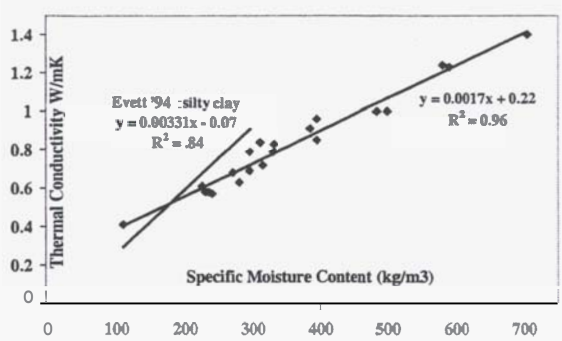

Figure 2. Thermal conductivity versus specific water content (all Karapiti and Tauhara soil samples) showing linear regression fit, and Evett's **(1994)** linear function for silty clay loam.

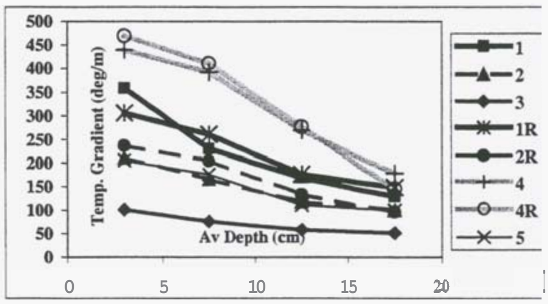

Figure **3.** Average temperature gradients versus midpoint depth for Karapiti sites **KP1** to **KP5** (R=repeated site occupation).

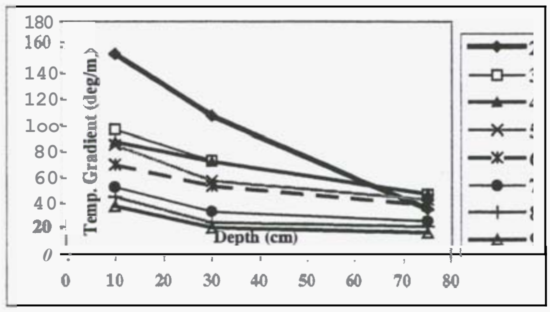

Figure **4.** Average **(1989-91, 5 am)** temperature gradients versus midpoint depth for Tauhara sites **TH2** to **TH9. (i.e.** 2 in legend refers to TH2 site)

**1** cm depth **to** 0.8 $m^{-1}$ at **75** cm depth. This slope change is partly a consequence of increasing water content and thermal conductivity with depth. Allis **(1999)** inferred a similar linear relationship from limited **1998** Dixie Valley **and 1979** Wairakei temperature data sets to assist with interpretation of infrared data.

Along the grass-covered, **100m** Tauhara test profile (i.e. between **TH9** and TH2 site) shallow heat flu increases from about 20 **to 100** W/$m^2$. At Karapiti, a range of about **70** to 400 W/$m^2$ was calculated. Thermal alteration is the most likely explanation for the higher thermal conductivity of the soils at the Karapiti sites (c.0.8 W/mK) relative to the unaltered Tauhara sites (c.0.6 W/mK). The higher clay content allows for better storage of condensates and therefore higher moisture content.

Table 1: Properties of Steaming Ground (Wairakei-Tauhara Field).

| Site Name | | $c_v$ | Date 2001 | $\sigma_w$ kg/m³ | $\sigma_d$ kg/m³ | $\sigma_p$ kg/m³ | $c_{eff}$ kJ/kgK | Θ kg/m³ | λ W/mK | ΔT/Δz °C/m | q W/m² |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **KP1/1** | a | 0.52? | 22-Feb | 770 | 490 | 2555 | **2.03** | **280** | 0.63 | **230** | **145?** |
| KP1/2 | b | 0.97 | 22-Feb | 1365 | 660 | 2580 | 2.56 | 705 | 1.40 | 109 | 153 |
| KP2/1 | a | 0.78? | 30-Mar | 995 | 725 | 2440 | 1.72 | 270 | 0.68 | 175 | 119? |
| KP2/1R | a | 0.80 | 4-Apr | 1215 | 830 | 2460 | 1.87 | 385 | 0.91 | 205 | 187 |
| KP2/1R | a | 0.80 | 21-Apr | 1210 | 880 | 2460 | 1.72 | 330 | 0.83 | 205 | 170 |
| **KP2/2** | b | 0.74 | 30-Mar | 1065 | 735 | 2500 | 1.85 | 330 | 0.79 | 93 | 73 |
| KP2/2R | b | 0.99? | 21-Apr | 1420 | **840** | 2455 | 2.18 | 580 | 1.24 | 78 | 97? |
| KP3/1 | a | 0.90 | 12-Mar | 1310 | 1000 | 2410 | 1.60 | 310 | 0.84 | 89 | 75 |
| KP3/1D | a | 0.84 | **12-Mar** | 1235 | 940 | 2415 | 1.61 | 295 | 0.79 | 89 | 70 |
| KP3/2 | b | 0.81 | **12-Mar** | 1320 | 925 | 2450 | 1.81 | 395 | 0.96 | 49 | 47 |
| KP4/1 | a | 0.78 | 21-Apr | 1150 | 665 | 2490 | 2.24 | 485 | 1.0a | 392 | 392 |
| KP4/1R | a | 0.72 | 24-Apr | 1005 | 505 | 2490 | 2.48 | 500 | 1.0a | 392 | 392 |
| KP4/2 | b | 0.97 | 21-Apr | 1340 | 750 | 2485 | 2.29 | 590 | 1.23 | 133 | 164 |
| KP5/1 | a | 0.70 | 21-Apr | 910 | 595 | 2395 | 1.97 | 315 | 0.72 | 200 | 144 |
| KP5/2 | b | 0.70 | 21-Apr | 995 | 600 | 2415 | 2.14 | 395 | 0.85 | 95 | 81 |
| **TH2** | a | 0.98 | 19-Feb | 910 | 615 | 2380 | 1.90 | 295 | 0.69 | 155 | 107 |
| **TH2R** | a | 0.96 | 17-Mar | 760 | 520 | 1680? | 1.87 | 240 | 0.57 | 155 | 88? |
| TH3 | a | 0.91 | 19-Feb | 950 | 725 | 2390 | 1.60 | 225 | 0.61 | 96 | 59 |
| TH8/1 | a | 0.83 | 19-Feb | 810 | 700 | 2230 | 1.26 | 110 | 0.41 | 44 | 18 |
| TH8/2 | b | 0.99? | 17-Mar | 830 | 600 | 1975? | 1.74 | 230 | 0.58 | 25 | 15? |
| TH9 | a | 0.99? | 19-Feb | 820 | 585 | 2310 | 1.77 | 235 | 0.58 | 37 | 21? |

Notes: R = repeat, D = duplicate sample, ? = uncertain data
Cores: a fkom 0-15cm, b fkom 15-30cm depth;
$c_v$ = volume compression ratio; $c_{eff}$ = effective thermal capacity;
$\sigma_w$, $\sigma_d$, $\sigma_p$ = wet, dry, particle densities; Θ = specific moisture content;
λ = thermal conductivity; ΔT/Δz = temperature gradient; q = heat flux.

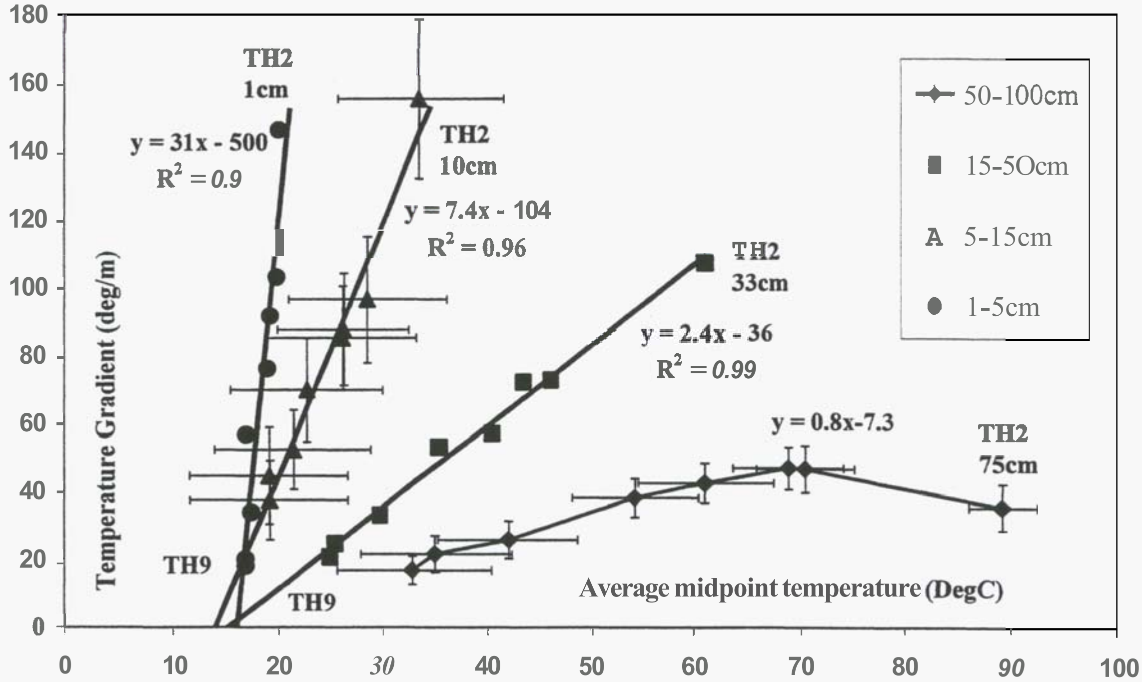


Figure 5. Temperature gradients versus midpoint temperatures for different depths at Tauhara sites TH2 to TH9. (Data fkom 1-cm depth use 1-5cm gradient.) Error bars show typical +-1 Std.Dev. range for the (1989-1991) 5 am data. Linear regression equations and $R^2$ values are shown. Slopes increase steeply towards the surface. Convection dominates above 70°C.

The reproducibility of our measurements was also tested at several sites (Table 1); the resultant error in heat flux is only greater than 10% for core samples with suspect density data. Uncertainties in density values are caused mainly by uncertainties in compression effects during sampling. Larger uncertainties in heat flux are indicated for sites over bare steaming ground (KP1 and KP4); these reflect uncertainties in temperature gradients because of convective heating fiom rising pulses of steam.

## 5. CONCLUSIONS

Thermal properties of steaming ground at Wairakei and Tauhara were assessed fkom monitoring of soil temperatures and simultaneous soil sampling. Analysis of diurnal temperature variations shows that the ***thermal diffusivity*** of pumice soils averages 0.4 E-6 $m^2/s$ and does not change significantly with depth. The ***thermal conductivity*** of these soils varies between c. 0.4 and 1.4 W/mK, with changes being controlled by their moisture content which can vary between 100 and **700** $kg/m^3$, the highest values occurring in intensely altered hot kaolin clay. The porosity of most samples varies between 50 and 75%. The highest saturation **(S>80%)** occurs at sites within bare steaming ground. Changes in the moisture content by evaporation, transpiration, condensation, and rainfall infiltration, cause simultaneous changes in shallow thermal conductivity, which varies also with time and depth. Changes in thermal conductivity induce changes of the opposite sign in the temperature gradient, which at shallow depths lies between c. 25 and c. 400 deg C/m.

In view of the relatively constant thermal diffusivity of the soils encountered, it is possible to obtain heat flux data fiom steaming ground using recording of soil temperature and simultaneous core sampling. The resulting error in heat flux values (of the order of 10%) has to be reduced, before any long term transient changes in heat transfer from steaming ground can be detected.

## 6. ACKNOWLEDGEMENTS

Dr.L.Wesley made facilities of the Soil Laboratory (School of Engineering, Univ. of Auckland) available for the core studies. The data logger was provided by Eddie Mroczek, the pressure charts by Duncan Graham, and the rainfall data by Contact Energy. Financial support **was** provided from the NZ Foundation of Research Science and Technology (CO5X0004).

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