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Heat Discharge of Steaming Ground at Karapiti (Wairakei), New Zealand

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ABSTRACT

The Karapiti fumarole field is arguably one of the largest coherent steaming ground areas associated with liquid-dominated geothermal systems. It covers 0.35 km^2 and transfers, during summer, 245 +/- 20 MW of heat to the surface. Two modes of discharge occur:

1) localized discharge of steam by fumaroles and steam vents (c. 107 MW), and
2) wide-spread diffuse discharge (steaming ground in the strict sense) involving both convective and conductive heat transfer (c. 69 MW each).

Assessment of heat discharged by fumaroles and steam vents involved measurement of the steam flux of selected fumaroles and analysis of the extent of all visible steam clouds.

Assessment of the diffuse discharge required measurement of the heat flux at over 100 sites using a ground calorimeter and recording of soil temperatures down to depths where boiling prevails. The total heat flux is dominantly controlled by the boiling point depth. The most intense heat transfer occurs within a 0.07 km^2 area where boiling occurs at depths less than 0.2 m; the area is also characterized by anomalous surface temperatures detected using aerial infra-red imagery.

1. INTRODUCTION

Thermal manifestations have been described as ‘steaming ground’ if they are derived from vapour which comes close to the surface of geothermal and volcanic-hydrothermal reservoirs. The term was introduced by Banwell et al. (1957) who were the first to assess the heat discharged by steaming ground over liquid-dominated geothermal reservoirs in New Zealand. Steaming ground can transfer a large amount of thermal energy to the surface, in some cases of the order of several hundreds of MW. The Karapiti fumarole field, also known as “Craters of the Moon” is part of the greater Wairakei-Tauhara system and is arguably one of the better known steaming ground areas worldwide. At Karapiti, heat is discharged directly by numerous fumaroles and steam vents, steaming craters, and hot mud pools. Heat is also discharged in a diffuse manner involving convective and conductive transfer through hot and warm ground, which covers at present an area of 0.35 km^2 (see Fig. 1). Some minor heat transfer (~2 MW) also occurs indirectly through heating of groundwater that discharges from warm springs in nearby streams.

Production from the Wairakei hot water reservoir has caused significant changes in heat output and active surface area at Karapiti during the last 50 years (Bromley and Hochstein, 2000). Until a few years ago, its heat output was assessed by using somewhat dated methods (Thompson et al., 1964) which have only recently been retested. By 1970, field methods had been developed which allowed zoning of steaming ground using patterns of reflective infra-red (IR) surveys (Hochstein and Dickinson, 1970) or thermal vegetation patterns (Dawson and Dickinson, 1970). Allis (1979a, 1979b) simplified the vegetation zoning method and identified the significant contribution of convective heat flux at elevated ground temperatures (>70 °C at 15cm). Since 1989, high-resolution, video-based, aerial IR surveys have been used at Karapiti on several occasions to monitor changes in the extent and intensity of hot ground (e.g. Bromley and Mongillo, 1991). However, to translate the surface temperature images directly into heat loss maps has required empirical relationships and assumptions that are not yet consistent and are poorly understood. (Mongillo and Graham, 1999, Allis et al, 1999).

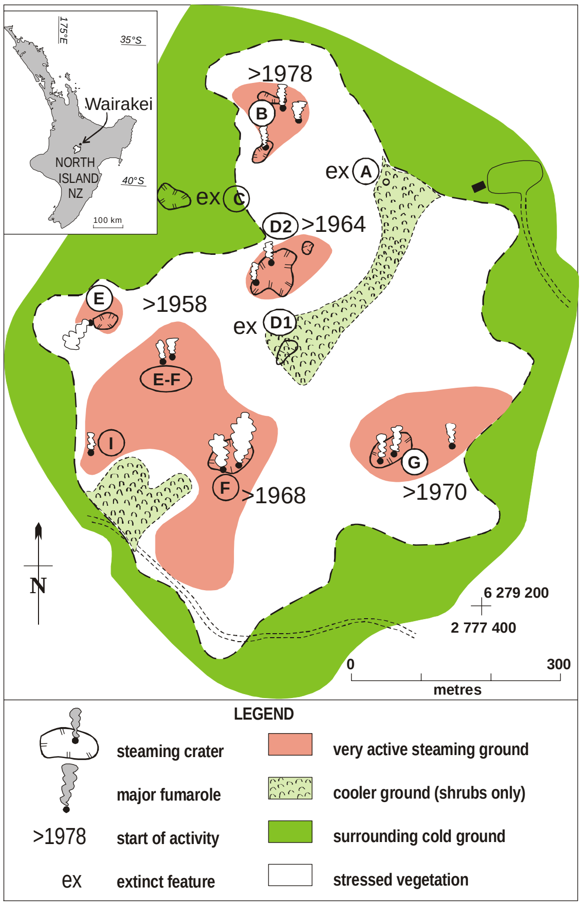

Figure 1: Overview map showing the Karapiti thermal ground area (North Island, NZ).

Published heat loss data of the Karapiti Field before 2000 are somewhat uncertain. In 1978, Allis (1979a) calculated a total heat loss of 220 MW, with estimated error bounds of +/- 20%. These remained unchanged 10 years later according to a qualitative reassessment by Mongillo and Allis (1988). With the benefit of thermal IR imagery, Bromley and Graham (1999) reassessed total Karapiti heat loss, using four grades of thermal ground, to be 200 +/- 40 MW, of which ~50% was from steaming ground. Increasing awareness of the environmental changes associated with the production of geothermal fluids, and the need to provide for better calibration and history matching of improved reservoir models, led us, in 1998, to renew the study of heat transfer in steaming ground. The assessment of the actual heat discharged in the Karapiti area became a specific topic. The results of these studies are summarized in this paper.

2. HEAT DISCHARGED BY FUMAROLES AND STEAM VENTS

Areas with intense steaming ground (aka fumarolic ground) often exhibit large steam vents (fumaroles or solfataras). At Karapiti most of the large fumaroles are associated with steaming craters resulting from shallow hydrothermal or steam eruptions. Hot mud pools occur on the floor of some craters. Most presently active craters developed after 1955 (see Fig. 1), the beginning of production from the nearby Wairakei bore field to generate electricity.

Assessment of heat output of the Karapiti Field was divided into the assessment of heat discharged by fumaroles and steam vents and heat discharged through hot ground. Methods were developed and tested which allow reproducible measurement of the steam mass flux of accessible fumaroles and steam vents (Hochstein and Bromley, 2000). Simultaneous measurements of dynamic pressure and temperature across a fumarole steam jet were used to obtain the heat discharge rate after reducing the disturbing effect of air inflow at the vent margins. The output of inaccessible fumaroles can be estimated from the heat output of accessible fumaroles plotted versus their normalised, projected steam cloud area visible in air photos. The best fit line through the data in a log-log plot gives the total heat output for the total steam cloud area (Hochstein and Bromley, 2001). Analysis of measurements over two years showed that the total heat output of all fumaroles with large steam clouds in the Karapiti area was 94 +/- 11 MW (1999/2000).

Smaller steam clouds over steam vents discharging < 0.3 MW could not clearly be identified in the air photos. The output of a few smaller, accessible steam vents was measured and the discharge of inaccessible vents was estimated by ranking their steam cloud volume from the ground. The total discharge of smaller vents was found to be of the order of 13 +/- 3 MW. Hence, the total heat output of all fumaroles and vents at Karapiti (relative to average ambient temperature of 15^{o}C) was found to be 107 MW.

3. HEAT DISCHARGED BY 'STEAMING GROUND'

Heat transfer to the surface of hot (steaming) ground from a boiling liquid subsurface involves convective transfer of minor steam and conductive transfer through a thin near-surface layer; their specific heat fluxes are referred to here as q_{conv} and q_{cond} respectively (unit W/m^2). Recent studies have shown that both fluxes contain time-variable components, namely a small daily component, an episodic component caused by infiltration after rainfall, and a seasonal component. The effect of these components is small if heat flux measurements are restricted to dry summer months when a reproducible total flux can be measured.

The total flux q_{tot} of steaming ground was first measured by Banwell et al. (1957) who used for their tests both a water-filled ground calorimeter (closed-bottom type) and an open-bottom calorimeter (differential psychrometer type). The latter type was refined by Benseman (1959) who measured flux values between 0.04 and 2 kW/m^2 over ground with near-surface temperatures between 30 and 99 ^{o}C respectively. Although the 'open-bottom' type of calorimeter reduces contact and interface heat transfer problems, which affect closed-bottom calorimeters, thermal stabilisation was a problem which resulted in poor reproducibility of the earlier measurements. The open-bottom calorimeter also did not allow separation of convective and conductive fluxes.

We re-designed a closed-bottom calorimeter which produced good results during calibration tests owing to its thin stainless-steel bottom plate. When tested in the field, reproducible q_{tot} measurements (relative error < +/- 10%) were obtained when surveys were made and repeated during dry summer months. The convective flux component q_{conv} was obtained from the condensation rate of steam at the bottom of the calorimeter; the conductive flux q_{cond} can be inferred from the difference of the two measured fluxes (Hochstein and Bromley, in press).

Soil temperature T versus depth Z profiles, beneath sites on steaming ground, exhibit a typical quasi-exponential shape (see Fig. 2 for five examples). These can be linearized by using the empirical function:

$$Z = \exp [C_1 (T_{BP} - T_Z)] + C_2, \qquad (1)$$

where T_Z is the temperature at depth Z, T_{BP} the boiling temperature (given by the atmospheric pressure), and C_1, C_2 a set of best-fit constants. The function allows, therefore, the assessment of boiling depth Z_{BP} from a set of T_Z data. The boiling depths (Z_{BP}) are listed in Fig. 2 for each soil temperature profile. It was found that the observed q tot measurements correlate well with the boiling depth data pointing to an empirical power-law relationship of the form:

$$q_{tot} = a [1/ (Z_{BP}/Z_0)^{b}], \qquad (2)$$

where (Z_{BP}/Z_0) is a dimensionless depth with Z_0 = unit depth (1m), a = 185 W/m^2, and b = 0.757. A relationship similar to equation (2) is indicated for the conductive flux q_{cond} with a = 97.3 W/m^2 and b = 0.709 which implies that the conductive flux at the surface at Karapiti is almost half of the total flux.

Measurements of soil parameters (specific densities, porosity, and moisture content) beneath the calorimeter sites showed that most of the conductive heat flux is driven by the condensation of rising vapour. The condensation occurs within a thin near-surface layer which is heated by subsequent liberation of latent heat. The process maintains a steep temperature gradient within the near-surface layer. The liquid saturation of pores within the shallow condensate layer rarely exceeds 70 %. Hence, not all rising vapour is quenched and some of it can reach the surface; this accounts for part of the convective flux observed. Evaporation within the near-surface layer contributes another portion.

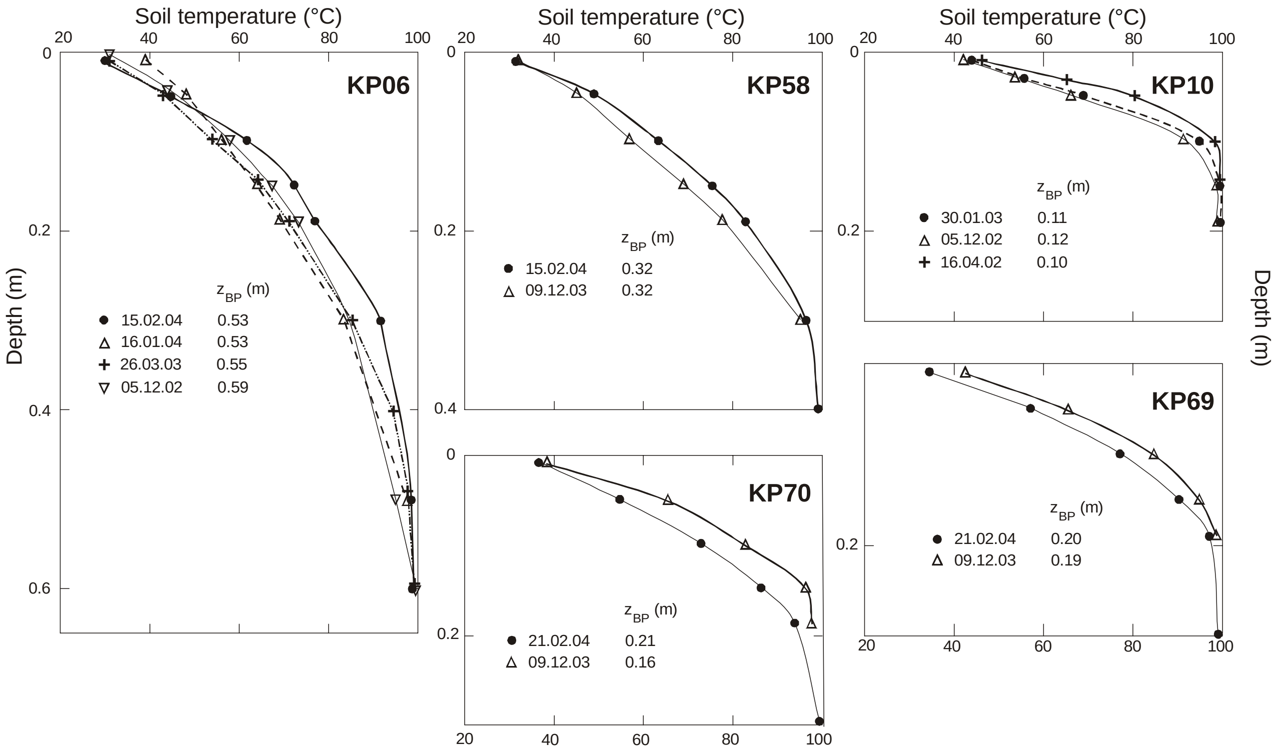

Figure 2: Soil-temperature versus depth profiles at selected sites (Karapiti thermal area) during summer months; for location of sites see Fig.4.

Liquid droplets form at the bottom of the shallow condensate layer and descend into the underlying 2-phase layer where some re-evaporation should occur. The whole setting has affinity with that of a 'heat-pipe' (Hochstein and Bromley, in press).

4. REPRESENTATIVE HEAT-FLUX SITES

Measurements of the total and the convective flux at single stations across a large area of steaming ground are time-consuming; during the summer months 2001/2 to 2003/4 we measured the flux values of just 18 stations, albeit using numerous repeat surveys. For the assessment of the heat discharged through the whole Karapiti steaming ground area, we recorded soil temperature profiles at another 86 stations during the summer of 2003/4. With this information the boiling depth at each station was obtained (using equation 1) and the total heat flux computed (using equation 2). Hence, heat discharged from sub-areas with similar boiling depth could be assessed. We found that the boiling depth obtained during dry summer months is generally repeatable. Representative values of sub-area heat flux can be obtained by avoiding anomalous sites, containing, for example, minor steam vents.

4.1 Changes in Boiling Depth with Time

Temperature-depth profiles were monitored at irregular intervals at a few selected sites over two years. It was found that the boiling depth increases during the colder season by up to 30% resulting in reduced total heat-flux values. However, q tot values measured at the same site during consecutive summers are compatible (see Fig. 2, site KP 06 and KP 10).

Similar conclusions were obtained by reprocessing temperature data at 5 depths (up to 1m) logged continuously over 2 years (1989-1991) at 8 sites that crossed the edge of an area of steaming ground at Tauhara golf-course, Taupo. Here, boiling depths were found to increase in winter by 15% to 30%, in response to a seasonal average air temperature decline of 12 degrees.

Soil temperatures also decrease after a long period of rainfall, such as during February 2004. Infiltration caused a decline in temperature at many sites down to boiling depth (see Fig. 2, sites KP 58, 69, 70). The boiling depth, however, was not significantly affected except at a few sites where infiltration was concentrated (for example, at KP 70). The value of Z_{BP} measured during dry summer months is therefore a relatively robust parameter for the assessment of heat flux modes.

4.2 Thermal Vegetation Zoning

The calorimeter sites were selected to cover the whole range of steaming, hot, and warm ground. In selecting a site we always checked that plants surrounding the site had a similar 'vegetation index'. The vegetation pattern over thermal ground is a rough indicator of boiling depth since the average height of plants and shrubs which grow on thermal soil is controlled by the vertical extent of their roots which, in turn, is restricted by boiling depth. Height and types of plants are also affected by other parameters such as availability of mineral nutrients and soil pH value, although temperature at the deepest root level is probably the most important parameter (Given, 1980).

Zoning of thermally stressed plants at Karapiti was originally used by Thompson et al. (1964), and later by Dawson and Dickinson (1970), to define coherent areas of thermal ground exhibiting similar ground temperatures (at 0.15 m depth). We used the more robust parameter of boiling depth for zoning. For this a 'vegetation index' ranging from 1 to 7 was assigned to thermal vegetation surrounding each site; from index 2 upwards the range of average plant height increases exponentially. The boiling depth (as log Z_{BP}) has been plotted in Fig. 3 versus 'vegetation index' (also a log scale). The apparently wide range of Z_{BP} of plants with the same index is reduced if one excludes dying shrubs (marked by D in Fig. 3) or stunted plants growing on leached, thermally altered soils in the northern part of Karapiti (marked by L in Fig. 3).

Vertical air photos (in colour) allowed a clear identification of intense steaming ground with vegetation index 2 and warm ground exhibiting taller shrubs (index 6 in Fig. 3). Sites with stunted vegetation were classified at ground level according to criteria listed in Fig. 3.

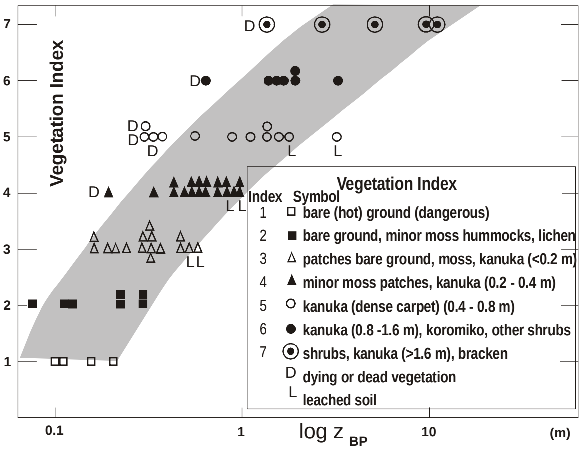

Figure 3: Vegetation Index and boiling depth (log scale) of sites with known heat flux (Karapiti thermal area).

5. CONSTRUCTING A HEAT-FLUX MAP

The boiling depth for each occupied site was first plotted on a map based on a colour air photo (Fig. 4). The area around each site was assigned to one out of 7 zones (see Table 1) which are closely linked to the vegetation index. The extent of the inner zones (1 and 2) is identified by light tonal patterns in the air photo and by anomalous surface temperature patterns in aerial infra-red (IR) images. Zone 3 is identified by subdued IR anomalies. The extent of warm ground covered by thermal shrubs (zones 6 and 7) and the surrounding cold ground (high standing pines trees and native bush) can also be recognised in the air photo and was used to outline the appropriate boundaries in Fig. 4.

Table 1: Heat discharge of zoned thermal ground (Karapiti)

Zone (i)	Vege. Index	Boiling Z_{BP}(m)	Area Ai(m2)	Qi_{tot} (MW)	Qi_{conv} (MW)
1	1	<0.1	~ 5200	7.2	3.8
2	2&3	0.1–0.2	63500	49.4	25.7
3	4	0.2–0.4	76000	35.0	17.6
4	5	0.4–0.8	135000	36.7	17.8
5	6	0.8–1.5	43700	7.2	3.4
6	7	1.5–3.0	31200	2.0	0.9
7	7	3 – 10			
		Sum	355000	137.6	69.2

5.1 Aerial Infrared Map

Repeat thermal infrared surveys have been conducted over the Karapiti thermal area in late summer of 1989, 1991, 1997, 1998 and 2000, in order to monitor changes by recording, on video-tape, images of surface thermal features at a resolution of approximately 1m. The helicopter-borne surveys are flown at night to minimize solar heating effects, at a height above ground surface of about 600m. The instrument used (FLIR FSI-2000) has a detector with an infrared wavelength band of 8-12 μm. Temperature calibration of the resulting imagery was achieved by flying over several identifiable water surfaces while measuring their temperatures. Care was taken to avoid periods of high humidity, strong winds, or fog, so that the masking effect of vapour emissions would be minimised. GPS was used to aid navigation and subsequent imagery location. A composite infrared image of the Karapiti area (Fig. 5) has been compiled from the 2000 IR survey (described in Bromley and Hochstein, 2000), using rectified images digitally captured from the videotape and overlaid on the air-photo. This image has been filtered and brightness-enhanced to aid with visual presentation, but the original data are recorded as 8 bit (0-255) grey-scale values covering a range in surface temperatures from 11.5^{o}C (ambient = black) to >63.5 ^{o}C (saturated = white), with a temperature resolution of about 0.2 ^{o}C.

Quantitative use of the IR imagery for assessing heat losses from steaming ground is confounded by the difficulties associated with measuring ground surface temperatures, the unknown mass of venting steam, and by the masking effects of thick vegetation and steam clouds. Using IR data from Dixie Valley, Wairakei, and Tauhara, various authors have deduced empirical relationships between conductive heat-flow and near-surface temperature:

$$Q_c \text{ (W/m}^2) = C\,(T_1 - T_{ambient}), \quad (3)$$

Where C = 7, and T_1 is at 1cm depth, from Allis et al (1999), while C = 27.5, and T_1 is ground surface temperature, from Mongillo and Graham (1999).

These differences illustrate the problem of applying IR data in a consistent manner to assessments of heat discharge. However, the IR data is still very useful for spatial interpolation between actual heat loss measurement sites, and for integration into total heat discharge values.

5.2 Heat Discharge of Steaming Ground

Using the information from air photo and IR anomaly interpretation, as well as field data, the extent of distinct steaming ground zones was defined (Fig. 4). Isolated anomalies based on a single site were disregarded. The area Ai covered by each thermal ground zone (i = 1 to 7) was obtained by integration. Using mean flux values for each boiling depth range (equation 2), subtotals of total and convective heat discharges were computed. These are listed in Table 1. Warm ground in zones 6 and 7 could not be spatially separated and were therefore assessed together. Zone 1 is mostly confined to the bottom and the margin of large steaming craters; heat discharged through this zone was assessed with less confidence because of difficult access, and large lateral variations in convective flux.

The uncertainty of the total heat discharged by steaming ground was estimated to be +/- 16 MW, reflecting errors in data used to derive equation (2) and zoning errors. The diffuse heat discharged through all thermal ground at Karapiti is 138 +/- 16 MW. The enthalpy of steam diffusing through the soil can be inferred by using a mean surface temperature for each zone listed in Table 1. With reference to a mean annual temperature of 15 deg C, the total heat transferred by diffuse steam of 69 MW points to a diffuse steam mass flux rate of 28 kg/s.

6. CONCLUSIONS

The total heat discharge across 0.35 km^2 at Karapiti (during summer) is 245 +/- 20 MW (2004); the resultant error assumes that all component errors cited are random (i.e. 11 MW for fumaroles, 3 MW for small steam vents, and c.16 MW for the steaming ground losses).

The dominant mode of discharge is by steam, amounting to 107 MW from visible vents, plus 69 MW from diffuse convective flux. This is equivalent to a steam mass flux of c. 68 kg/s, which is much higher than the mass flux of 22 kg/s calculated from the latest reservoir model simulation (O'Sullivan 2004). Heat transferred by steam amounts to c. 72% of the total heat discharged. Up to 11 kg/s of this mass flux could originate from conductively–heated or solar-heated and re-evaporated rainfall (1m/yr across 0.35 km^2); the balance derives from primary high-pressure steam or boiled groundwater that has been drawn in from surrounding areas.

Seasonal flux data indicate that heat discharged by diffusely steaming ground is not constant during the year but shows some variations, typically within the range of 15% to 30%. Average annual heat discharge will be somewhat smaller than the average summer heat discharge given above.

Heat discharge has varied with time since exploitation of Wairakei began. An update of the history of heat loss estimates is presented in Fig. 6. A key finding is that heat discharge at Karapiti has not significantly decreased since 1978, contrary to calculated discharges from the current reservoir model, decreasing from 200 to 60 MW since 1978 (O'Sullivan, 2004). Observed trends are also apparently inconsistent with continuing declines observed in the "south-west" steam-zone pressure (c. -0.4 bars/year).

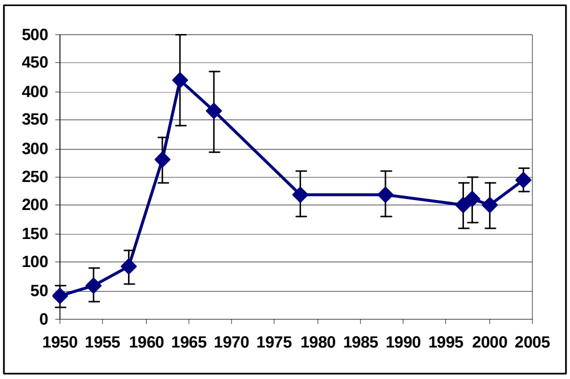

Figure 6. Total heat discharge estimates at Karapiti.

Thermal IR imagery provides a useful means of mapping areas of similar surface temperature, for use in calculating total heat loss. However, convective heat loss, particularly from fumaroles, cannot be assessed in this way, and the masking effects of thick vegetation diminishes the usefulness of IR for distinguishing lower grades of heated ground from ambient conditions.

Heat discharged by steaming ground can now be measured more accurately using the methods which we have developed. The study is a reference survey which can be used to monitor future changes in heat output of this area.

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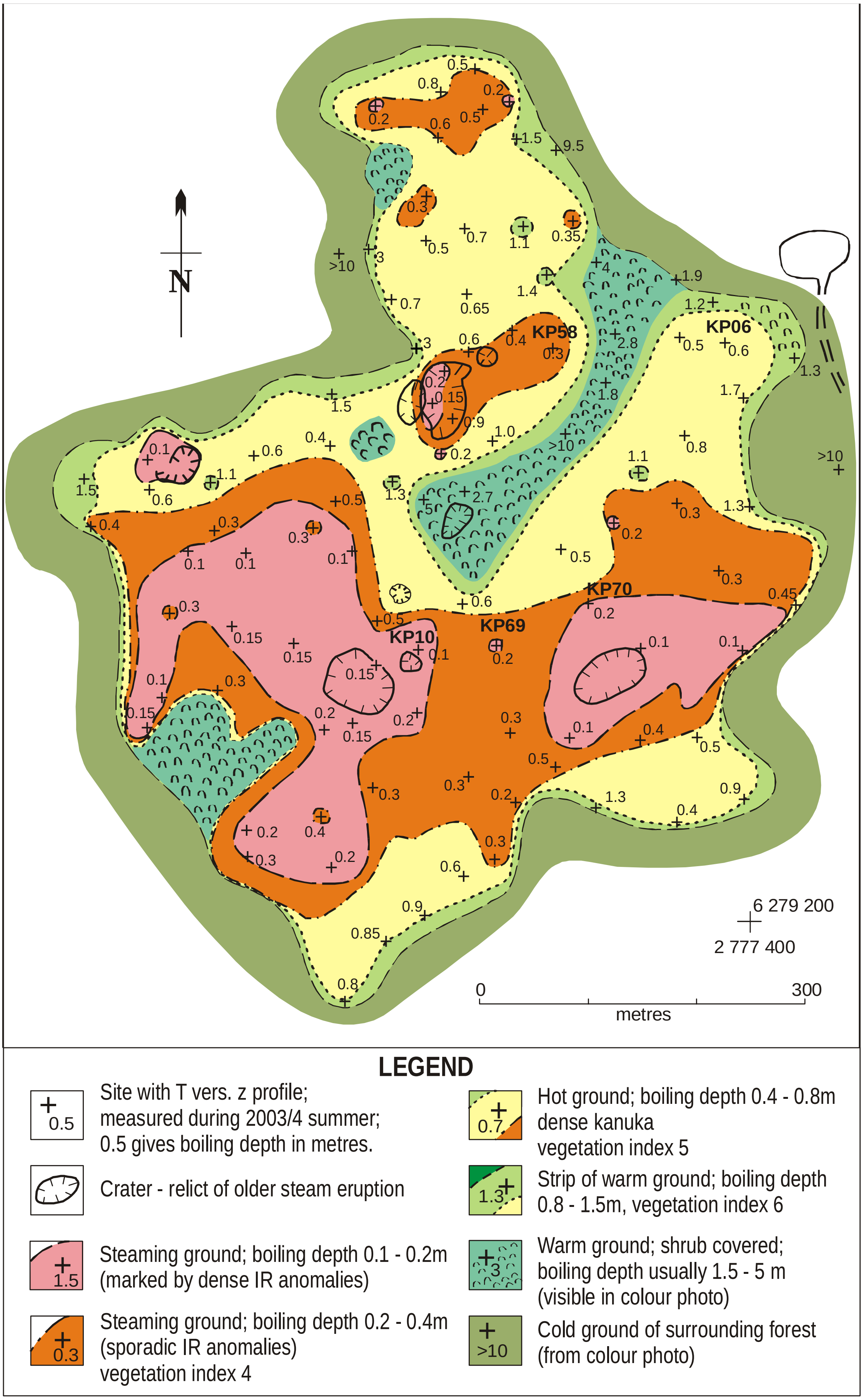

Figure 4: Map showing sites where heat flux of thermal ground was either directly measured or inferred from known boiling depth (Karapiti thermal area).

Figure 5: Thermal infrared map of Karapiti area, obtained from a mosaic of images from the 2000 IR survey, rectified to an air-photo. A 2-m wide wooden boardwalk can be seen in the image as a dark line contrasted against the anomalously hot ground.