CROWN PARK THERMAL AREA, TAUPŌ: TAKING A PULSE

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ABSTRACT

Regular, ongoing monitoring of surface thermal features gives an insight into the health and sustainability of the underlying geothermal resource. Data collected over the long-term in particular, can provide invaluable information about sub-surface conditions as the resource is utilised. Time and budgetary restraints have precluded monitoring at many of the publically-owned thermal features in the Taupō area.

Crown Park thermal area is one of several active surface thermal features located in Taupō that is not regularly monitored. The thermal area is located within a public park near the south-western resistivity boundary of the Tauhara Geothermal Field, and comprises multiple, intermittently active fumaroles.

As part of the 'Our Geothermal Area' pilot project—a joint science education initiative with GNS Science—a group of Taupō-nui-a-Tia College students commenced monitoring of the Crown Park thermal feature in March 2016. Monitoring activities include: measuring temperature-depth soil profiles along three transect lines across the thermal area, quantifying fumarole activity, including steam and soil temperatures and gas composition, and measuring ambient conditions. Relevant data from a nearby weather station is also recorded.

At the time of writing, preliminary data show marked variations in shallow ground temperatures and fumarole gas concentration levels that appear to be related to local anomalous weather events. Continued data collection over the ensuing months / years will provide further insights into the status and behaviour of this thermal feature.

The long-term goal for the 'Our Geothermal Area' initiative is for all Taupō high school students to be involved in monitoring the public-owned active thermal features around Taupō, where it is safe to do so. All data collected by the students will be available on a public-access database, currently being developed by GNS Science.

1. INTRODUCTION

Regular, long-term monitoring of active thermal areas can provide invaluable information about the status and sustainability of the underlying geothermal resource, in both its natural state, and as the resource is utilised.

Surface discharge monitoring is a quick and relatively simple method of determining the amount of heat a geothermal area emits. Heat lost at the surface via steaming ground and fumaroles can provide insight into the size and status of the geothermal resource. Heat is transferred to the surface from a boiling liquid sub-surface. The process involves convective transfer of minor steam and conductive transfer of heat through a thin near-surface layer.

Surface heat flow is known to be affected by time-variable components (e.g., Seward and Prieto, 2015; van Manen and Wallen, 2012), such as daily and seasonal variations, as well as episodic variations due to local weather phenomenon, e.g., rainfall. It is, therefore, important to monitor the ambient conditions of both the ground and the atmosphere, while monitoring a geothermal area.

Gas composition of fumaroles provides insights about the chemical make-up and structure of a geothermal system. Changes in gas compositions may suggest variations in subsurface interactions between the geothermal system and groundwater. Carbon dioxide (CO_2) is the most abundant gas in geothermal systems (Nicholson, 1993). It is primarily of magmatic origin but can also be produced by thermal alteration of minerals in the hydrothermal system, and from solutes in meteoric waters. Methane (CH_4) is a non-magmatic and slow-reacting gas, and is a good indicator of fluid-rock interactions occurring within the hydrothermal environment, although biogenic sources of CH_4 cannot be excluded. Hydrogen sulphide (H_2S) is a typical lower temperature gas and its predominance indicates reaction within the superficial hydrothermal environment.

In March 2016, a group of Taupō-nui-a-Tia College (Taupō College) students began regularly monitoring the active thermal area at Crown Park, Taupō as part of the 'Our Geothermal Area' project: a joint education initiative being developed by GNS Science and Taupō College that aims to encourage more high school students to stay in science (Sanders et al., 2016). It is planned that all data collected by the students at Crown Park will be available via the project website currently being developed by GNS Science.

This paper reports on some of the monitoring data collected during the first five months of the project. It focuses on changes in ground temperatures, inferred heat loss and fumarole conditions observed between 15th March and 2nd August 2016.

1.1 Crown Park thermal area geological setting

Crown Park thermal area is one of several active surface features in Taupō that is not regularly monitored. It is located in a public park on the eastern fringes of Taupō township, near the south-western resistivity boundary of the Tauhara geothermal field (as defined by Risk et al., 1984; Figure 1A).

The active thermal area occurs within a ~50 m wide, ~3 m deep, comma-shaped depression located in the otherwise subdued topography (likely anthropological influence) of the Crown Park sports fields. To the immediate south is a ~6 m deep, east-west trending drainage channel that likely originated at the lower flanks of Mt Tauhara to the east.

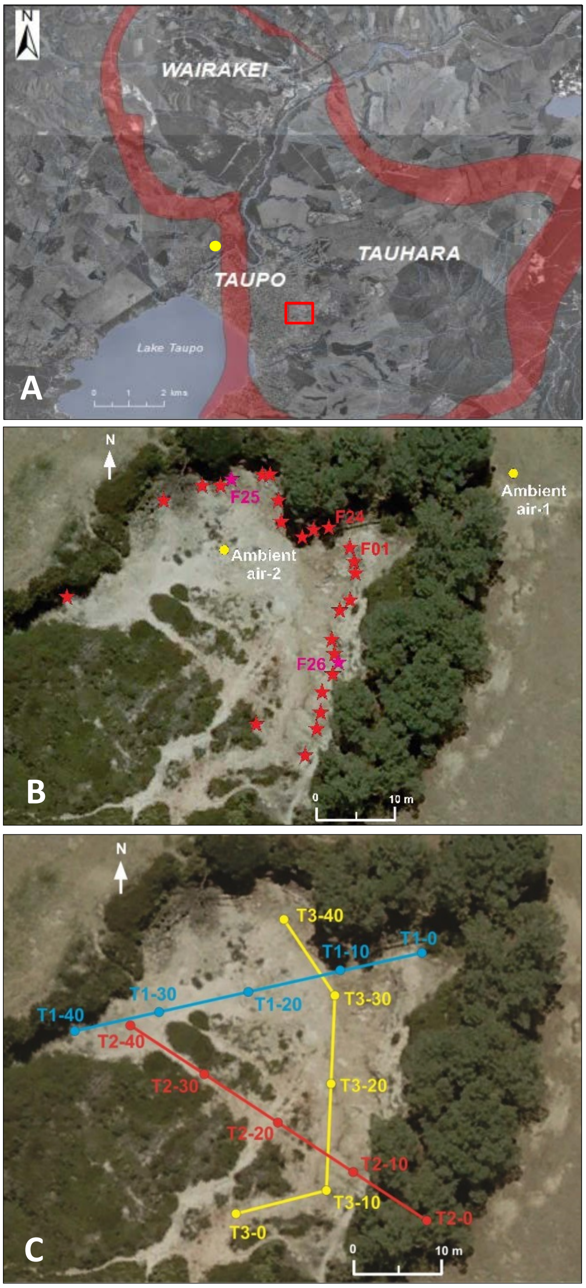

Figure 1: A. Location of Crown Park thermal area (red square) in relation to the Wairakei-Tauhara geothermal field resistivity boundary (red shading) as defined by Risk et al. (1984). Yellow dot = location of ambient soil measurement. B. Location of fumaroles (red and pink stars) and ambient air measurements (yellow dots). C. Location of transect lines (blue line = Transect 1; red line = Transect 2; yellow line = Transect 3).

The active thermal area is characterised by multiple, intermittently active fumaroles, and hydrothermally-altered pumiceous soils, derived from the 1.8 ka Taupō eruption (Rosenberg et al, 2009).

Twenty-six fumaroles have been identified and mapped by the Taupō College students at the Crown Park thermal area. These are all located around the boundary of the geographic depression, predominantly at the eastern and northern boundary (Figure 1B). Most of the fumaroles are characterised by collapse craters, some undercutting the base of the low cliffs bounding the thermal area.

Localised subsidence developed in close proximity (~300 m north-east) to the Crown Park thermal area in the late 1990s. Bromley et al. (2009) inferred declining water level in the shallow (<50m) boiling aquifer as a potential cause.

2. METHODOLOGY

2.1 Crown Park data collection

Monitoring of the active thermal area at Crown Park was undertaken by the Taupō College students every two to four weeks. At each monitoring visit, soil temperatures were measured along one of three 40 m-long transect lines (Figure 1C). Nine monitoring visits have occurred between 15th March and 2nd August, 2016; three visits for each transect line, with six to eight weeks between monitoring visits at each of the transect lines.

During monitoring visits, soil temperature profiles were measured at 5, 10, 15, 20, 25, 50 and 100 cm depths, at 10 m intervals along the designated transect line (Figure 1C). Additionally, 20 cm deep soil temperatures were measured at 1 m intervals along the same transect line. Temperature measurement sites along each transect line were named by the transect line number (i.e., T1, T2 or T3), and the distance (m) the measuring site was located along the length of the transect line, e.g., location T1-10 was located 10 m distance from the start point (T1-0) of Transect 1.

Fumaroles were assigned numbers F01 to F24, in a clockwise fashion from the fumarole closest to the access point into the thermal area (Figure 1B). Fumaroles F25 and F26 were identified at later dates, after several monitoring visits. Fumarole monitoring was undertaken at each of the nine monitoring visits and involved documenting visible and audible fumarole activity (steam), measuring fumarole steam temperature and gas composition (of active fumaroles), and recording 20 cm deep soil temperature (all fumarole sites, active and non-active). The 20 cm depth fumarole soil temperatures were measured 20 cm horizontal distance from the fumarole vent / collapse crater edge.

Attempts were initially made to quantify fumarole steam activity using a handheld anemometer (attached to a wooden pole) to measure steam velocity. Due to the diffuse and sometimes sporadic nature of the steam plumes, this method proved unsuccessful. At present, students note the height above the vent at which the fumarole steam dissipates and record a short video documenting the steam activity.

Ambient air and soil conditions were recorded at each monitoring visit. Ambient air conditions (temperature, wind speed and gas concentration) were measured at two sites (ambient air-1 and ambient air-2; Figure 1B). Ambient soil temperature at 20 and 100 cm depth was measured at a non-geothermal site located approximately 3.5 km north-west of Crown Park, near the junction of Huka Falls Road and State Highway 1 (Figure 1A). Additionally, continuous shallow-soil temperatures are monitored at a borehole site located at Wairakei (~7 km north of the Crown Park thermal area) to determine how thermal properties of the ground vary due to rainfall and atmospheric conditions (Seward and Prieto, 2015; Seward et al, 2013).

Soil, fumarole steam and air temperatures recorded during monitoring visits were measured using 1 m and 20 cm length K-type thermocouple temperature probes and Yokogawa TX10 digital thermometers. Temperature probes were kept in place at each measurement site until temperature reading stabilised to ± 0.1°C. To measure fumarole steam temperatures, the temperature probe was placed as close to the source of steam as possible to try to avoid any influence from entrained cooler air; however, absolute steam temperatures were hard to determine.

Ambient wind speed was measured using a handheld anemometer, accurate to 0.1 m s^{-1}. Fumarole gas and ambient air composition were measured using a handheld gas detector (Dräger X-am 5600) that measures multiple gases simultaneously using different sensors. CH_4 and CO_2 are measured by infrared sensors (accurate to ± 1.5%), while H_2S is measured by an electrochemical sensor (accurate to ± 2%). Measurements were collected by holding the gas detector as close to the source of the steam as possible and waiting for the CO_2 level to stabilise to within 0.01%.

All Crown Park data were digitally recorded during monitoring visits on custom-designed data-collection forms specifically developed by GNS Science using the Fulcrum Mobile Form Builder and Data Collection platform.

Weather data (e.g., daily rainfall and air temperatures) used in this paper was recorded at the Taupō Airport weather station located 5 km east of Crown Park, and was downloaded from the NIWA National Climate Database (https://cliflo.niwa.co.nz/).

2.2 Data Analyses

Standard site temperatures at the Crown Park thermal area are assumed to be the residual soil temperatures, determined by subtracting the ambient from the measured temperature, to remove (or reduce) anomalies in daily temperature variations. Residual soil temperatures referred to in this paper were determined using the ambient soil temperatures continuously recorded at the Wairakei borehole, because this provided a more complete dataset of temperatures at various depths than the ambient soil temperatures measured during monitoring visits.

Heat loss at the surface was determined using methods described by Bromley et al. (2011), which were derived from numerous studies undertaken at Karapiti thermal area, Wairakei, New Zealand (Bromley and Hochstein, 2000, 2005; Hochstein and Bromley, 2001, 2005). Heat loss is calculated from the boiling point depths determined from temperature (T) – depth (Z) profiles of the upper 1 m of the subsurface. Boiling point depths are determined from an empirically derived formula (Hochstein and Bromley, 2005):

$$Z_{BP} = \exp[c_1(T_{BP} - T_Z)] + c_2 \qquad \text{[EQ 1]}$$

Where T_z is the temperature measured at depth Z, and c_1 and c_2 are constants (c_1 = -0.025, and c_2 is a fitted site specific factor dependant on T_z), and T_{BP} is the boiling point temperature (98.6ºC for Tauhara area at an average atmospheric pressure). Once Z_{BP} is determined, total heat flux (Q_{tot}) is calculated using:

$$Q_{tot} = a\left(\frac{z_{BP}}{z_o}\right)^{-b} \qquad \text{[EQ 2]}$$

Where a = 185 Wm^{-2} (empirically derived constant; Hochstein and Bromley, 2005), z_o = 1 m, and b = 0.757. Bromley and Hochstein (2005) derived a secondary equation to determine the conductive component (Q_{cond}) of the heat flow. A relationship similar to EQ 2 was indicated for Q_{cond} at Karapiti thermal area with constants a = 97.3 Wm^{-2} and b = 0.709.

For fumarole gas composition, the Dräger gas detector measures CH_4 in % LEL (Lower Explosion Limit). The LEL is defined as the concentration of combustion gas (stated in volume % [Vol.%]) at which, under standardized conditions, the gas-air mixture can be ignited and will continue to burn on its own accord (Dräger Safety, 2015). The LEL of methane in air, for instance, is 4.4 Vol.%. Accordingly, a gas sample containing 1.0 Vol.% of methane in air cannot be ignited. For this study, the % LEL unit was converted to Vol.% of CH_4 using the formula:

$$C_{CH4}\,(\text{Vol.\%}) = C_{CH4}\text{LEL} \times 4.4 \qquad \text{[EQ 3]}$$

Where C_{CH4} (Vol.%) is the CH_4 concentration in volume per cent, C_{CH4} LEL is the concentration of combustion gas CH_4 in LEL per cent and 4.4 is the conversion number to volume per cent unit.

3. RESULTS AND DISCUSSION

3.1 Soil temperature

Five temperature-depth profiles were measured to 1 m depth at 10 m intervals along each transect line (Figure 1C). Results are shown in Figure 2. Soil temperatures along each of the transect lines varied significantly. For example, T1-10 exhibits significantly higher soil temperatures than the other profiles measured on Transect 1 (Figure 2). In most cases, soil temperatures at 1 m depth along each of the transects remained fairly consistent (generally within 5°C) between monitoring visits, while surface temperatures varied by up to ~40°C (Figure 2).

To compare time-variations of ground temperature in the Crown Park thermal area, residual soil temperatures were calculated (as described in section 2.2) for each of the nine monitoring visits and combined into three datasets corresponding to the first, second and third visit to each transect line. Residual temperatures for each dataset are plotted as isotherm contours (Figure 3) using the Kriging method in Surfer8.

Figure 3A shows residual isotherms at 20 and 100 cm depths (from 10 m interval temperature-depth profile data) for the three datasets. The highest residual soil temperatures at 20 and 100 cm depths are distributed in a north-south-trending line along the eastern margin of the thermal area, coinciding with the location and spatial distribution of several active fumaroles (Figure 1B). Residual isotherms for the second visit dataset show markedly lower residual temperatures, particularly at shallow depth (20 cm) and at locations T3-20 and T3-30, than those for the first and third visit datasets (Figure 3A).

Measured temperature-depth profiles were not significantly different for the second monitoring visits to Transects 1 and 2, but were markedly cooler during the second monitoring visit to Transect 3 (7^{th} June, 2016; Figure 2). Weather conditions recorded at Taupō Airport (Figure 4) show a marked decrease in average air temperature in the

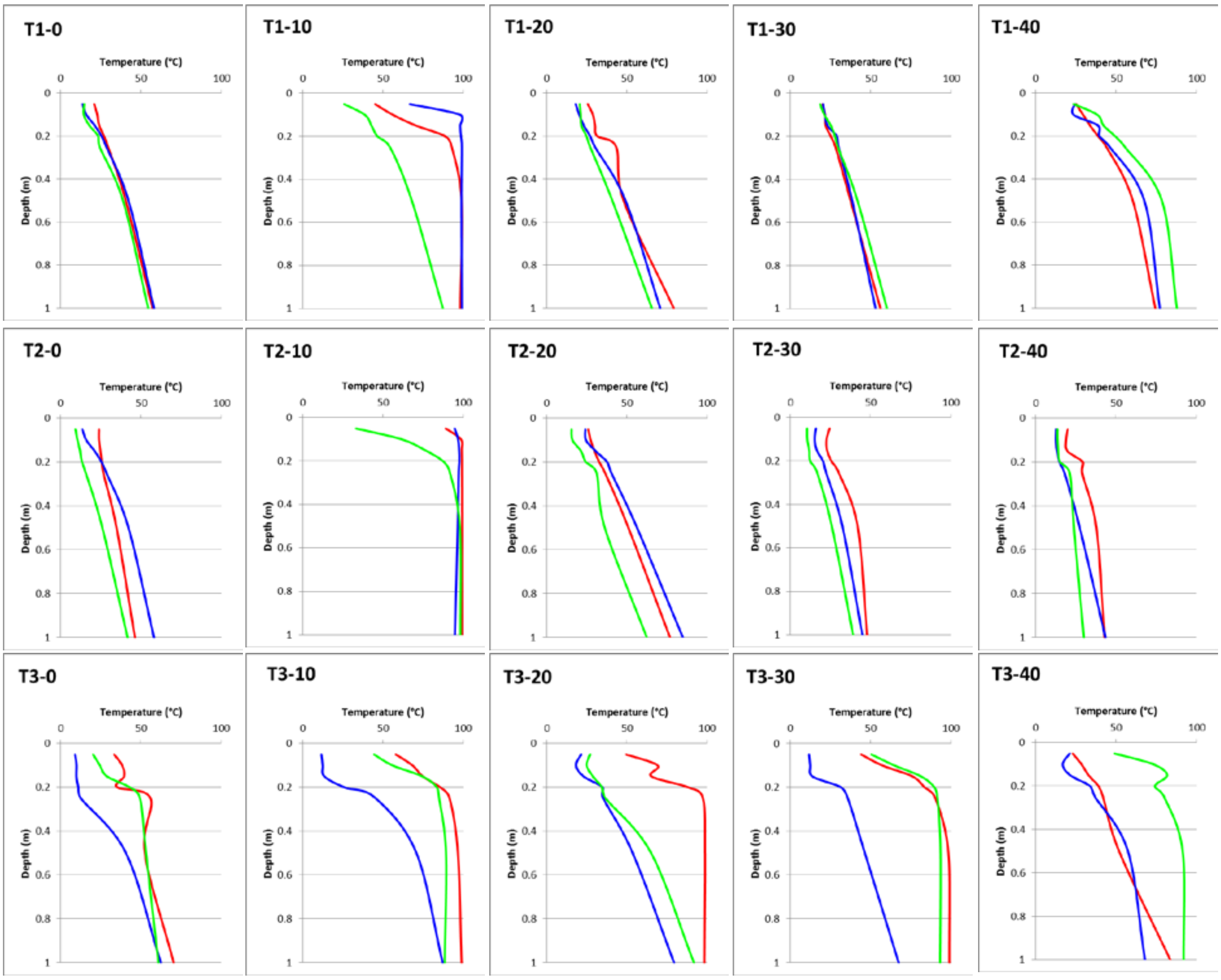

Figure 2: Temperature-depth soil profiles for each of the five, 10 m interval measuring locations on the three transect lines at Crown Park. Soil temperatures were measured at 5, 10, 15, 20, 25, 50 and 100 cm depths. Line colours represent different monitoring dates of each transect line as follows: red = 1st visit at each line (T1-15th March; T2-6th April; T3-12th April); blue = 2nd visit (T1-10th May; T2-24th May; T3-7th June); green line = 3rd visit (T1-21st June; T2-5th July; T3-2nd August).

week prior to the 7th June monitoring visit, and higher than average accumulated rainfall in the preceding three weeks. The shallower soil temperatures at the Crown Park thermal area therefore appear to be significantly influenced by these atmospheric changes.

Soil temperatures were also measured at 20 cm depth, at 1 m intervals along each transect line. High-resolution 20 cm depth residual isotherms (contoured using 1 m interval data from each transect line; Figure 3B) display a more localised distribution of high soil temperatures around some measuring sites (e.g., T1-10, T2-10, T3-10, T3-20 and T3-30) at shallow depths, than is shown by the lower-resolution (10 m interval data) 20 cm depth isotherms in Figure 3A.

3.2 Surface Heat loss

Surface heat loss from the Crown Park thermal area is calculated from the measured temperatures at each temperature-depth profile site using EQ 2. Depth to boiling point was determined for each site using the methodology outlined in section 2.2. Table 1 summarises the results.

From the data collected, temperature-depth profile measuring sites can be categorised into 3 groups based on their boiling point depths. Figure 5, shows the averaged temperature profiles of each site within these groups. Those sites with shallow boiling point depths (Figure 5A) are sites with high heat flow, and will respond to seasonal and episodic events differently than those with deeper boiling point depths (Figure 5C). It will be interesting to trace their behaviour over future visits. It is assumed that those with deeper boiling point depths will be affected to greater depths by seasonal change and episodic rainfall than those with shallower boiling point depths.

3.3 Fumarole activity

The twenty-six fumaroles identified at Crown Park thermal area (Figure 1B) were monitored during each of the nine monitoring visits, including recording visible and audible fumarole steam activity, measuring fumarole steam temperature and gas composition, and recording 20 cm deep soil temperature.

The fumaroles located along the eastern boundary of the thermal area are generally more visibly active than the other fumaroles in the thermal area, although steam activity has been notably variable throughout the monitoring period. Specific vents are not observed at most fumarole craters;

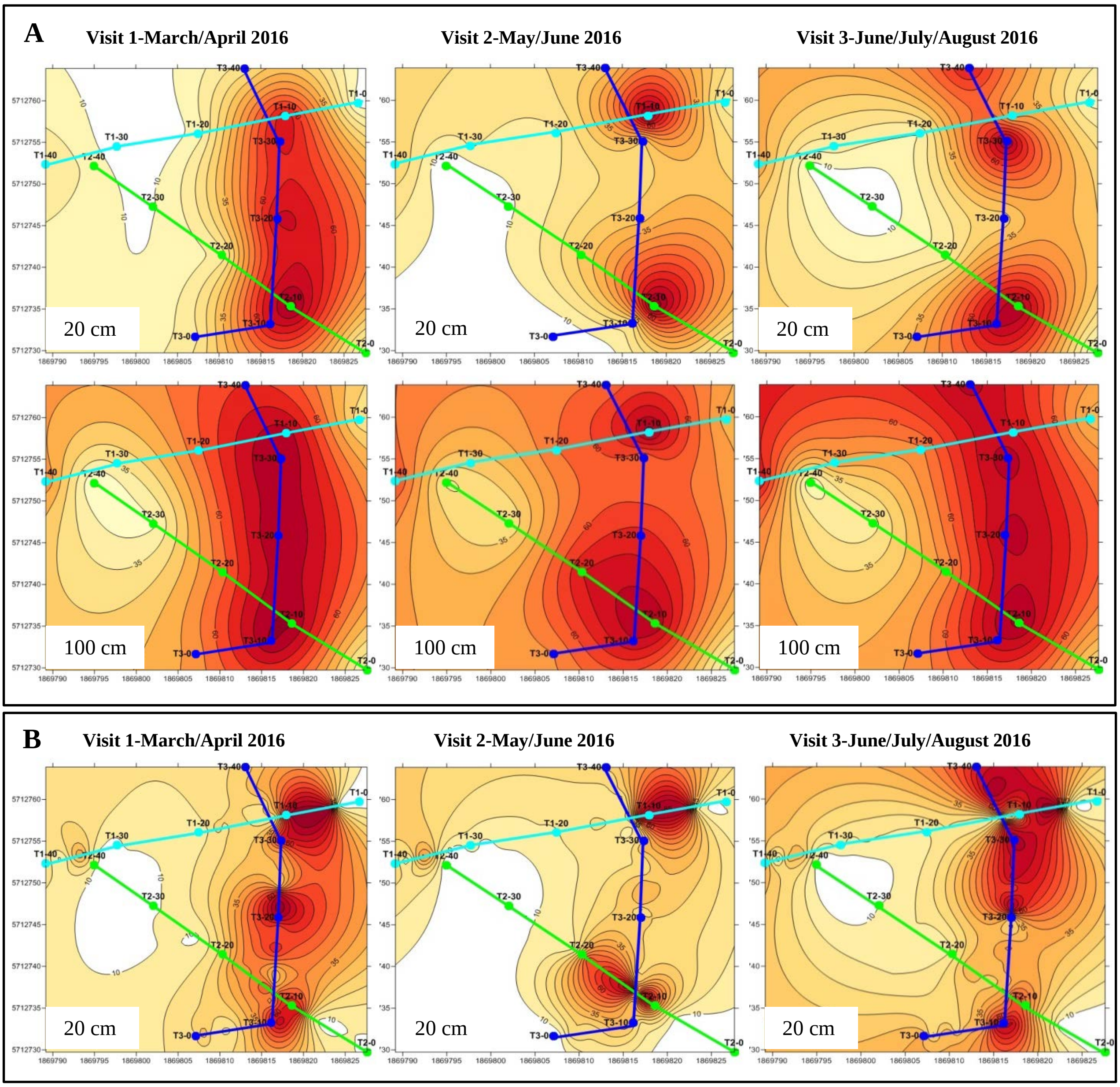

Figure 3: Residual soil temperature isotherms combining data from the 1st, 2nd and 3rd monitoring visit at each transect line (see Figure 2 caption for monitoring visit dates). A. Isotherms for 20 and 100 cm depths from 10 m interval locations along transect lines. B. Isotherms for 20 cm depth from 1 m interval locations along transect lines.

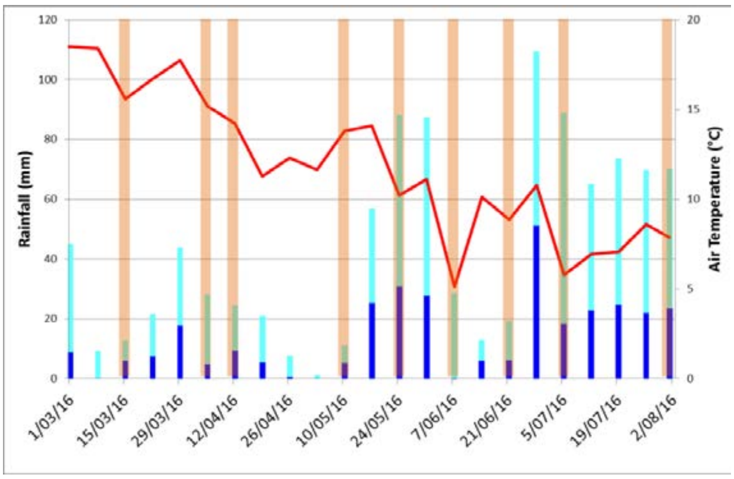

Figure 4: Weather data recorded at Taupō Airport between 1 March and 2 August, 2016. Orange shading = dates of monitoring visits; dark blue bars = accumulated rainfall over the week preceding monitoring dates; light blue bars = accumulated rainfall during the fortnight prior to monitoring; red line = average weekly air temperature.

fumarole activity generally comprises diffuse steam escaping through the collapse crater floor or walls, albeit somewhat localised in places. Steam activity and steam temperature have been difficult to quantify / measure and although monitored, are not discussed further in this paper.

Fumarole soil temperatures measured at 20 cm depth are typically near boiling and are generally consistent, both between fumaroles and between monitoring dates (Figure 6); however, they do appear to be significantly influenced by anomalous weather conditions. For example, the marked overall decrease in fumarole soil temperatures measured on 7th June and 5th July, 2016 (indicated by red arrows in Figure 6) coincide with periods of markedly lower air temperature and periods of higher than average rainfall in the days preceding these two monitoring dates.

The increased rainfall allows the cold atmospheric temperatures to penetrate the ground, affecting the shallow soil temperatures.

Fumarole gas compositions were also measured at each monitoring visit. Figure 7 shows the changes in concentration of CO_2 and CH_4 over the monitoring period.

A significant increase in CO_2 and CH_4 concentration was measured at some fumaroles on 21st June (Figure 7). Comparison with rainfall data (Figure 7) shows 96 mm of accumulated weekly rainfall between 3rd May and 7th June, inferring a significant influx of meteoric water into the hydrothermal system. This likely cooled the system leading to increased steam condensation, and therefore, higher concentrations of CO_2 and CH_4 escaping to the surface (Glover and Mroczek, 2009). However, there was no significant increase in fumarole CO_2 and CH_4 concentration measured on 7th June (one week after the accumulated rainfall), suggesting that some time was required for the meteoric water to percolate down to the thermal aquifer. This also suggests that those fumaroles that displayed significantly higher gas concentrations on 21st June (Figure 7) may be more directly connected to the deeper geothermal system than those with no significant increase.

There were no apparent trends in H_2S concentration during the monitoring period. This is likely due to H_2S being easily scrubbed in the hydrothermal system because of its high solubility

Table 1: Summary of boiling point depth (Z_{BP}), and total (Q_{tot}) and conductive (Q_{cond}) heat flow estimates from soil temperatures measured at 10 m intervals on Transects 1, 2 and 3 between 15th March and 2nd August 2016. Boiling point depths are given in metres (m), total and conductive heat flow in Wm^{-2}.

	Transect 1			**Transect 2**			**Transect 3**		
Monitoring Date	**15/03/16**	**10/05/16**	**21/06/16**	**6/04/16**	**24/05/16**	**5/07/16**	**12/04/16**	**7/06/16**	**2/08/16**
	T1-0			***T2-0***			***T3-0***		
Z_{BP}	3.7	3.7	4.1	6.5	3.7	5.9	2.4	2.8	5.5
Q_{tot}	69	69	63	45	69	48	95	86	51
Q_{cond}	39	39	36	26	39	28	53	48	30
	T1-10			***T2-10***			***T3-10***		
Z_{BP}	0.6	0.3	1.4	0.1	0.2	1.6	1.0	1.5	3.6
Q_{tot}	264	424	141	1057	626	128	192	136	70
Q_{cond}	135	209	76	488	301	69	100	73	40
	T1-20			***T2-20***			***T3-20***		
Z_{BP}	1.5	2.2	2.4	1.8	1.4	2.5	0.7	1.6	1.2
Q_{tot}	131	101	95	120	145	91	230	127	162
Q_{cond}	70	56	53	65	77	51	119	69	86
	T1-30			***T2-30***			***T3-30***		
Z_{BP}	3.6	4.5	3.2	10.3	6.3	7.0	0.8	2.5	3.9
Q_{tot}	71	59	77	32	46	42	213	94	66
Q_{cond}	40	34	43	19	27	25	111	52	38
	T1-40			***T2-40***			***T3-40***		
Z_{BP}	2.4	2.7	1.8	13.4	5.5	16.9	1.4	3.5	1.5
Q_{tot}	95	88	121	26	51	22	142	72	134
Q_{cond}	52	49	66	16	29	13	76	41	72

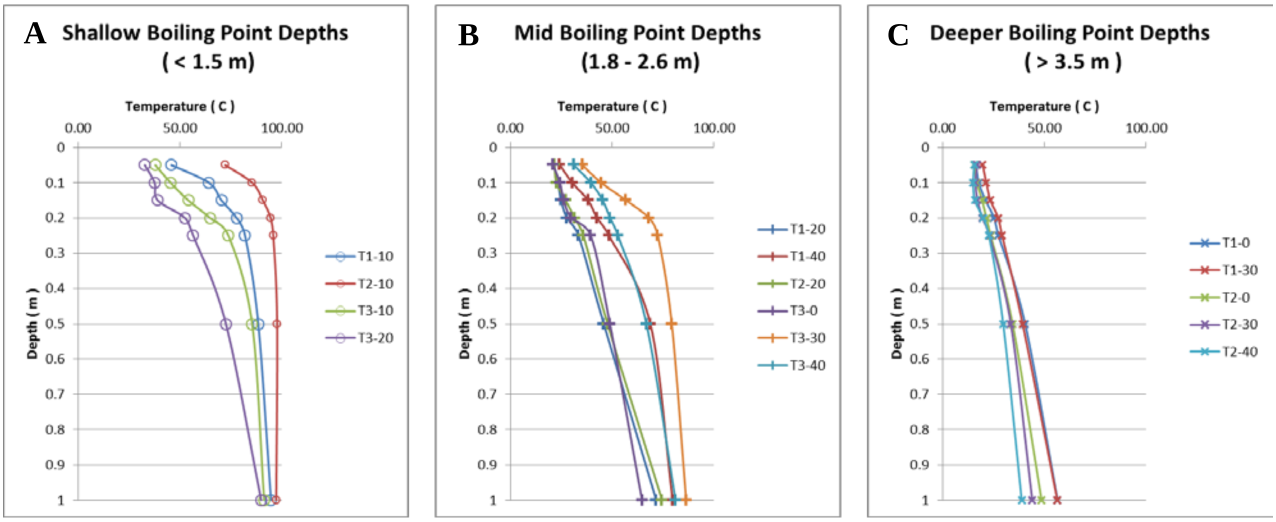

Figure 5: Averaged soil temperature-depth profiles measured at Crown Park thermal area. Profile sites have been separated into those with A. "Shallow Boiling Point Depths" (hotter sites), B. "Mid Boiling Point Depths", and C. "Deeper Boiling Point Depths" (cooler sites).

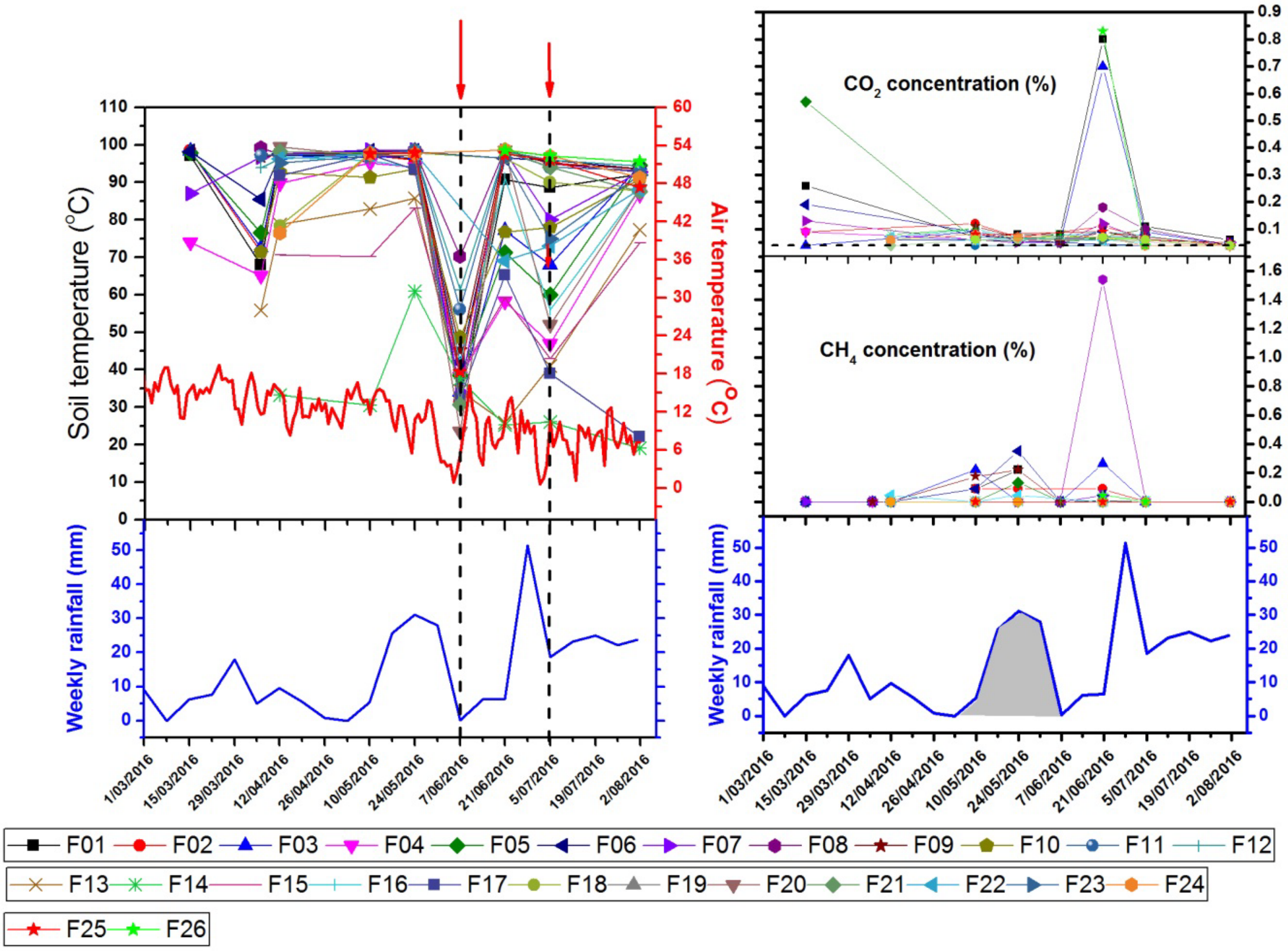

Figure 6: Left: Fumarole soil temperatures (top graph) measured at 20 cm depth between 15th March and 2nd August 2016, compared with daily air temperature (red line plotted on secondary vertical axis) and weekly accumulated rainfall (blue line, bottom graph) over the same period. The red arrows and the black dashed lines highlight data collected on 7th June and 5th July, 2016 monitoring visits. Right: Fumarole CO_2 and CH_4 concentrations (top two graphs) measured between March and August 2016, compared with weekly accumulated rainfall (blue line, bottom graph). The horizontal black dashed line (top graph) represents atmospheric CO_2 concentration (0.04 %).

4. SUMMARY

Soil temperatures along one of three transect lines were measured every six to eight weeks at the Crown Park thermal area as part of the 'Our Geothermal Area' education project. Temperature-depth profiles were measured to 1 m depth at 10 m intervals, and 20 cm depth at 1 m intervals along each 40 m-length transect. At each monitoring visit, steam observations and soil temperature measurements were recorded at identified fumaroles within the active thermal area.

Variations observed in soil temperatures, particularly at shallow depths are influenced by meteorological conditions. Temperature-depth profiles show that there are two key relationships between soil temperatures and depth. The cooler sites (deeper boiling point), generally show a linear relationship, while hotter sites show an exponential relationship with depth.

The spatial distribution of the fumaroles, particularly those with visible steam activity, is consistent with the distribution of higher soil temperatures. Preliminary results from the initial five months of data collection suggest that fumarole gas compositions are significantly influenced by local rainfall and atmospheric temperatures.

The frequency of monitoring visits, combined with the relatively close spacing of soil temperature measuring sites along each transect line, has provided an interesting glimpse into thermal activity fluctuations at Crown Park over the monitoring period, and the factors influencing these. Data collected to date provide the basis for a comprehensive dataset in an area not previously monitored, which, with continued regular monitoring, may have applications in multiple areas of geothermal science. Over time, it is expected that these data will provide greater insight into seasonal and episodic variations affecting soil temperatures and fumarole activity at the Crown Park thermal area, and highlight how they affect the surface heat loss in this area.

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