2014 Thermal infrared survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields

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ABSTRACT

An aerial thermal infrared (TIR) survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields was undertaken on 6-7 March, 2014. Approximately 2700 TIR images were processed and mosaicked to produce a single, 16 bit image with a ground pixel size of approximately 2 m x 2 m (Figure A1). The purpose of this report is to summarise the method of data collection, and present the final TIR image and accompanying brief interpretation.

The TIR data is of good quality and enables numerous geothermal and non-geothermal surface features to be identified and mapped to relatively high spatial accuracies (<5 m) within the limitations of the survey. The locations of TIR anomalies interpreted to be caused by geothermal activity are in general agreement with areas of known surface geothermal activity. Several areas where thermal seeps may be discharging into Lake Rotorua in the Rotorua City, Mokoia Island and Rotokawa areas are identified.

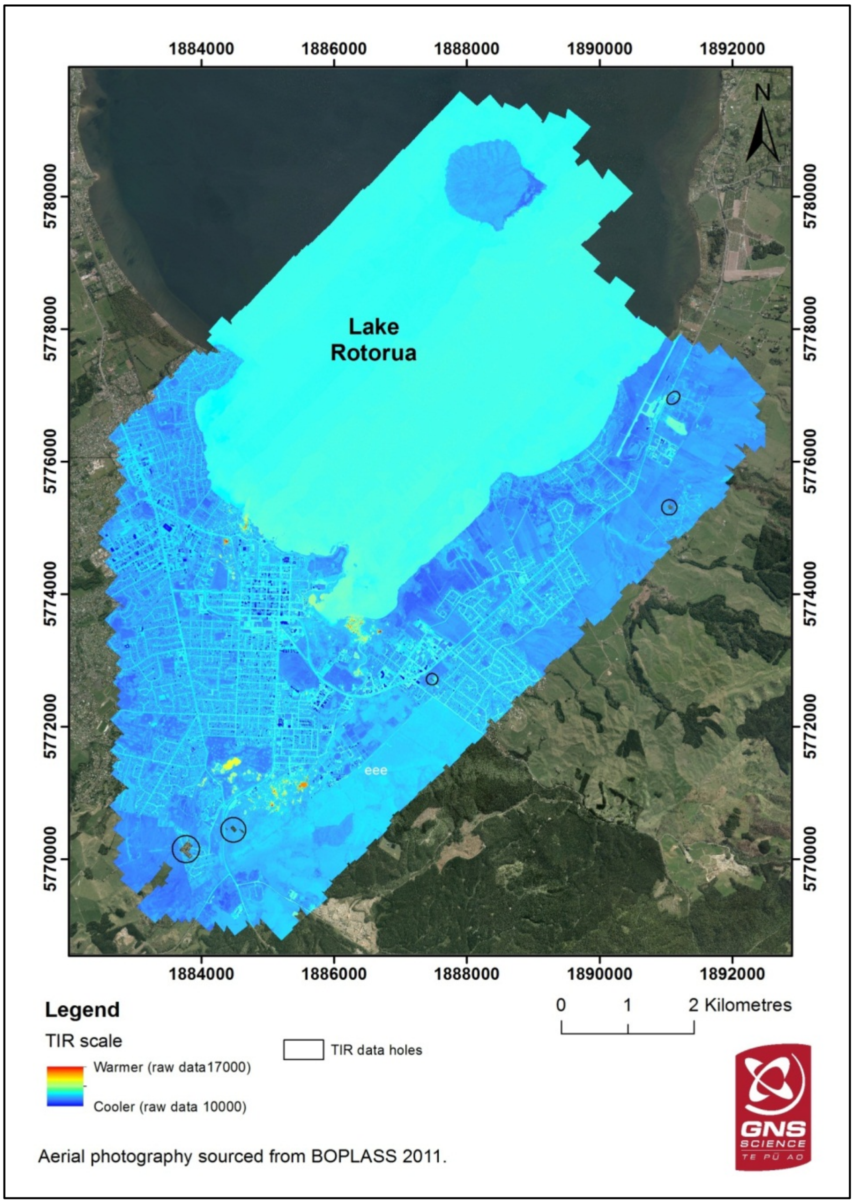

Figure A1 2014 TIR image showing the raw TIR data in the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields.

KEYWORDS

Rotorua Geothermal Field, Lake Rotokawa-Mokoia Geothermal Field, aerial thermal infrared, surface geothermal features.

1.0 INTRODUCTION

Aerial thermal infrared (TIR) surveys of geothermal areas have been used for identifying and monitoring surface geothermal features for over 24 years in New Zealand (e.g., Mongillo, 1994; Mongillo and Bromley, 1990; Mongillo *et al*., 1995). The technique is based on the principle that objects having temperatures above 0º K emit TIR radiation with energy dependant on temperature. The radiation can be detected by specialist instruments. Aerial TIR data is collected by attaching a TIR camera and recording instrumentation to an aircraft and flying over areas of interest. Addition of navigation and ground data can ensure accurate location of the TIR anomalies.

Quantitative aerial TIR data can be difficult to interpret due to factors affecting the measured TIR signal, such as humidity, distance between the sensor and the source, and emissivity. However, the technique has been successful in identifying the locations of thermal anomalies and obtaining estimates of relative temperature changes in geothermal areas thus making it a useful mapping and monitoring tool. This is particularly effective when data between surveys can be compared.

The TIR data presented in this report was collected as part of the Geothermal Resources of New Zealand Research programme to provide a TIR dataset of the Rotorua and Lake Rotokawa-Mokoia areas, Rotorua that can be used by researchers, local and regional authorities, and other users. The purpose of this report is to present high quality TIR data in a useable format and interpretation along with a discussion of the data and interpretation limitations.

2.0 SETTING

The Rotorua Geothermal Field (RGF) is located at Rotorua City, in the central part of the North Island, New Zealand (Figure 2.1). The geology of the RGF area is described in detail by Wood (1992) and is summarised here. The RGF lies at the southern end of the Rotorua caldera that formed about 230 ka ago, producing the Mamaku Plateau Formation (Leonard *et al*., 2010). Since the caldera formation, the area has been subjected to small scale dome forming eruptions, transient lakes, erosion and sedimentation. The Mamaku Plateau Formation, sediments and rhyolitic domes/flows are the three key geological units in the RGF. Numerous faults are interpreted from drill logs cutting the RGF and have some influence in providing permeability that focusses the flow of geothermal fluids (Wood, 1992; Giggenbach and Glover, 1992).

The 30-50 ohm-m contours of the 500 m array spacing resistivity map (Bibby *et al*., 1992) (Figure 2.1) provide an indicative extent of low resistivity strata likely to be associated with geothermal activity at about 250 m depth. This shows that the RGF is coincident with much of Rotorua City and extends into the southern part of Lake Rotorua. Surface geothermal features of the RGF are largely constrained within this boundary; however, geothermal activity is also seen on Mokoia Island and near Lake Rotokawa, which are considered geothermal areas that are discrete from the low resistivity anomaly associated with the RGF.

Geothermal resources in the Rotorua area have long been used for cultural, domestic and commercial uses, including bathing, cooking, heating, tourism, and natural products. 'Abnormal' surface geothermal feature behaviour (summarised in Allis and Lumb, 1992) gave rise to public concerns about excessive use of the geothermal resource through well takes for domestic and commercial heating. This resulted in a government-lead bore closure programme in 1987. The programme involved closing geothermal bores within a 1.5 km radius of Pohutu Geyser, and implementation of a Rotorua Geothermal Management Plan in an effort to protect surface geothermal features from further deterioration. A management plan for the RGF is currently in place and is managed by the Bay of Plenty Regional Council.

Over 1500 surface geothermal features are mapped in the RGF and Lake Rotokawa-Mokoia Geothermal Fields (Figure 2.1). Surface features include geysers, hot pools, mud pools and thermal ground. In the case of the RGF, these can be grouped into four main geographical areas: Kuirau Park, Government Gardens, Ngapuna and Whakarewarewa (Figure 2.1). Water chemistry of the RGF indicate that chloride, steam heated and mixed waters all occur within the RGF (Stewart *et al*., 1992; Mroczek *et al.,* 2011).

Aerial TIR surveys have been flown over the RGF in 1972 (Dickenson, 1973), 1988 (Mongillo, 1988) and in 1990 (Mongillo and Bromley, 1992). Thermal anomalies associated with surface geothermal features could be identified in all surveys with some increases in thermal activity identified between the 1988 and 1990 surveys at Ohinemutu (Figure 2.1) (Mongillo and Bromley, 1992). The extent of all three surveys were limited however, and do not cover the RGF entirety. The data presented in this report is collected to complement the previous three RGF TIR surveys, allowing for the different techniques and technology used to capture the TIR data. The data quality has been improving with each TIR survey.

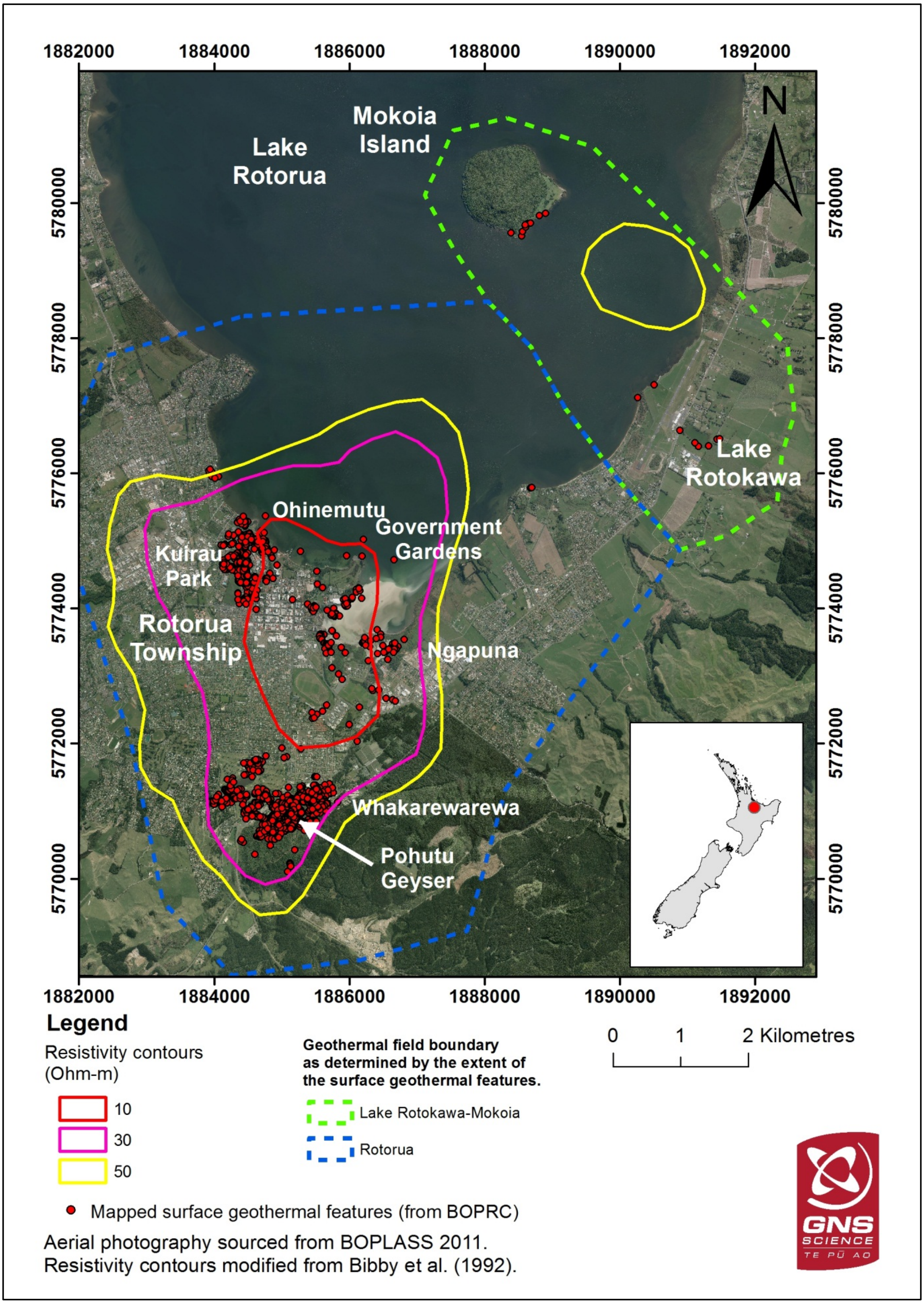

Figure 2.1 Location of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields as determined by the extent of the surface geothermal features.

3.0 METHODOLOGY

The March 2014 TIR survey was designed to encompass areas where surface geothermal features are mapped in the RGF, Mokoia Island and the Lake Rotokawa areas. For comparison purposes, it also covers areas flown in the 1988 and 1990 TIR surveys. The current survey area was larger than the previous surveys to ensure the whole RGF was covered. Also, a fixed-wing aircraft was used to collect data in this survey which enabled faster and greater coverage compared to the helicopter-borne method of data collection used in the previous two TIR surveys.

A Flir A615 camera (with 25 mm lens and an uncooled microbolometer detector in the 7.5-13 µm wavelength band) was mounted into an Aero commander 680F twin engine aircraft for data collection. Navigation and camera control was achieved using Aviatrix (Version 5 Dec 2013). Aircraft speed was to target 90-120 knots. The TIR survey was flown on a clear night (no cloud or fog) between 9:15 pm on the 6 March and 00:20 am on the 7 March to minimise solar effects.

A flight plan is required for aircraft navigational purposes and to control when the TIR camera takes an image. Flight plans are usually designed to have an aircraft flying in straight lines while taking images. The survey area is usually transected by several flight lines, which are designed to ensure that there are no gaps between adjacent images or between images for neighbouring flight lines. It is standard practice to allow sufficient overlap of images in case the aircraft does not fly exactly along the intended flight line.

The flight plan for this TIR survey assumed:

- Flir A615 camera with a 25 mm lens.
- Flight elevation of 960 m above ground.
- 70% forward overlap for images along the line.
- 35% side overlap for images on neighbouring lines.

Data collected as part of the survey includes a 16 bit (over a temperature range of -40°C to 150°C), 640 x 480 pixel, 601KB TIF image and a metadata file. The TIF image records the RAW data from the TIR camera and gives each pixel a value of between 0 and 65,000. This is raw data and has not been adjusted for thermographic parameters such as air temperature, emissivity etc. The metadata files store information about the image such as Global Positioning System (GPS) location, aircraft heading and speed, and camera details.

TIR imagers measure the amount of thermal radiation sensed by the detector. Images are affected by the emissivity of the ground, reflections from surrounding sources, size of the source, distance to the target and radiation absorption by the atmosphere. Steam and fog are also significant absorbers of infrared (IR). Some data may be affected by steam absorption in areas of natural geothermal activity and man-made features such as steam discharging structures (e.g., water discharge channels) particularly where higher temperature water/steam is discharged. Tall vegetation and steep banks can also mask or obscure thermal anomalies and may affect data quality. Changes in the lake and stream levels in the study area can affect hot water seepage along the lake shore and stream banks.

Temperature at control sites are measured by a ground team at the same time as the TIR survey is undertaken to help interpret and calibrate the TIR data. Water temperatures are measured at selected sites that cover the expected temperature range of the surface geothermal features based on past experience. Water temperatures are measured with a Yokogawa TX10 digital temperature meter connected to a K type thermocouple. Water temperature was also measured with a handheld IR thermometer for comparison purposes. A “track-it” temperature data logger was installed at temperature control sites where the site could not be accessed during the TIR survey (e.g., closed swimming pool). Data from the temperature loggers is used to estimate the water temperatures at the time the image over these sites were collected.

A simple linear temperature calibration between the TIR data and the measured water temperature data is derived using the temperature data and by reading the data from the TIR image at the location that the temperature was measured. This assumes that the temperature measured at each site remains constant until the TIR image is collected (i.e., the order that temperatures are measured from the control sites by the ground team is not typically the order in which the TIR images are captured by the TIR camera. This can cause differences in timing between capture of the TIR image and measuring the temperature at the ground control site). This relationship provides a water temperature estimate from the TIR data as there are many factors that will affect a calculation of the temperature of an object. It should also be noted that the relationship derived is only applicable to water bodies and not hard surfaces.

Spatial control sites are used to assess the spatial accuracy of the final TIR image. Objects (e.g., steel plates on grass) or patterns (e.g., intersection of a concrete footpath with a road) considered to have a distinctive thermal anomaly relative to background thermal conditions were surveyed using a Trimble GeoXH differential GPS receiver. GPS data were differentially corrected to the base station at Utuhina (Rotorua) resulting in coordinates with estimated horizontal errors of no more than 0.5 m. The locations of the spatial control sites are compared to the location of the object identified in the TIR image to obtain an estimate of horizontal error of the TIR image.

The TIF files were mosaicked by Spatial Scientific using AeroMosaic. This software is specifically designed to mosaic TIR images based on automatic feature identification and comparison with features in orthographic photographs, resulting in a single geo-registered 16 bit TIF image covering the entire survey area. The software uses nearest-neighbour sampling and does not use colour balancing so that temperature data in the imagery are preserved. Seamlines/cutlines are placed along linear features (roads etc.) so that the final mosaic is visually pleasing. For this report, the produced image was resampled on a 2 m x 2 m pixel size using bilinear resampling.

Field-truthing of selected thermal anomalies was done to confirm that the TIR signals are caused by surface geothermal activity. This was done by visiting a selection of thermal anomalies identified from the TIR survey and measuring the temperature of the target using either an handheld IR thermometer (used for most measurements) or a Yokogawa TX10 digital thermometer connected to a K-type thermocouple (used for easily accessible water sites).

The handheld IR thermometer uses an IR method of measuring temperature. As a result, measured temperatures can be affected by such factors as humidity (e.g., steam), material type, thermal reflections and distance to target. Two methods of using this instrument were used to identify thermal anomalies:

1. A temperature range was measured of the target object, by collecting continuous measurements as the IR thermometer was aimed at different parts of the target. This

was generally done for water targets that were unsafe to access, and targets that were clearly geothermally influenced e.g., a geothermal hot spring.

2. A temperature range was measured of the target area / object by collecting continuous measurements as the IR thermometer was aimed at different parts of the target (the "anomaly temperatures") (same as 1. above). In addition, this was repeated for areas of similar material types **outside** of the anomalous area to obtain "background" temperatures. Areas with inferred anomalous temperature can be compared to background temperatures, to obtain temperature differences that could be used to identify areas where geothermal inputs could be present. This was used to help identify "warm ground" features where geothermal influence may not necessarily be clear.

Caution is required using the absolute temperatures measured by the IR thermometer as many of the TIR targets were roads/pavement/concrete which are affected by solar heating and became warmer as the day progressed. Method 2 above was designed to address these effects. However, in some cases, ground temperatures may have got so warm as to mask other thermal effects. This could occur where there are small additional thermal inputs to the target. In this report, these areas are not regarded as geothermal areas in the interpretation.

Based on the measured temperatures and physical observations of the targets, the area received a 'geothermally influenced' or not 'geothermally influenced' designation.

4.0 RESULTS AND DISCUSSION

An aerial TIR survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields was flown on 6 March, 2014 between approximately 21:15 pm and 00:20 am on the 7 March with R. Reeves in the aircraft operating the data collection software and B. Scott and J. Hall making the ground-based temperature measurements. The survey was completed with 25 flight lines (Figures 4.1 and 4.2) and collected approximately 2700 TIR images. Line 13 (Figure 4.1) was re-flown (in the opposite direction) due to the aircraft getting off-line and missing several photo points. However, the aircraft again got off the line and missed some photo points. The line was not repeated because collectively all photo points were obtained when both flight data was taken into consideration. The flight lines were flown in reverse order to their numbering (i.e., Line 25 was flown first) because Line 25 was closest on the approach to the survey area. Flight altitude for the survey varied between 1185 m to 1380 m above mean sea level (amsl). Lower flight altitudes generally occurred along Line 4 and the higher flight altitudes occurred along Line 16.

Weather was generally calm and clear for the March 2014 TIR survey, although small patchy clouds above the survey altitude were noticed towards the end of the survey at the end of Line 2. This is not thought to have a significant impact on the data quality for this line. Little variation in air temperature was measured during the survey. The air temperature measured at Ngapuna ranged between 11.6°C and 13.3°C between 21.00 pm and midnight with a temperature low occurring at 22:40 pm (Bay of Plenty Regional Council, 2014a). The level of Lake Rotorua was low with a measured lake level of 279.658 m amsl at 22:30 pm (NZDST) (Bay of Plenty Regional Council, 2014b).

Figure 4.2 shows a false colour mosaicked TIR image of the raw data. Raw data ranges from 0 (cooler) to 21485 (warmer). The colour scale on Figure 4.2 (and subsequent figures) has been set to display data with pixel values between 10000 and 17000 (which equates to a water temperature range of about -5 to 67°C) to emphasise areas of possible thermal activity (red and yellow colours in Figure 4.2). The four main areas of surface geothermal activity at RGF (Kuirau Park, Government Gardens, Ngapuna, and Whakarewarewa, Figure 2.1) have TIR anomalies interpreted to be caused by geothermal activity. Not all elevated TIR anomalies are associated with surface geothermal activity, e.g., spa pools heated with an electrical heater will give an elevated thermal anomaly which is not caused by geothermal activity. Roads, infrastructure and Lake Rotorua can be seen as cool thermal anomalies (light blue colours) in Figure 4.2.

Five small ‘holes’ or data gaps are identified in the mosaicked TIR image (Figure 4.2). ‘Holes’ occur where there is no overlap between neighbouring images. This probably occurred when the aircraft has either rolled or pitched outside of tolerances, resulting in an incorrect camera orientation at the time the image was taken.

Twenty one spatial control sites (Appendix 1, Figure 4.3) and 16 temperature control sites (Appendix 2, Figure 4.3) were used to constrain the TIR data. Spatial control of the final TIR image is good, with an average difference between the differential GPS coordinate and the target in the TIR image of 1.08 m, and the largest difference is 3.34 m at site s3 (Figure 4.3). This indicates that the image has been mosaicked to a high quality at the spatial control sites.

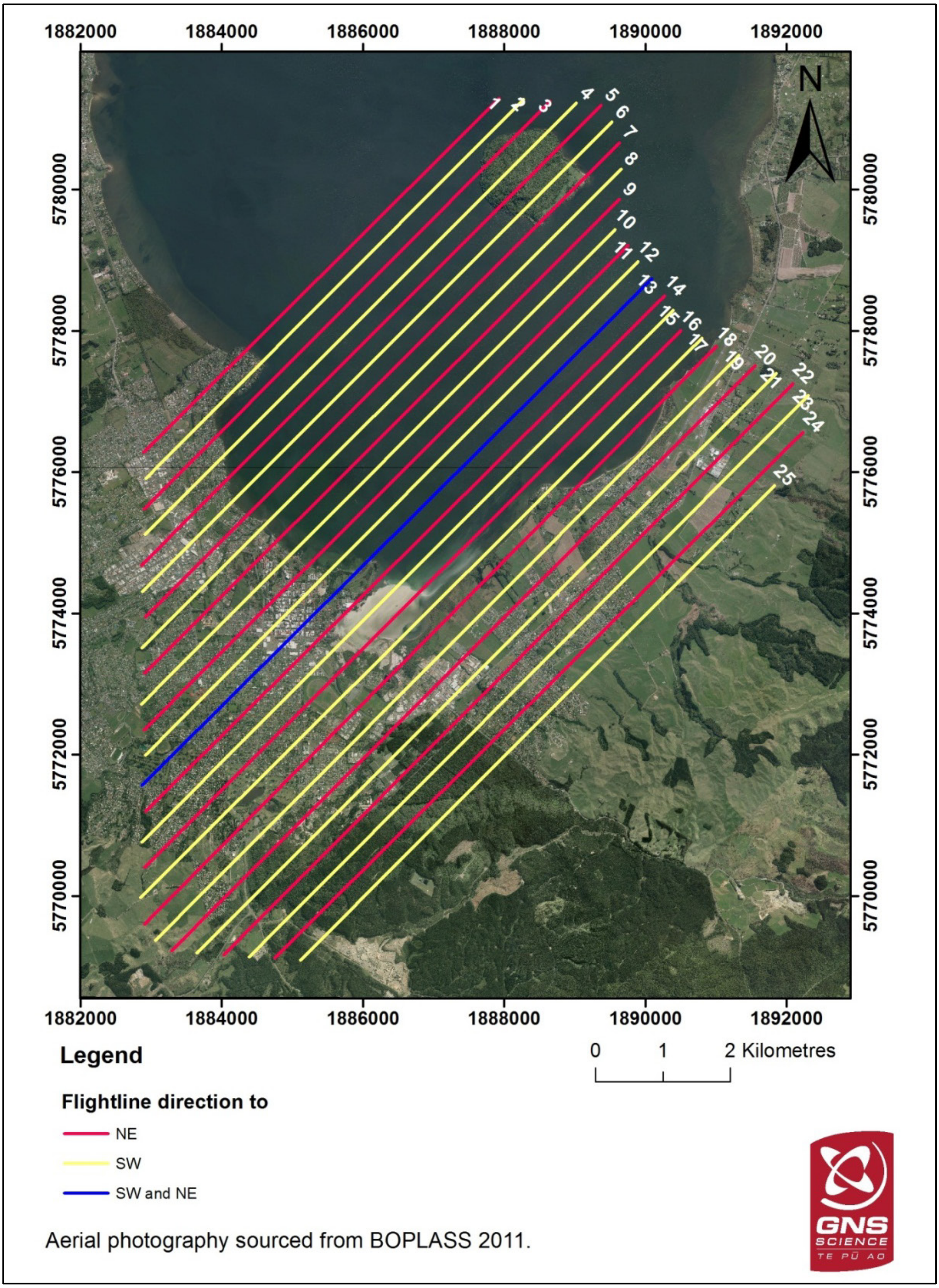

Figure 4.1 2014 TIR survey flight lines with different colours representing different flight directions.

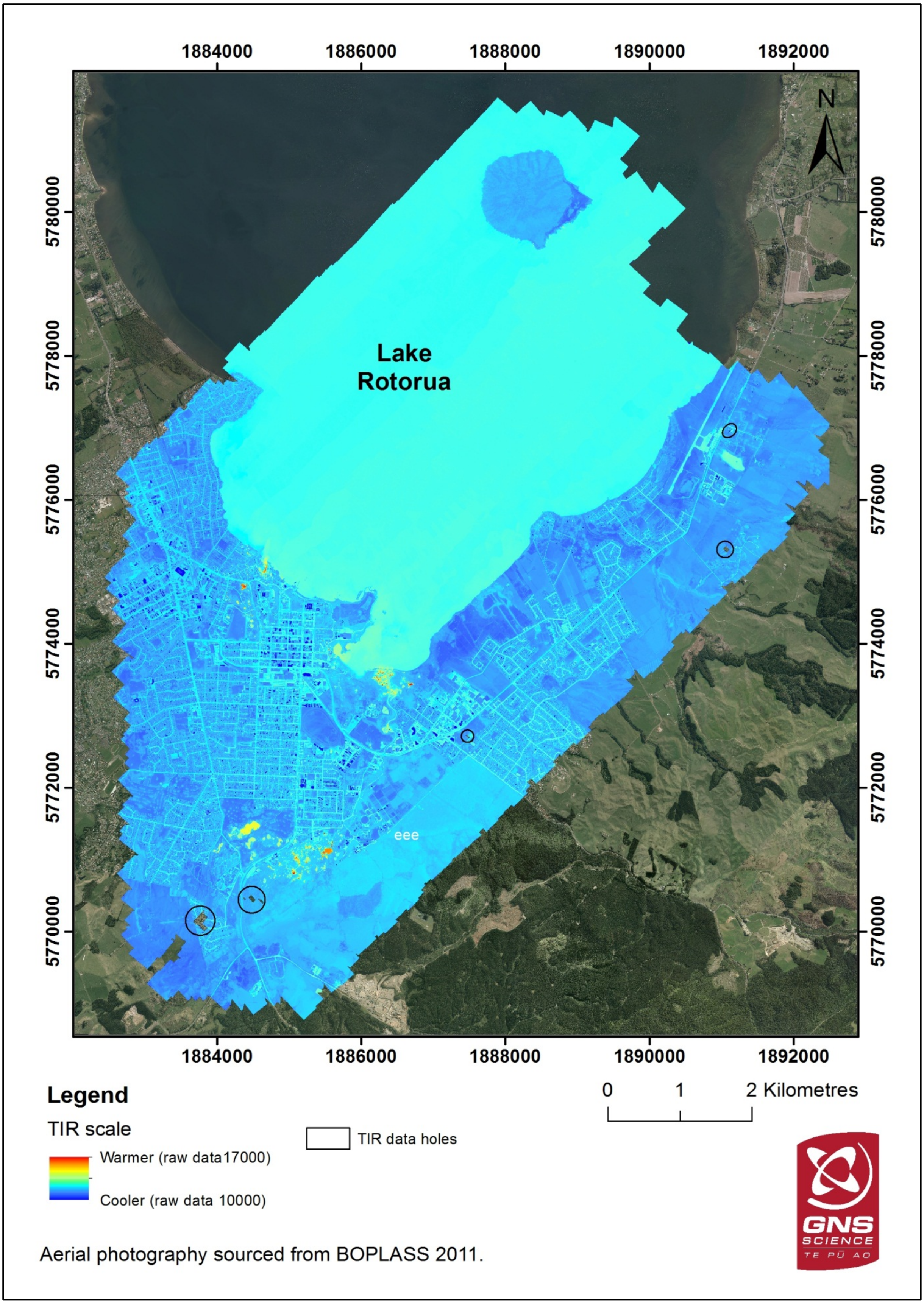

Figure 4.2 2014 false colour TIR image showing the raw TIR data and gaps in the data.

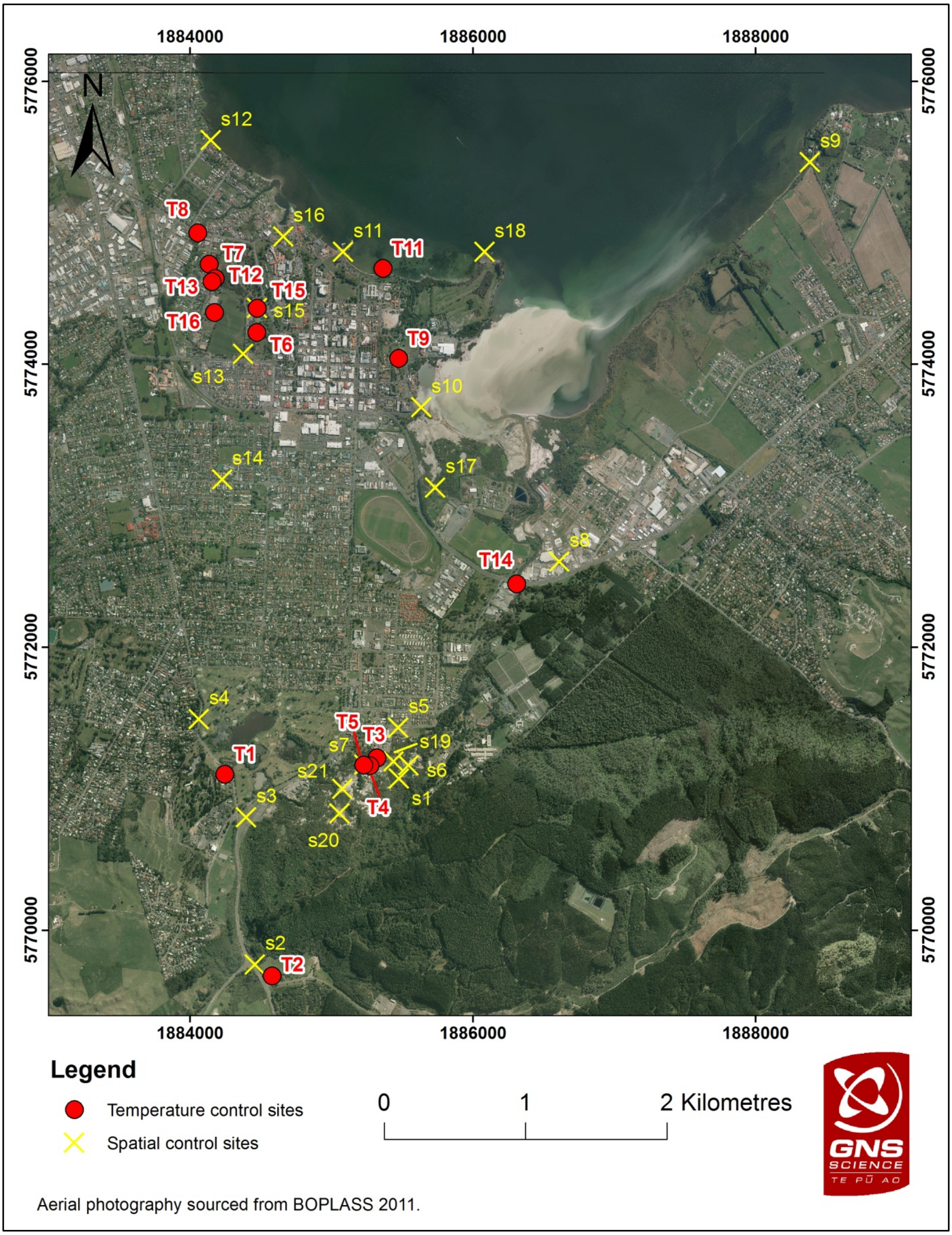

Figure 4.3 Location of the spatial (Appendix 1) and temperature control (Appendix 2) points.

Figure 4.4 shows the relationship between the raw TIR data and the water temperatures measured at the time of the survey. A linear relationship can be used to obtain an estimate of temperature for surface thermal and non-thermal waters from the raw data. A large data scatter from the linear interpolation line is likely to reflect higher water temperatures (>60°C), and is probably caused by steam between the target and the sensor absorbing TIR radiation.

Appendix 3 and Figure 4.5 show the 63 targets that were ground-truthed on 14 and 26 August 2014, based on thermal anomalies identified in Figure 4.2. 34 targets are interpreted to have geothermal inputs. 11 thermal anomalies in the suburb of Lynmore are interpreted to be non-geothermally influenced. These targets had marginal thermal anomalies, with most anomalies on roads at road intersections or under large trees. Small elevated TIR anomalies on roads may be an effect of emissivities caused either by differences in the materials used for road construction or where the road has been smoothed at intersections.

Figure 4.6 shows the TIR image for the Whakarewarewa, Ohinemutu and Sulphur Bay areas (see Figure 4.5 for locations). The Whakarewarewa TIR image (Figure 4.6A) shows TIR anomalies associated with surface thermal activity in the Te Puia, Whakarewarewa, and the golf course areas. Thermal features consist of lakes, springs, hot ground, pools and geysers, and correspond to areas of known geothermal activity. Horizontal surface thermal gradients can be observed in large surface features such as Lake Roto-a-Tamaheke, with hotter thermal areas in the west of the lake. Also apparent in this image is the variation of TIR signal associated with building roofs (blue colours). This variation is likely to be caused by differences in the thermal properties of the roofing materials (emissivity) as well as differences in temperature associated with heating and insulation.

Figure 4.6B shows the TIR image for the Ohinemutu area. Elevated TIR anomalies associated with geothermal activity can be seen in Ohinemutu and Kuirau Park. Two large areas of elevated TIR anomalies can be seen:

1. Kuirau Lake (Feature RRF0601) is a thermal lake, with hotter (red colour, Figure 4.6B) thermal inputs (assumed to be hot springs) in the north-eastern part of the lake. The hot area is estimated to have a surface water temperature of about 82°C as calculated from the TIR data.
2. Thermal discharges assumed to be from hot springs, hot streams and bore discharges into a small inlet of Lake Rotorua. The thermal signature of the hot water plume can be seen discharging into the main body of Lake Rotorua.

Numerous small TIR anomalies interpreted to be caused by hot spring discharges can be seen around the lake shore of Lake Rotorua in this area.

Figure 4.6C shows the TIR image in the Sulphur Bay area. Key TIR anomalies interpreted to be associated with geothermal activity include discharges on the western side of Sulphur Bay, and thermal anomalies close to the mouth of the Puarenga Stream. Numerous TIR anomalies around the lake shore in both of these areas are interpreted to be caused by geothermal water/gas discharges. TIR anomalies associated with the Polynesian Pools spa complex and the Blue Baths pool complex are also apparent.

Figure 4.7 shows the TIR image of Mokoia Island (Figure 4.7A) and the Lake Rotokawa (Figure 4.7B) areas. The Mokoia Island image show numerous small elevated TIR anomalies around the south eastern shore of the Island that are interpreted to be caused by geothermal water seeps. The locations of the TIR anomalies agree well with the locations of mapped surface geothermal features (Figure 2.1), with additional seeps identified in the TIR imagery. No obvious thermal anomalies occur on, or around, other parts of the Island, although most of the island is densely vegetated which may obscure the TIR signal.

Figure 4.7B shows the TIR image of the Lake Rotokawa area. The TIR image has few elevated TIR anomalies that can be unequivocally attributed to geothermal causes. Lake Rotokawa and a spring east of Lake Rotokawa are the only two TIR anomalies interpreted to be caused by geothermal fluids in Figure 4.7B. Very slightly elevated thermal anomalies occur along part of the lake shore (within the crimson polygon, Figure 4.7B) that may be related to shallow discharges of thermally effected groundwater, although these may also be from groundwater seeps, water from discharge drains, or other causes (e.g., weed). Rotorua airport and its associated infrastructure are clearly visible in the TIR image.

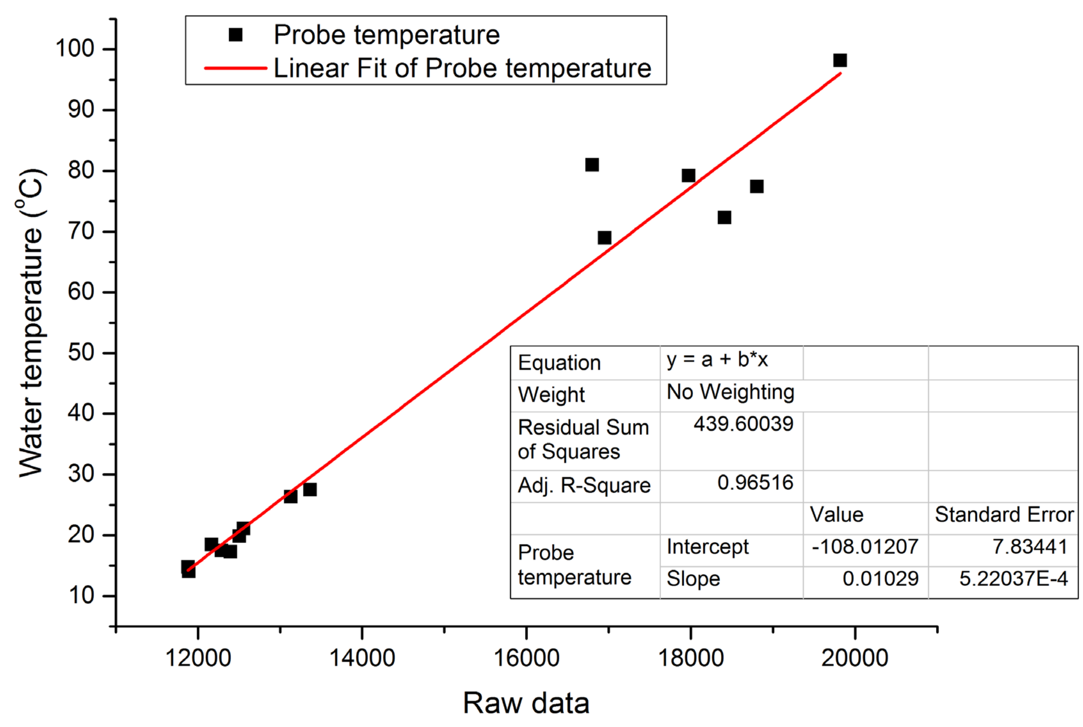

Figure 4.4 Relationship between the raw TIR data and measured water temperatures.

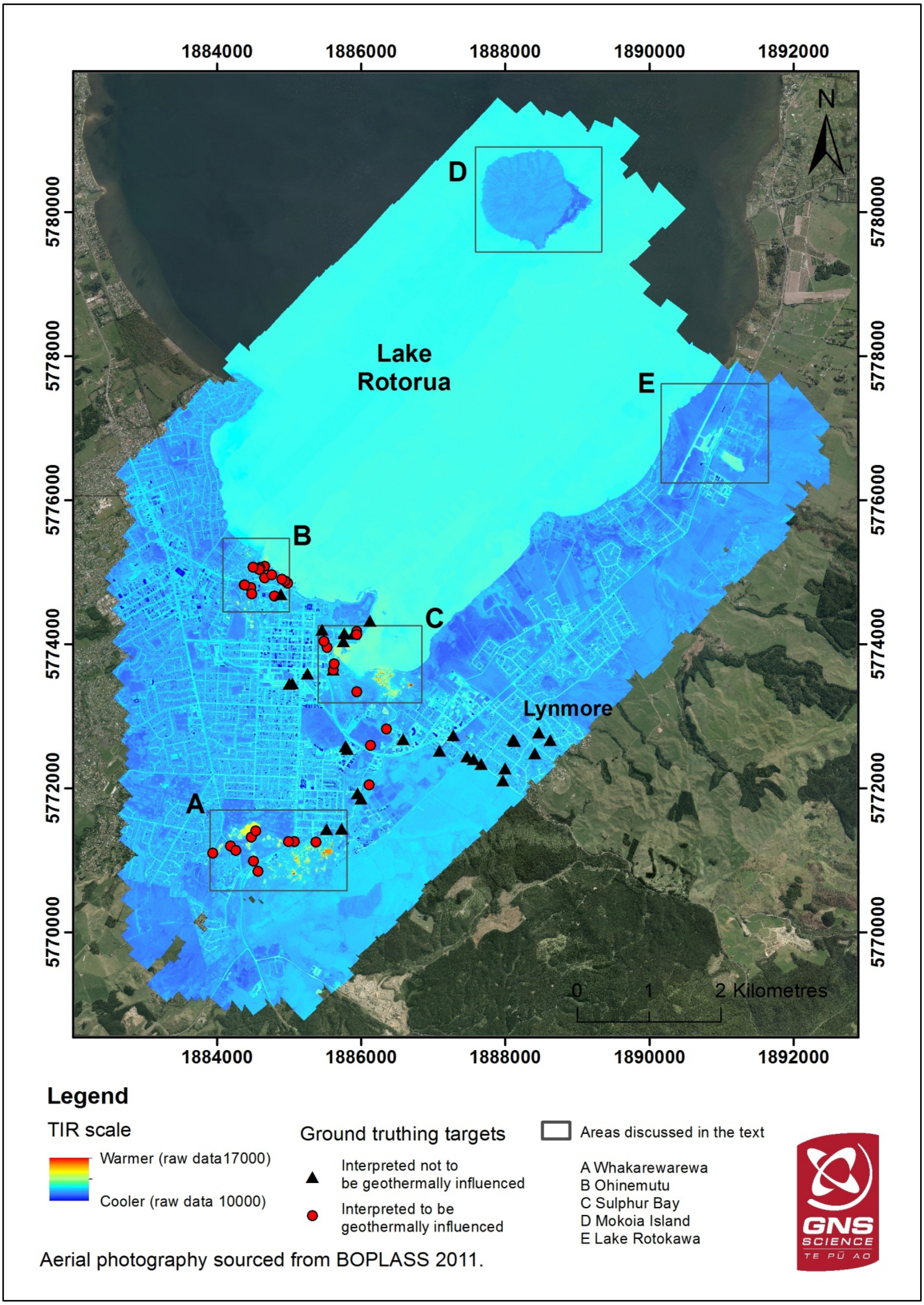

Figure 4.5 Locations of sites visited to ground-truth the TIR data.

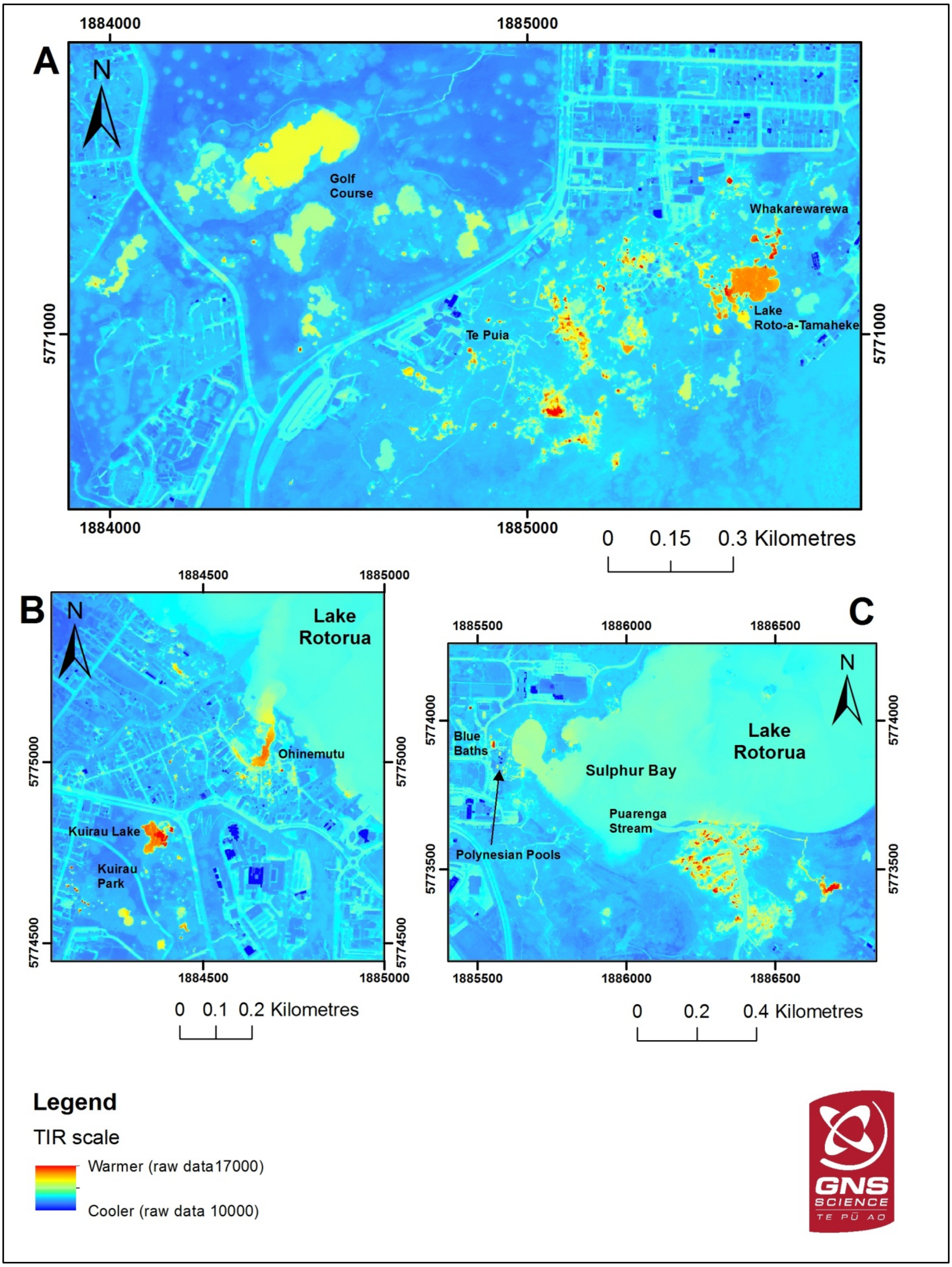

Figure 4.6 False colour TIR images of the raw TIR data in the: Whakarewarewa (A), Ohinemutu (B) and Sulphur Bay (C) areas.

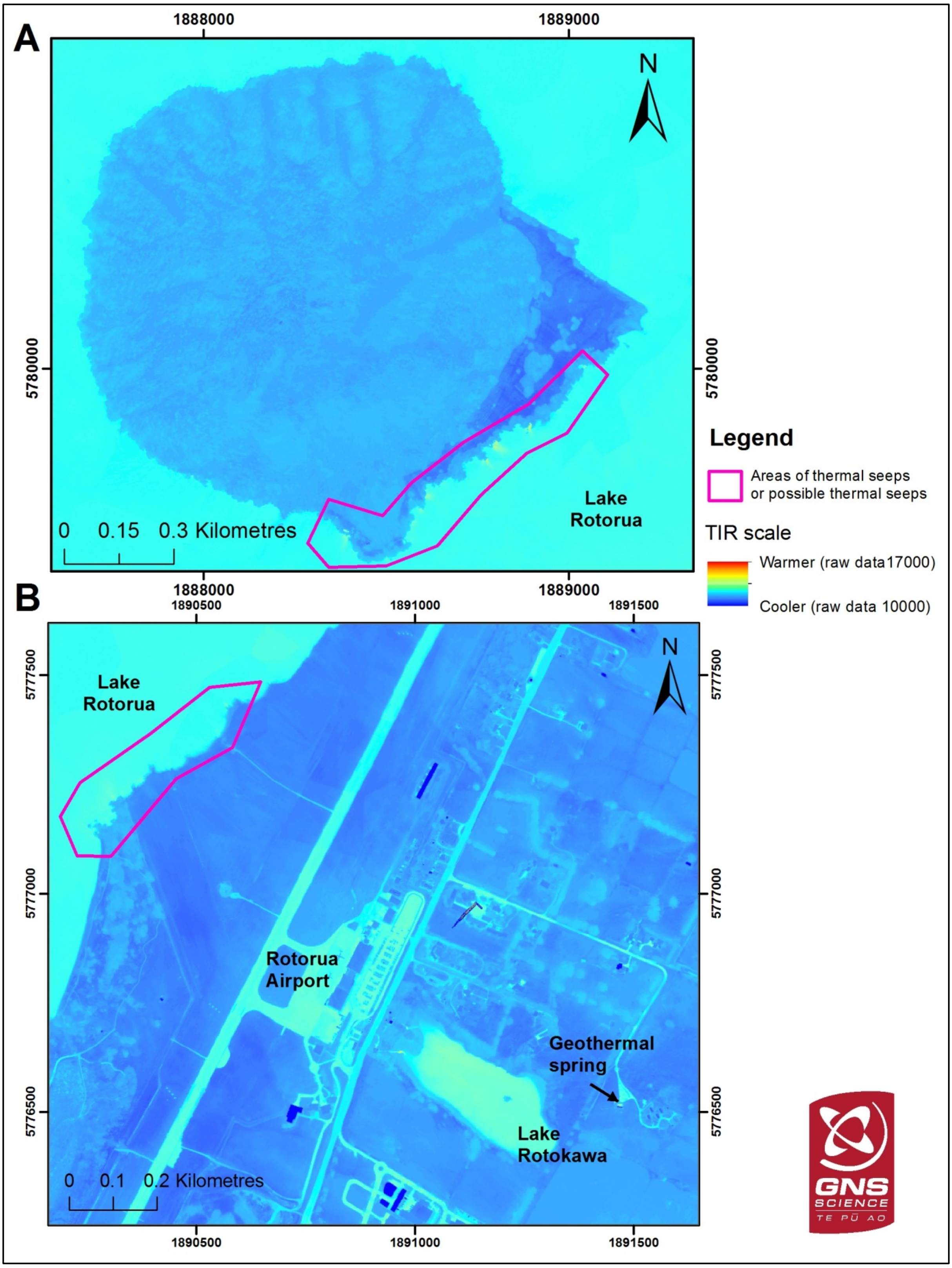

Figure 4.7 False colour TIR images of the raw TIR data in the: Mokoia Island (A) and Lake Rotokawa (B) areas.

5.0 SUMMARY

An aerial TIR survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields was undertaken on 6 March, 2014 between approximately 21:15 pm and 00:20 am on the 7 March. TIR images were mosaicked and resampled resulting in a single, 16 bit image with a ground pixel size of approximately 2 m x 2 m. The survey was complemented with water temperature measurements at the time of the survey enabling temperatures to be estimated for surface thermal and non-thermal water features over the entire TIR coverage area. A selection of thermal anomalies was ground-truthed to enhance the value of the collected TIR data.

TIR anomalies associated with surface geothermal activity in the study area generally agree with areas of known surface geothermal activity. The TIR data is of good quality and enables numerous geothermal and non-geothermal features to be identified and mapped to relatively high spatial accuracies (<5 m), considering the survey limitations. Features that can be identified include hot springs, pools, hot ground, streams and man-made objects such as roads, swimming pools and houses. Some small elevated thermal anomalies are apparent outside of known geothermal areas. Ground-truthing indicates that the cause of these may be due to the thermal characteristics of materials that have been imaged in these areas.

The 2014 TIR survey provides a useful dataset that can be manipulated in a GIS system for a range of applications, e.g., comparisons to other TIR surveys, hazard identification, geothermal surface feature identification, regional and district planning, and monitoring over time.

6.0 ACKNOWLEDGEMENTS

The authors wish to acknowledge Andrew Smith from the Rotorua Aquatic Centre, Clare Ngatai from the Rotorua Thermal Holiday Park, Blair Millar from the Whakarewarewa Thermal Village Tours for allowing GNS Science to measure water temperatures of pools and/or thermal features for this survey. This work was funded from the Geothermal Resources of New Zealand Research programme managed by GNS Science and funded by the Ministry of Business, Innovation & Employment.

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APPENDICES

APPENDIX 1: SUMMARY OF SPATIAL CONTROL SITES

Easting and northing are the coordinates of the spatial control mark derived from the differential GPS survey.

TIR easting and TIR northing are the coordinates of the spatial control mark as identified off the final TIR image.

Total distance difference is the difference in the total distance between the surveyed coordinate and the TIR coordinate.

Site	Easting	Northing	TIR Easting	TIR Northing	Total distance difference (m)	Comment
s1	1885477.026	5771073.355	1885477.422	5771073.329	0.40	Middle of bridge, at corner before outlet
s2	1884459.502	5769758.997	1884459.1	5769760.5	1.56	Metal plate
s3	1884398.541	5770799.798	1884401.128	5770797.69	3.34	Metal lid, opposite SH5/Old Taupo Road intersection
s4	1884062.602	5771492.781	1884062.552	5771492.673	0.12	Centre of drive
s5	1885473.932	5771433.228	1885473.7	5771433.734	0.56	Corner of drive and road
s6	1885544.804	5771166.611	1885545.303	5771166.326	0.57	Lake Roto-a-Tamaheke outlet, east side of stream
s7	1885235.427	5771170.041	1885234.906	5771170.676	0.82	Whakarewarewa, corner of concrete path
s8	1886610.952	5772606.724	1886611.168	5772609.615	2.90	Corner of new drive and road
s9	1888384.617	5775428.954	1888384.101	5775427.727	1.33	On concrete, approx. 5 m in from gate
s10	1885636.257	5773696.51	1885636.316	5773696.436	0.09	Corner of concrete car park
s11	1885084.476	5774795.269	1885083.191	5774796.011	1.48	Gas tank, 2 x 1 m metal lid
s12	1884148.244	5775583.493	1884148.933	5775584.227	1.01	Edge of concrete
s13	1884376.828	5774072.787	1884376.524	5774072.379	0.51	NW corner of car park
s14	1884229.262	5773187.657	1884229.67	5773187.024	0.75	Corner of car park
s15	1884475.935	5774397.242	1884476.418	5774396.339	1.02	Fountain
s16	1884660.493	5774904.626	1884660.92	5774904.819	0.47	NE corner
s17	1885735.168	5773129.918	1885736.907	5773128.015	2.58	West side of pool
s18	1886082.945	5774794.211	1886082.427	5774793.63	0.78	End of jetty
s19	1885440.458	5771193.428	1885441.127	5771194.167	1.00	Whakarewarewa, end of cobbles
s20	1885058.177	5770827.705	1885058.391	5770827.599	0.24	Waikite geyser, approx. 2 m from vent
s21	1885078.452	5771001.01	1885079.455	5771001.671	1.20	Corner of grass and concrete

APPENDIX 2: SUMMARY OF WATER TEMPERATURE DATA

Name	Easting	Northing	Location	Time measured	Air temperature (°C)	TIR gun temperature (°C)	Yokogawa/datalogger temperature (°C)	Comment
T1	1884247	5771103	Installed logger in the middle of cold pool.	22:20			17.5	Temperature taken from logger at 22:20
T2	1884582	5769677	Stream, approx. 100 m east of culvert.	22:40	9.2	14.1	14.1	
T3	1885323	5771218	Puarenga Stream off bridge.	22:25	14.4	18	17.3	
T4	1885272	5771163	Parekohoro (RRF0284), approx. 4 m East of corn cooking area.	22:15	16.6	90.8	98.2	Lots of steam on pool surface
T5	1885231	5771169	Pool (RRF0287) next to path/baths.	22:20	16.5	64.3	69	Pool below overflow
T6	1884472	5774225	Lake (RRF3059) straight off middle of building, Kuirau Park.	20:35	15.3	25.5	26.3	
T7	1884136	5774708	Parekaumoana hot pool (RRF0657), Tarewa Street.	21:08	16.2	67.9	72.3	Water level low. Weak steam off surface
T8	1884055	5774930	Utuhina Stream at Lake Rd bridge.	20:55	15.8		14.8	Centre of bridge, north side.
T9	1885475	5774041	Rachael Spring (RRF3178)	21:50	17.8	69.8	77.4	
T11	1885366	5774677	Lake Rotorua, half way down jetty.	21:45	16.3	20.8	21.1	
T12	1884179	5774608	Edge of pool (RRF0713), approx. 3 m from fence.		15.2	77.1	81	
T13	1884156	5774584	At outlet of Mayors Mouth (RRF0715).	21:15	15.5	79.3	79.2	
T14	1886311	5772447	Puarenga Stream at Te Ngae Rd bridge.	21:59	15.5	20.7	19.9	
T15	1884476	5774396	Cold pond in Kuirau Park.	21:30	16.4	18.4	18.5	
T16	1884174	5774366	Installed logger at Aquatic centre outside pool, approx. 5 m from East side, centre of pool.	23:30			27.5	Temperature taken from logger at 23:30

APPENDIX 3: SUMMARY OF GROUND TRUTHING SITES

Site	Easting	Northing	Anomaly temperature range (°C)	Background temperature range (°C)	Comment	Anomaly interpreted to be caused by geothermal activity?
1	1885044	5773457	5.3	5	Temperatures get slightly warmer towards the building.	No
2	1884999	5773457	5.2	5	Temperatures get slightly warmer towards the building.	No
3	1885256	5773595	5-6.3	4-4.9	Temperatures get slightly warmer towards the building.	No
4	1885782	5772587	17.6-19.8	18.6-19.9	H_2S smell from neighbouring thermal area ?	No
5	1887469	5772446	5.2		Anomaly on "shiny" part of road.	No
6	1887563	5772410	4-5.5	3.5-3.8	Anomaly on "shiny" part of road.	No
7	1887664	5772343	4.7-5.5	3.9-4.3		No
8	1887965	5772112	4-5.5	3.8-5		No
9	1888000	5772278	5-6.5		Measured a large area of road.	No
10a	1888126	5772660	7.3	6.6	Some anomaly, but not interpreted to be caused by geothermal. Under tree.	No
10b	1888107	5772679	6.3-8.1	6.6	Some anomaly, but not interpreted to be caused by geothermal. Under tree.	No
11	1888407	5772488	5.7-7.5		Area of new tar seal.	No
12	1888626	5772671	6.2-7	6.2-6.6	No clear reason for thermal anomaly.	No
13	1888465	5772777	8.2-9.2		No clear reason for thermal anomaly.	No
14	1887086	5772527	8.5-11.2	8.4-10.8	No clear reason for thermal anomaly.	No
15	1885807	5772549	11.2-14	11.8-13.1	H_2S smell probably from nearby thermal area.	No
16	1887280	5772737	15.9-17.3	14.5-16.5	Anomaly close to building. No obvious geothermal.	No
17	1885949	5771933	19.8-23.5	16.4-21	Brown staining of concrete may be causing the anomaly.	No
18	1885998	5771859	12.2-15.5		Bridge. No clear geothermal.	No

Site	Easting	Northing	Anomaly temperature range (°C)	Background temperature range (°C)	Comment	Anomaly interpreted to be caused by geothermal activity?
19	1886111	5772049	45.3-54.9		Thermal seeps, H_2S gas.	Yes
20	1884659	5775084	23.7-61.4		Thermal seeps + steam. Measured 20 cm ground temps of 47, 77.3, 79.8, 80.2 and 65.4 Deg C.	Yes
21	1884588	5775063	31.8		Measured ground temp at 1 cm = 30.4 deg C. Yellow colouring on the ground. Bare compact pumice/sand.	Yes
22	1884587	5775038	21-35.5	19.3-24.2	Brown staining on concrete. Warm to touch.	Yes
23	1884656	5774923	26.9-38.4	18.2-23	Brown staining on concrete.	Yes
24	1884494	5775069	21.2-27.3	18.1-20.2	Small area (2 m x 2 m) on tar seal on corner.	Yes
25	1884790	5774674	17.7-20.8	15.7-17.2	Small area (5 m x 4 m) on tar seal. Have included, however, not clear.	Yes
26	1884883	5774696	18.3-21	14.7-19.9	Small area at join of different types of tar seal. Have not included, however, not clear.	No
27	1884186	5771200	13.5-14.9	9.1-9.2	SH5 next to thermal area.	Yes
28	1884258	5771139	13.5-15	7.3-8.1	SH5, close to bus stop.	Yes
29	1884467	5774790	12.2-17.2	9.6-9.9	Start of Ranolf Street.	Yes
30	1884477	5774702	9.9-16.9	8.6-8.9	Ranolf Street, gas vents under road + manhole.	Yes
31	1884374	5774828	20.2-30.9		North end of Kuirau Lake.	Yes
32	1884378	5774823	25.7-33.5		East side of Kuirau Lake. Location has been adjusted.	Yes
33	1885456	5774207	9.1-10.2	8.4-9.2	Government Gardens Road. No obvious geothermal cause.	No
34	1885767	5774157	12-14.8	13.1-14.3	Concrete outside the Energy Events centre. No obvious cause.	No
35	1885897	5774148	11.2-12.1	10.4-11.4	Tar seal. Although no clear heat anomaly, H_2S staining of concrete in area.	No

Site	Easting	Northing	Anomaly temperature range (°C)	Background temperature range (°C)	Comment	Anomaly interpreted to be caused by geothermal activity?
36	1885939	5774178	14.2-17.2	13.3-13.8	Tar seal road. Close to under-road drain. H_2S smell.	Yes
37	1885934	5774134	14.8-20		Warm, bubbling pool, strong H_2S.	Yes
38	1886124	5774325	13.3-16	10.7-13.3	Tar seal. Next to sign. H_2S smell. Not clear if actual thermal spot.	No
39	1885752	5774047	12.5-16.8	12.5-14.2	Not clear. Repeated measurement at night.	No
40	1885527	5773960	20-30.2	15.9-17.1	Next to fire hydrant access. H_2S staining of the concrete.	Yes
41	1885482	5774043	45.7-65.6		Rachael Spring. Steam.	Yes
42	1885612	5773651	16.2-19.1	14.4-18.6	Hotel car park. No clear thermal anomaly.	No
43	1885613	5773643	29.7		Stream next to car park.	Yes
44	1885620	5773731	20.9-28.8		On lakeshore. Can see bubbling and H_2S smell.	Yes
45	1885936	5773345	16.2-57.2	13.3-17.7	Several steaming areas.	Yes
46	1886349	5772824	22.2-57	14.8-15.6	Steaming ground on true left bank.	Yes
47	1886129	5772596	20.9-37.1		Geothermal lake at Puarenga Park	Yes
48	1886582	5772685	20.2-21		Road. No clear evidence for geothermal.	No
50	1884754	5774970	29.2-62.7	24-26.3	Seeps from under cobbles. Can hear boiling.	Yes
51	1884975	5774847	52.1		Lake Rotorua lake bed temperature. Numerous seeps in this area.	Yes
52	1884938	5774879	51.3		Lake Rotorua measured from cracks in the concrete boat ramp.	Yes
53	1884897	5774908			Not visited, but steaming beach at this location can be seen.	Yes
54	1884502	5770992	18.7-73.2		Bubbling mud pots.	Yes

Site	Easting	Northing	Anomaly temperature range (°C)	Background temperature range (°C)	Comment	Anomaly interpreted to be caused by geothermal activity?
55	1884472	5771322	14.3-18.6		Warm lake with brown scum.	Yes
56	1884534	5771411	24.9-27.8		Large geothermal lake.	Yes
57	1885068	5771263	25.5-35.5	24.3-25.1	In car park. Steam coming up vent close to the hottest anomaly.	Yes
58	1885518	5771438	17.1-17.8	14.5-15.3	Road. No clear evidence for geothermal.	No
59	1884565	5770849	21-34.4	19-20.4	White concrete, concrete has some cracks in area of thermal anomaly.	Yes
60	1883941	5771106	14.7-36.2		Geothermal pool at northern end.	Yes
61	1885725	5771444	13.9-15.2	14.3-14.5	Road under trees.	No
62	1884992	5771263	19-24	12.3-15.8	Car park. Not clear if is a thermal anomaly caused by geothermal.	Yes
63	1885372	5771255	16.3-21	15-16.3	Car park. Not clear if is a thermal anomaly caused by geothermal.	Yes

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