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Using Time-Series Aerial Thermal Infrared Surveys to Determine Near-Surface Thermal Processes at the Ohaaki Geothermal Field, New Zealand

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ABSTRACT

Repeat aerial thermal infrared surveys (TIR) are used to monitor changes in the extent and intensity of surface thermal activity. Aerial TIR surveys conducted in 1989, 1998 and 2013 at the Ohaaki Geothermal Field, New Zealand, are compared and interpreted with respect to such changes. These may be caused by natural variations, or by reservoir pressure, temperature and phase changes associated with operation of the Ohaaki Geothermal Power Station, since its 1988 commissioning. Aerial TIR data shows areas of increased steam heating between 1989 and 1998. These were followed by cooling of some areas of steam-heated ground between 1998 and 2013, resulting in fewer active surface thermal features.

Some locations of steam-heated surface thermal activity in 1998 and 2013 are somewhat different compared to locations observed in 1989. This suggests that near-surface permeable pathways, particularly for rising steam, have changed. This could be caused by the development of alternate pathways during the increased steam heating phase between 1989 and 1998, as well as other processes such as tension cracking of the ground surface at the edges of a local subsidence bowl.

Thermal seeps into the adjacent Waikato River are identified in the aerial TIR data. Most river-side thermal seeps present in 1989 near bore BR20 (an area affected by subsidence) were no longer visible by 1998, and are inferred to have ceased or become submerged. Only a few small seepage areas were detectable by aerial TIR in 2013.

Observations of the increase and then subsequent decrease in surface thermal activity based on the TIR data are consistent with other thermal feature monitoring data in the Ohaaki area.

1. INTRODUCTION

Infrared (IR) radiation is part of the electromagnetic spectrum. The wavelength of IR light is not visible to the human eye, having wavelengths just below the red end of the visible spectrum. The thermal part of the IR spectrum (TIR) has wavelengths ranging from 3 microns to over 30 microns and is typically perceived as radiated heat. The amount of TIR emitted by an object increases with increasing temperature. Consequently, TIR measurements are useful for remotely obtaining the surface temperature of an object.

TIR remote sensing techniques to identify, measure and monitor thermal features in geothermal fields has been in use since at least the 1970s e.g. Hochstein and Dickinson (1970) and Pálmarsson et al. (1970). A variety of technologies have been used to investigate TIR anomalies at geothermal fields. These include satellite imagery (e.g. Coolbaugh et al., 2007; Mia et al., 2012), airborne surveys (e.g. Mongillo, 1994; Haselwimmer et al., 2013) and handheld TIR cameras (e.g. Eneva et al., 2007; Lynne and Yagüe, 2012). The type of technology used depends on the purpose of the survey, the required resolution, the area to cover, budget and field specific constraints such as terrain and vegetation cover.

Aerial TIR measurements have proved to be useful in identifying thermal anomalies in environmental, volcanology and geothermal studies (e.g. Haselwimmer et al., 2013; Mongillo and Wood, 1995; Torgersen et al., 2001). Long wavelength infrared (LWIR, 8-12 microns) has been used at most New Zealand high-temperature geothermal fields for over 24 years to successfully identify and monitor geothermal surface manifestations. Aerial TIR surveys are particularly useful in geothermal investigations, since;

- The temperature contrast between the geothermal features (warm-hot) and background levels (cold) can readily be detected and mapped.
- A greater range of thermal feature types can typically be detected compared to regular ground-based monitoring (e.g. the technique can identify areas of warm ground that field staff might miss).
- Surveys can cover large areas and include areas difficult or unsafe for field staff to access.
- Survey data can be collected in a consistent manner so repeat thermal images can easily be compared.
- Based on our experience in New Zealand, TIR images collected by fixed wing aircraft can be significantly more stable (e.g., reduced blur, less camera swing) than when TIR data has been collected using unmanned aerial vehicles or helicopters).

If the TIR data is collected consistently with accurate flight navigation data, it is possible to develop large scale aerial TIR maps suitable for geographic information systems that facilitate detailed analysis. Data collected this way over time can then be used to monitor large-scale thermal features, and help investigate and understand changes in the surface thermal features with geothermal development.

1.1 Study Area

The Ohaaki Geothermal Field is located close to the eastern boundary of the Taupo Volcanic Zone (TVZ) in the central part of the North Island, New Zealand (Figure 1). The surface thermal features of the geothermal field include numerous areas of hot ground and steam heated pools over an area of approximately 10 km^2. The Waikato River divides the Ohaaki Geothermal Field into Eastern and Western borefield sectors.

Large-scale discharge testing occurred at the Ohaaki Geothermal Field between 1967 and 1974 (the testing period). This was followed by a recovery period until 1988. A 108 MW$_e$ geothermal power station was commissioned in 1988 with much of the development of the geothermal field occurring between 1988 and 1995. The power station has been generating approximately 40 MW$_e$ since about 2000. The testing and development periods resulted in drawdown of the reservoir pressures causing some environmental changes at or near the ground surface. This has included subsidence, loss of a flowing chloride spring, changes to the shallow groundwater and changes to the surface thermal features (Hunt and Bromley, 2000; Glover et al., 2000).

This paper demonstrates the usefulness of the aerial TIR technique for surface thermal feature monitoring and is used to contribute to the understanding of changes in near-surface heat-transfer processes during geothermal production.

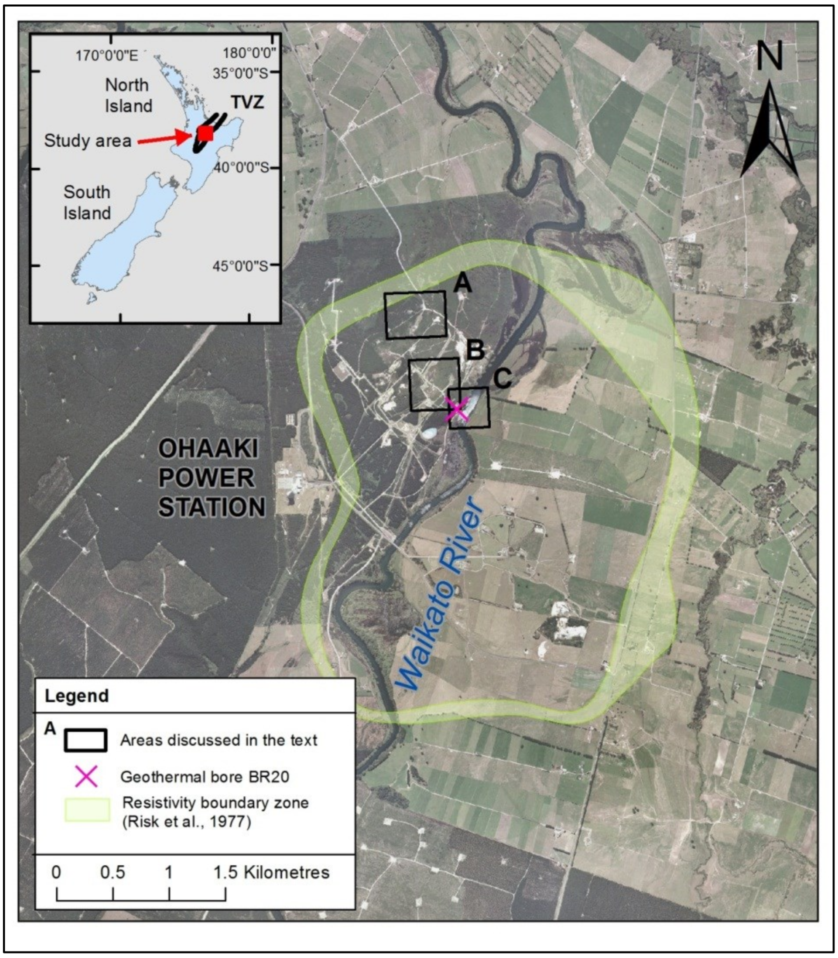

Figure 1: Location of the Ohaaki Geothermal Field.

2. METHOD

Aerial TIR data of the Ohaaki Geothermal Field were collected at night on 13/4/1989, 27/2/1998 and 29/4/2013 (Mongillo, 1989; Bromley, 1998; Reeves, 2013). Aerial TIR data from the 1989 and 1998 surveys were collected using Flir 1000A and Flir 2000 TIR cameras respectively, mounted to a helicopter and recorded onto a VHS videotape. Aerial TIR data for the 2013 survey was collected using a Flir A615 TIR camera mounted to a fixed wing aircraft and collected digital images recorded to a computer. Data for all three surveys were mosaicked for the areas of interest and compared.

Presentation of the TIR images have been standardized to false colour images using equivalent temperature scales for ease of comparison. The colour scale used to present the 2013 TIR data is based on an inferred (water emissivity) temperature range of between 10°C and 40°C. This temperature range was selected to be consistent with that of the 1998 TIR survey, which was based on calibration imagery using fixed gain and range settings for the earlier Flir 2000 instrument (Bromley, 1998). It is assumed that the 1989 and 1998 TIR data were calibrated to the same temperature range.

Factors that can affect data interpretation when comparing between TIR surveys include; differences in data collection (e.g., equipment, flight elevation, time of year, spatial and temperature resolution), temperature range (or gain) set during data collection, differences in data processing techniques, and changes in screening of the ground surface by vegetation between surveys. Although a variety of factors can influence interpretation of the TIR anomalies between surveys, large scale changes are readily discernible.

3. RESULTS AND DISCUSSION

Aerial TIR images over selected areas of the Ohaaki Geothermal Field for the three surveys can be seen in Figures 2, 3, and 4. Major differences between the TIR images can be seen, that include changes in surface thermal features and the river water temperature.

Figure 2 shows time series aerial TIR images of an area in the northern part of the geothermal field near a cultural site (Area A, Figure 1) that has shown heating and cooling since development commenced. The 1989 TIR data shows a strong linear NNE aligned thermal feature next to the grass-covered cultural site with a series of diffuse features to the southwest. By 1998, the original linear feature has almost disappeared; however, thermal activity along an adjacent pair of north-trending features, to the southwest, has increased. These features represent steam-heated ground and steaming vents. Surface thermal activity in the area reduced between 1998 and 2013 with only one of the north-trending linear features to the south of the cultural site area remaining. This reduction is probably due to declining pressures and reduced steam-flow from the near-surface geothermal aquifers. The linear features are possibly associated with near-surface tension-fractures which cross the top of a buried rhyolite dome (see Massiot et al., 2011 for a recent geological review).

The strong linear feature that occurs in the 1989 survey, but that disappeared before the 1998 survey, is interesting in that thermal activity did not increase at this feature compared to other near-by features. This suggests that the source of steam to this feature was isolated from the other features to the south-west. Bromley (1998) suggests that the increases in linear thermal features in some areas may be due to subsidence induced tension cracks allowing more steam to vent at the surface between 1988 and 1998. It may also be possible that shallow subsidence effects, through local stress and strain readjustment, may have also reduced permeability on some linear features thereby reducing steam upflow. Alternatively, different amounts of thermal clay alteration, mineral deposition or dissolution on some fractures (from acidic steam condensate) may, over time, have changed their relative permeability to steam flow.

Figure 3 shows time series aerial TIR images in the central part of the Western Borefield (Area B, Figure 1). These images show a large increase in surface thermal activity between the 1989 and 1998 TIR surveys and then a subsequent decrease in thermal activity between 1998 and 2013. Most of the thermal anomalies in the images are caused by steam-heated ground or steaming vents. Thermal anomalies associated with a steam-water separation plant (SP2, Figure 3) are apparent in all three images. Increase in thermal activity between 1989 and 1998 is through the development of largely north–south trending linear features. Bromley (1998) attributed these anomalies to increased steam venting (from boiling groundwater) through subsidence induced cracks, because this area is within a local subsidence bowl where the ground experienced increased tension (Carey et al. 2013, Bromley and Reeves 2013). Since 1998, despite ongoing subsidence, further decreases in pressure of the near-surface geothermal aquifers, accompanied by cooling and reduced boiling, have reduced steam upflow into the groundwater and through to the ground surface, resulting in a reduction of surface thermal features in 2013.

Permanent changes in shallow permeability for steam upflow zones have apparently occurred given that areas of thermal activity in 2013 are very different to those in the 1989 survey. Potential explanations for reduced permeability include clay alteration, or the local compressive effects of subsidence. Increased permeability may be due to pathway erosion caused by steam flow or local extension effects of subsidence.

Figure 4 shows time series aerial TIR images along an area of the Waikato River near bore BR20 (Area C, Figure 1). Thermal anomalies along the western bank of the Waikato River in this area are interpreted to be warm water seeps. The increased temperature of the river water in the 1998 aerial TIR image compared to the 1989 and 2013 images is caused by seasonally warmer ambient conditions in February 1998 compared to April 1989 and 2013. There are no TIR anomalies along the western edge of the Waikato River in this area of the 1998 image. However, the river level was 0.4m higher during the 1998 survey compared to the 2013 survey. These differences may have masked the presence of some warm water seeps.

Mongillo (1998) also noted an apparent large decrease in thermal anomalies along the western edge of the Waikato River in this area between the 1989 and 1998 aerial TIR surveys (Figure 4). Some warm water seeps are still apparent in the 2013 TIR image (inside the black circle, Figure 4), although it can be seen that the number of thermal water seeps has apparently reduced compared to the 1989 TIR image. Although it is quite likely that a decrease in thermal seeps in this area has occurred, we note that other factors that could impact the interpretation of the TIR data include: the relative river level between surveys, a change in the location of the river channel between surveys, and the effects of subsidence on seepage locations. Interpretation of apparent temperature changes in TIR data must also take into account changes in surface materials, such as development of roads, and differences in vegetation, because these will impact on properties such as thermal emissivity which affects apparent surface temperature.

The observed changes in surface thermal activity through thermal infrared monitoring at the Ohaaki Geothermal Field are consistent with observations of changes in monitored surface thermal features at Ohaaki. Surface thermal feature monitoring at more than 20 thermal features in 1988, 1997 and 2011 show that the intensity of surface thermal activity has changed at many Western borefield sites, with an increase observed in some steam-heated areas in 1997, followed by a decrease by 2011 (Carey et al. 2013, Rissmann 2010). Monitoring is important because changes in the areas of steam-heated thermal activity have the potential to impact on existing infrastructure (e.g. roads, pipelines) and on the location and type of thermotolerant vegetation growing in these areas.

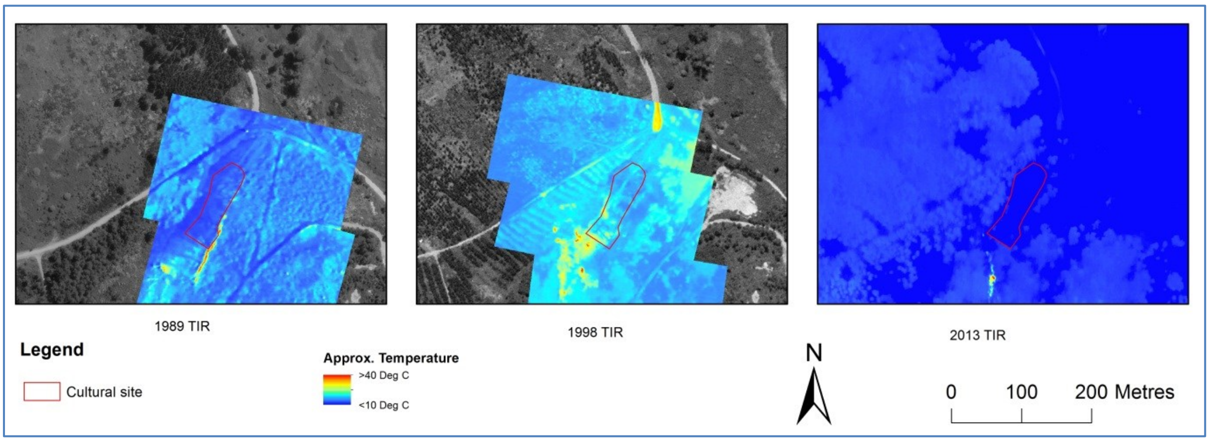

Figure 2. False colour TIR images of Area A (Figure 1). The red polygon represents the same area in the three TIR images. An aerial photograph underlying the 1989 and 1998 TIR images shows roads and trees.

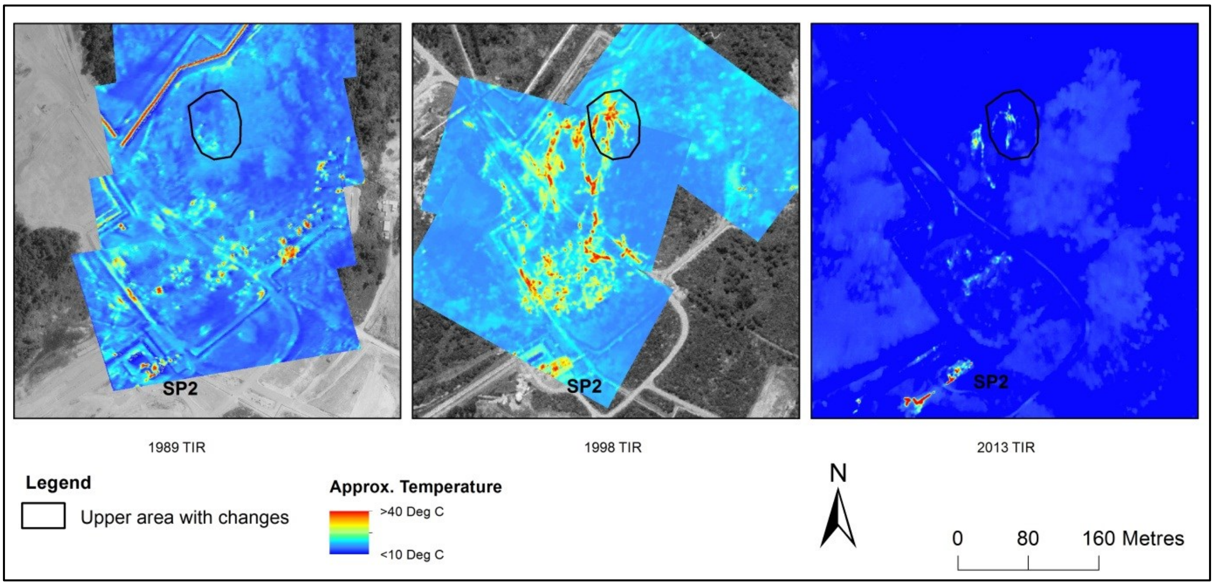

Figure 3. False colour TIR images of Area B (Figure 1). The black polygon represents the same area in the three TIR images. A black and white aerial photograph underlies the 1989 and 1998 TIR images. Man-made thermal anomalies associated with the separation plant (SP2) appear in all three images.

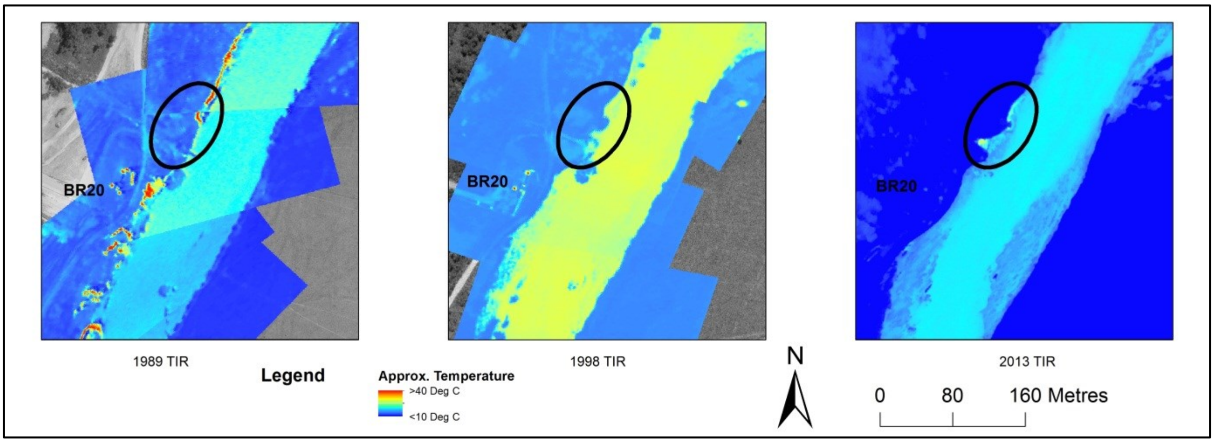

Figure 4. False colour TIR images of Area C (Figure 1). The black ellipse represents the same area in the three TIR images. A black and white aerial photograph underlies the 1989 and 1998 TIR images. Note that the river temperature was warmer in February 1998, and river level fluctuations (~1m) affect the bank edge and hot water seepage rate.

4. CONCLUSIONS

Aerial TIR imagery from the Ohaaki Geothermal Field collected in 1989, 1998 and 2013 clearly show areas of increasing and decreasing surface thermal activity at Ohaaki. The data suggest that the surface geothermal features at Ohaaki have:

- Changed in intensity over time, probably as a result of a combination of natural changes and reservoir pressure and temperature changes during operation of the geothermal power station from 1988.
- Changed locations in some areas, probably as a result of sub-surface deformation which may have both increased and decreased near-surface permeability, particularly affecting the upflow of steam originating from boiling groundwater. An alternative explanation for thermal feature changes is the possibility of shallow permeability changes originating through clay alteration, mineral deposition, or rock dissolution by acidic steam condensate fluids.

Within the limitations of spatial resolution and surface temperature calibration, the use of time-series aerial TIR as a technique to monitor surface thermal features, on a geothermal-field scale, has proven successful at Ohaaki.

5. ACKNOWLEDGEMENTS

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