Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Innovative Remote Sensing Methodologies That Honor Cultural legacies for Effective Management of Geothermal Resources for Future Generations: Whakarewarewa, Rotorua Geothermal Field, New Zealand

Ka Tukuna Ki Te Ātea o Tāne-nui-a-Rangi Whakareretanga. Kia Āmiorangi Haere I te Papa o Whakarewarewa anā whakamua Ki Whakarewarewa Aotearoa

James Warbrick[1], Diane Bradshaw[2], Andrew J. Rae[2], Nick Macdonald[2], Rogier Westerhoff[2], Robert Reeves[2], Salman Ashraf[3]

1. Whakarewarewa Village Charitable Trust, PO Box 6148, Whakarewarewa, Rotorua, New Zealand.

2. GNS Science, Private Bag 2000, Taupo 3352, New Zealand

3. GNS Science, PO Box 30-368, Lower Hutt, 5040, New Zealand

a.rae@gns.cri.nz

Keywords: Māori, indigenous communities, kaitiakitanga, resource guardianship, resource management, remote sensing, Rotorua, Whakarewarewa-Arikikapakapa, WorldView-3, Shortwave Infrared SWIR, hydrothermal mineral mapping, silica sinter, kaolinite, Thermal Infrared TIR, vegetation mapping, UAV, photogrammetry, potentiometric map.

ABSTRACT

Statement of Association

Geothermal resources are regarded as taonga - resources that are inherited from the ancestors and highly-prized. Among the first voyagers who came from the ancestral land, Hawaikii, to New Zealand (Aotearoa) on the Arawa waka (canoe) was the tohunga, (expert practitioner) Ngātoroirangi. On his travels around the district, Ngātoroirangi climbed Tongariro (volcanic mountain) to survey the whole country from its summit. As he climbed the slopes of the mountain, the cold became unbearable, almost freezing him. He called on his sisters in Hawaikii to send him fire. On hearing his call, his sisters sent two taniwha (mythical monster) underground, Pupu and Te Hoata, to bring him fire. The passage the two taniwha took, and the places where they surfaced became the connecting route of the geothermal system – from Whakaari (White Island), via Kawerau, Rotorua and Taupō and on to Tongariro, distributing geothermal resources in the Rotorua districts including Rotoma, Taheke-Tikitere, Waikite-Waiotapu-Waimangu, Ohaaki and Orakei-Korako. Places where surface geothermal activity was present were highly-favoured as places for settlement. All geothermal areas have traditional cultural and spiritual associations for the affiliate Te Arawa Iwi/Hapū. There was considerable mana associated with iwi whose lands included geothermal resources.

Geothermal resources were used in various ways. Hot pools (Ngāwhā, puia, waiariki) provided hot water for cooking and bathing. Hot ground was used for cooking holes and ovens. Mud from some pools had medicinal properties, especially in the treatment of skin infections such as ngerengere. Paint and dyestuffs such as Kōkōwai (red ochre) were obtained from hydrothermally altered ground. Many hot pools had well-known therapeutic qualities in the treatment of muscular disorders, rheumatic and arthritic ailments, as well as skin conditions. Some had other qualities and were known as wāhi tapu, for example, a place for ritual cleansing after battle, or other spiritual qualities linked to medicinal or therapeutic use, or incidents of the past. Some had a tohunga associated with them. Some were burial places. Many hot pools are still regarded as wāhi tapu, or sacred places.

In the 19th Century there was a hive of tourism activity in and around Lake Tarawera and Lake Rotomahana. The people of Tuhourangi had seen the potential in geothermal activity of the lakes district, and at Te Wairoa, as an economic bastion. The beauty of the Pink and White Terraces attracted many tourists to Rotomahana to see an eighth natural wonder of the world. Even after the eruption of the three peaks – Tarawera, Ruawāhia and Wāhanga on 10 June 1886 when the Pink & White Terraces were drowned in a deepened Lake Rotomahana – affiliate Te Arawa Iwi/Hapū continued to utilise the geothermal resources of the Rotorua Region (Bay or Plenty Regional Council).

The latest remote sensing technologies demonstrate greatly enhanced spectral and spatial resolutions, at reduced costs that promote availability. This has led to more easily obtained datasets that are of superior quality across a broader spectrum of parameters that are useful for resource management. The insights gained from these data provide a foundational scientific knowledge-base and a greater capacity for resource monitoring of both natural changes and impacts from human activities. Management of cultural properties and environmentally sensitive whenua with remote sensing indices and spatial analytical techniques can provide a range of strategies suitable for land and resource conservation. Early determination of these changes allows for easier resource management and the long-term preservation of its cultural and environmental heritage that underpin the principles of kaitiakitanga (guardianship).

This paper combines the indigenous and western science perspectives of the Whakarewarewa geothermal area. The approach aims to show how the latest and innovative technologies can contribute to indigenous growth and development that foster capabilities in a culturally respectful and appropriate manner.

Bay of Plenty Regional Council. https://www.boprc.govt.nz/your-council/working-with-iwi/statutory-acknowledgements/

1. INTRODUCTION

Remote sensing mapping techniques that use satellite, aircraft, and UAV (unmanned aerial vehicle) platforms for identifying, documenting and categorising geothermal areas for monitoring and exploration purposes are being increasingly utilized, as improving technologies have lowered costs, promoted availability and enhanced both spatial and spectral resolutions. There are significant advantages for their use in geothermal environments as they greatly minimize impacts on the ground, in and around geothermal surface features that are commonly culturally sensitive and scientifically significant. Geothermal sites in steep and/or heavily vegetated areas are remotely assessed easily and with lower health and safety risks. These methods and techniques are fully consistent with kaitiakitanga (guardianship), in that they allow for geothermal monitoring and characterization in a low-impact and safe way.

GNS Science implements thermal infrared (TIR) imaging and photogrammetry for monitoring of geothermal areas with fixed-wing aircraft and UAV platforms, respectively. Dual TIR surveys over the Rotorua Geothermal Field (Figure 1) enabled comparison of data between 1992 and 2014, to identify any temporal changes in surface thermal activity across the surveyed area (Reeves and Rae, 2016). Processing and mosaicking of ~2700 TIR images produced a 16-bit image with a ground pixel size of ~2 m^2. The survey successfully identified two areas where geothermal activity had decreased over the twelve years and established that there were no significant changes in other areas. Photogrammetry from a UAV platform above Whakarewarewa, a large active area within Rotorua Geothermal Field, has resulted in a potentiometric map that establishes the water level across the active geothermal area, an important base-line parameter for monitoring changes in the shallow hydrology.

Satellite mapping of vegetation types and their seasonal and temporal variations is a well-established technique. Recently, more advanced satellites (Sentinel-1 and -2) have created the opportunity for more detailed vegetation mapping in hydrological and groundwater studies (Westerhoff, 2017). Application of these satellite data to geothermal areas can help to better assess changes in vegetation types possibly caused by geothermal-induced thermal and chemical anomalies (Burns and Leathwick, 1995). GNS Science is presently building capability for remotely sensed mineral mapping using the WorldView-3 (WV3) satellite platform (Durance et al. 2017). This platform has multi-sensor bands capable of capturing short wavelength infrared (SWIR) imagery at relatively high spatial and spectral resolutions that advance the technique for mapping geothermal mineral occurrences.

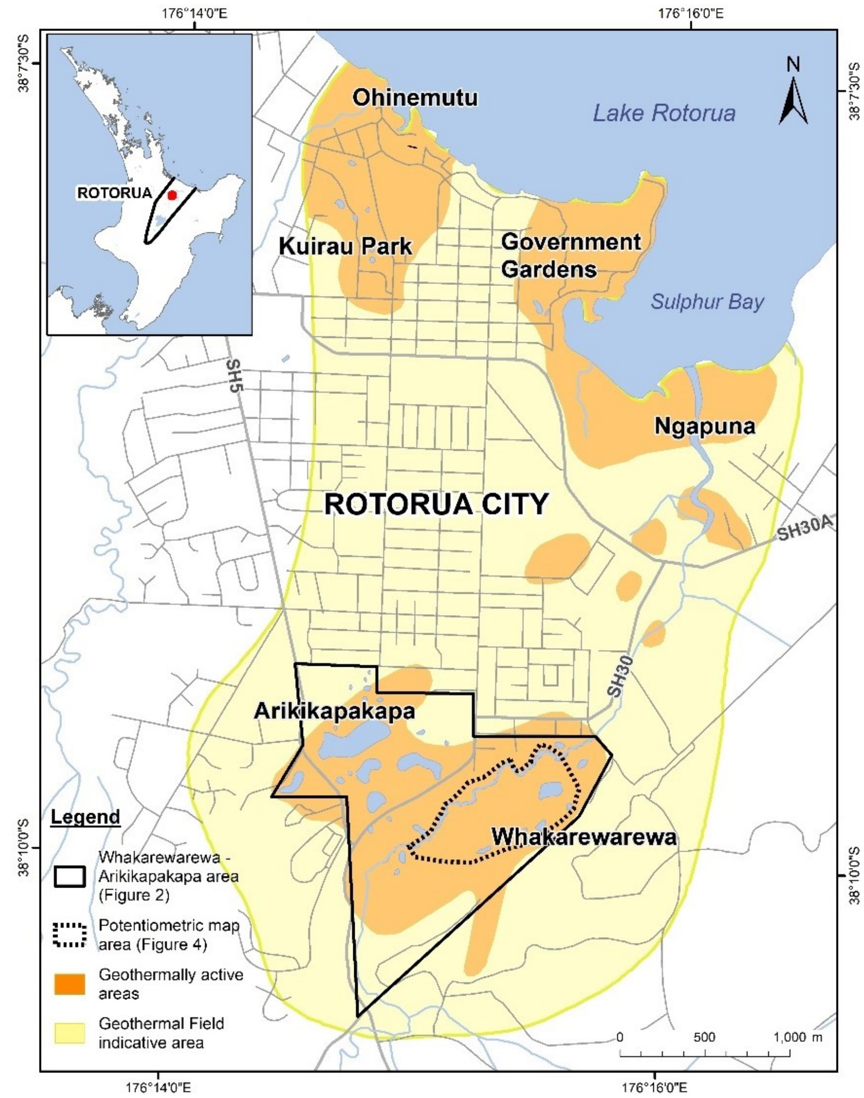


Figure 1: Location of Whakarewarewa-Arikikapakapa geothermal area, in the southern part of Rotorua Geothermal Field, and Rotorua City.

This study focuses on a well-known and studied geothermal area, Whakarewarewa-Arikikapakapa (Lloyd, 1975), in the Rotorua Geothermal Field (Figures 1 and 2A). We use various remote sensing techniques from the complete range of remote platforms to map thermal ground, the potentiometric surface, vegetation types and outcropping hydrothermal minerals. These techniques allow for monitoring of a broad suite of parameters important for resource management, in a safe and low impact manner that respects the principles of kaitiakitanga.

Whakarewarewa and Arikikapakapa are the two main areas of geothermal activity in the southern part of the Rotorua Geothermal Field, which is transected by NE-trending faults (e.g. Pohaturoa and Whakarewarewa Faults). These faults likely provide permeable pathways for geothermal fluids to ascend and discharge at the surface in the Whakarewarewa Valley.

A wide range of features types occur in the Whakarewarewa Valley. More than five hundred geothermal features (Figure 2B). ranging from geysers, steam vents, boiling mud pools, effervescent and boiling springs and turbid pools. Fluid derived from the deep primary geothermal reservoir, which has ascended directly to the surface with minimal mixing and dilution, forms springs of clear, hot (70-100°C), neutral to alkaline (pH 6.5-8) chloride water. This water is saturated with respect to silica, and springs typically have aprons or terraces of amorphous silica sinter. The largest of these terraces occur around the Pohutu Geyser (~3100 m^2), and also at Waikite Geyser (~2700 m^2; Figure 2A). Acidic features such as mud pools and ponds of turbid water typically occur at slightly higher elevations or on impermeable ground. Hydrogen sulfide (H_2S) gas, derived from the boiling of geothermal fluids (between 10–100 m below ground surface), mixes with oxidized meteoric ground water to produce acid sulfate waters that dissolve the surrounding rock and alters rock forming minerals to kaolinite and sulfates. These processes result in the degradation of ground, forming the mud pools and collapse holes that are common at Whakarewarewa. The largest of these is the roughly circular feature, Frog Pond (Ngamokaiakoko) (~560 m^2; Figure 2A).

At Arikikapakapa geothermal features are mostly located within the confines of the Rotorua Golf Course and are all of acid sulfate type, consisting of boiling mud pools, turbid acid pools, steam venting and barren ground. Significant features are the large warm pools or small lakes (Lakes Tangatarua, Tunoe and Arikikapakapa) of turbid water (Figure 2A). The largest, Lake Arikikapakapa, measures 330 m x 175 m across. The feature with the largest area of exposed mud is labelled as Golf Course mud pool (~7600 m^2) in Figure 2A.

2. INTERFACE BETWEEN VISION MĀTAURANGA AND WESTERN SCIENCES

Vision Mātauranga – unlocking the Māori innovation potential – is a key goal of the New Zealand government to include in the national science landscape. Mātauranga Māori is dynamic and locally specific, based on longstanding interactions of post-modern technology between people and their surrounding environment. We have applied and tested the latest remote sensing technology to map important geothermal monitoring parameters across the Whakarewarewa-Arikikapakapa geothermal area, Rotorua, Taupō Volcanic Zone, New Zealand.

Māori mythology and Māori traditions are the two major categories into which the legends of the Māori of New Zealand may usefully be divided. The rituals, beliefs, and the world view of Māori society were ultimately based on an elaborate mythology that had been inherited from a Polynesian homeland and adapted and developed in the new setting (Biggs 1966).

In Māoridom Tāne-nui-a-rangi is the progenitor of mankind and the forests. He ascended from earth to the heavens and returned with three knowledge directories (or baskets). This framework is used today to enhance indigenous knowledge, ritual of literature, philosophy and all humanities, acquired through careful observation. Described here as historic, cultural, spiritual, and biophysical; often these three baskets are expressed in a spatial or geographic context. Tāne-nui-a-rangi is a metaphor describing the journey of striving for knowledge through time and space – of the place of post-modern technology between people and their surrounding environment. The relationship between the universe and earth today reaffirming that the use of remote sensing technologies can benefit and value traditional knowledge within dynamic geothermal environments. These strands of knowledge show significant convergence with Western scientific understanding of the past record of the natural environment. Whereby, scientists benefit from the cultural perspective, and Māori gain important insights about their whenua (land).

The WorldView-3 (WV3) commercial satellite, launched in August 2014, has multi-sensor bands capable of capturing short wavelength infrared (SWIR) imagery at high spatial and spectral resolutions (i.e., 7.5 m pixel size; 8 wavelength bands, 1195 – 2365 nm). Using these wavelengths, images from this satellite can be used to map surface mineral occurrences within large areas (>56 m^2) at superior spectral and spatial resolutions than historical ASTER satellite instrumentation. The method demonstrates how the high spatial resolution of WV3 imagery enables mapping of geothermal features between vegetation, in areas of relatively high vegetative cover.

Thermal infrared (TIR) imaging of the Rotorua geothermal field using fixed-wing aircraft was able to highlight thermal features at 0.7 m spatial resolution. Integration with vegetation maps defined by Sentinel (1A, 2A and 2B) satellites showed thermal features are commonly surrounded by low-lying shrubs and trees (mixed manuka and kanuka). UAV photogrammetry was able to define the potentiometric surface across the thermal area, making an invaluable tool for monitoring changes in shallow groundwater levels.

3. ON-GOING CONNECTEDNESS WITH GEOTHERMAL

Geothermal energy is a taonga, with intrinsic value in the traditional Māori world, and economic and sociological value to contemporary Māori. Utilization of geothermal energy has potential to provide a range of commercial and non-commercial benefits at local, regional and national levels.

Whakarewarewa is the legacy and home of the Tūhourangi-Ngāti Wāhiao people, who have been sharing their unique way of life with visitors from all around the world for over two hundred years. Since the early 1800s, local residents have hosted and welcomed guests into their homes and backyards, demonstrating the utilization of the natural geothermal wonders for cooking, bathing and heating. The people of Tūhourangi-Ngāti Wāhiao have been the pioneers of the tourism industry in Rotorua and NZ. It is their goal to continue the legacy and to follow in the footsteps of their ancestors.

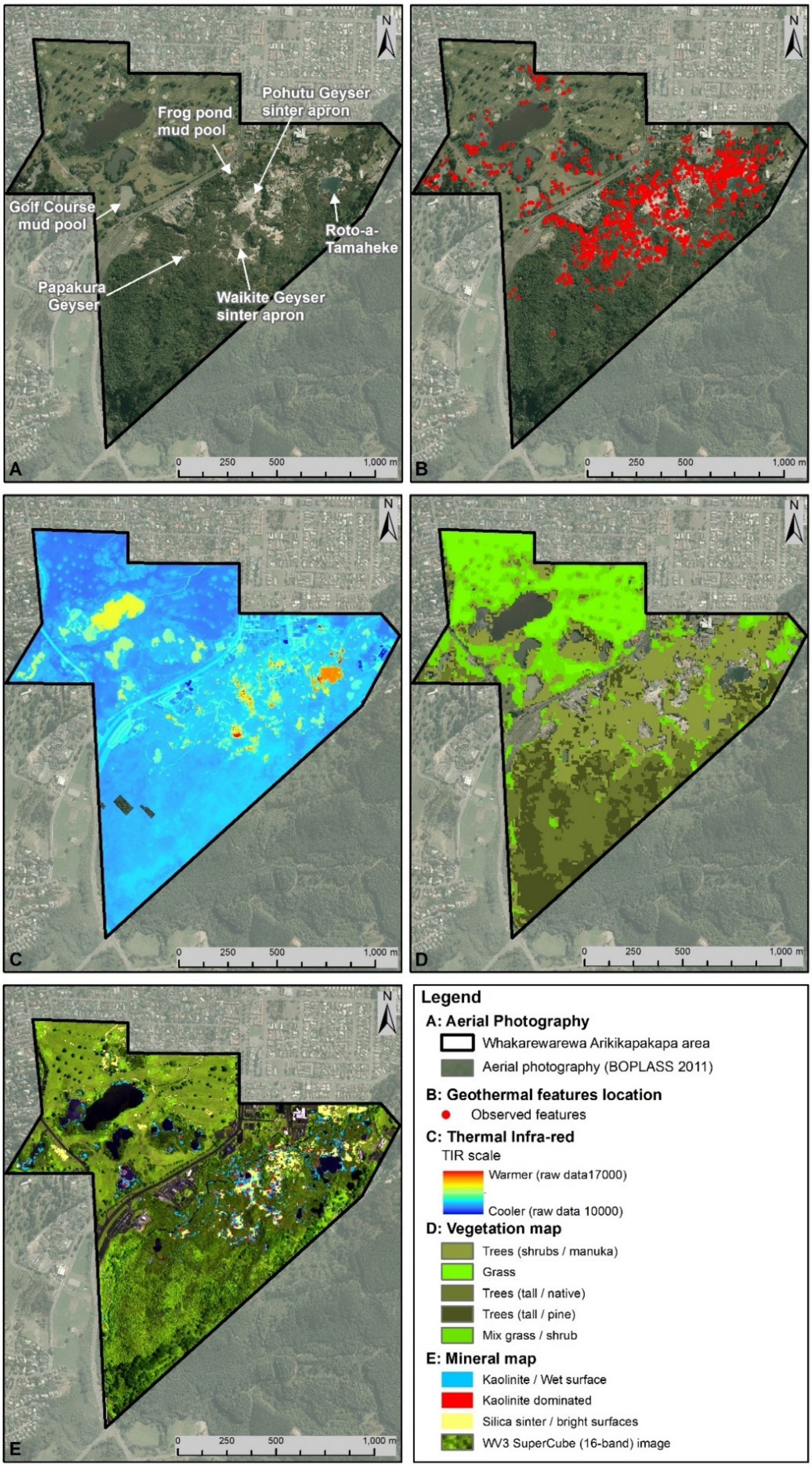


Figure 2. A. Aerial photograph of the Whakarewarewa-Arikikapakapa geothermal area, with significant features mentioned in the text labeled. B. Aerial photograph showing the distribution of geothermal features at Whakarewarewa-Arikikapakapa occurring in the GNS Science Geothermal and Groundwater Database. C. False color TIR image of the raw TIR data for Whakarewarewa-Arikikapakapa. D. Vegetation map of Whakarewarewa-Arikikapakapa. E. Mineral map of Whakarewarewa-Arikikapakapa.

Māori retain tikanga (traditional customs and protocols) concerning surficial thermal features and provide kaitiakitanga of the geothermal systems. In the past, development has adversely affected some thermal areas and resulted in irreparable damage to surface features, buildings etc. Even small-scale activities over long periods can be damaging (e.g. past balneological treatments at Queen Elizabeth Hospital, Rotorua, and their effect on Tianakore—a mud pool—at Arikikapakapa).

In Māori society, understanding the nature of environments and environmental indicators represents one of the earliest forms of hazard mitigation used in New Zealand. Insights can be gained from the settlement patterns of Tūhourangi impacted by natural hazards for example the 1886 Tarawera eruption and loss of the Pink and White Terraces. Their oral histories of early warning signs, displacement impact and adaptation can complement scientific knowledge today. Recorded observations relevant to earth science inherent in Māori oral tradition can be compared with those recorded in conventional western geological science.

4. TREATY OF WAITANGI OBLIGATIONS AND THE RESOURCE MANAGEMENT ACT

Regional Councils (New Zealand's top tier of local government) are responsible for monitoring geothermal resource development through the Resource Management Act (1991) (RMA), so Māori must balance their commercial aspirations with a realistic assessment of the capacity of the geothermal resource to support sustainable development.

All persons acting under the RMA, including applicants, councils and tangata whenua (people who have authority in a particular place) must consider the principles of the Treaty of Waitangi (New Zealand's founding document) an agreement signed in 1840 between the British Crown and Māori whereby Māori cede governance to the Crown. Part II of the RMA contains several specific provisions relating to tangata whenua and how they must be considered in RMA processes. These are:

- **Sections 6(e) and 6(f)** require that "the relationship of Māori and their culture and traditions with their ancestral lands, water, sites, wāhi tapu (sacred grounds) and other taonga (treasures)" and "the protection of historic heritage from inappropriate subdivision, use and development" is recognized and provided for.
- **Section 7(a)** requires that 'kaitiakitanga' (guardianship) is paid regard to.
- **Section 8** requires that the principles of the Treaty of Waitangi are taken into account. All project activities will therefore take into account both the Crown's need to adhere to the principles of the Treaty of Waitangi, and also the requirements of the RMA with respect to tangata whenua.

5. KAITIAKITANGA CONVERGENCE

There is a level of kaitiakitanga that should be acknowledged, respected (for example, perhaps through consultation) and on occasion formalised (such as via establishment of a committee with power). Kaitiakitanga, or guardianship, is a traditional process that defines the practice of protecting and managing the environment. The concept of exploring the expressions of the earth arises from a recognition that many Māori communities are seeking to preserve their culture and identity, and the relationships that culture and identity derive from. The exercise of guardianship; and in relation to a resource, includes the ethic of stewardship based on the nature of the resource itself. This is particularly the case in relation to contemporary issues, such as those relating to the environment and future management of natural (e.g. geothermal) resources. This approach is founded on traditional concepts of Māori knowledge, new technology applications, environmental planning and monitoring where indigenous approaches and perspectives are fundamental (Neilson G. et al 2010).

6. REMOTE SENSING WHAKAREWAREWA-ARIKIKAPAKAPA: CURRENT PROJECTS

6.1 Thermal Infrared Mapping

Reeves et al. (2014) summarize data collection, processing and image mosaicking form an aerial thermal infrared (TIR) survey over the Rotorua geothermal Field on 6-7 March 2014, from 21:15 through to 00:20. Data were collected from a light fixed-wing plane mounted with a Flir A615 thermal infrared camera, recording at 7.5 – 13 μm wavelengths, that was connected to a digital recording (16 bit images) and navigation system. Images had an approximate spatial pixel size of 0.7 m^2, but were resampled to 2 m^2 as described by Reeves et al. (2014).

A sub-dataset from this survey is presented in this paper. The resulting TIR image for our area of interest (Figure 2C) shows thermal anomalies associated with surface thermal activity in Whakarewarewa-Arikikapakapa. Highlighted features include the small lakes and ponds in Arikikapakapa, as well as Lake Roto-a-Tamaheke in eastern Whakarewarewa. Hot springs, pools, mud pots and hot ground comprise many of the smaller thermal anomalies in Whakarewarewa. Surface thermal gradients are recognized across some of the larger features, with hotter areas occurring in the western part of Lake Roto-a-Tamaheke, and the western parts of Lake Arikikapakapa being somewhat cooler (Figure 2C).

Three small rectangular "holes" in the southern part of the image (Figure 2C) was where the aircraft was either off course or had a high pitch/yaw that resulted in no data collection. These small areas are located above vegetated area, away from areas of geothermal activity.

6.2 Vegetation Mapping

The Sentinel-1 satellite mission provides synthetic aperture radar data of land and ocean from a constellation of two satellites (Sentinel-1A was launched in April 2014, Sentinel-1B was launched in April 2016). The satellites provide data with a 10 m^2 resolution, typically every three to four days. The radar data is hardly affected by clouds (i.e., it provides data in all weather, day and night).

The Sentinel-2 satellite mission provides multi-spectral data from a constellation of two satellites (Sentinel-2A was launched in June 2015; Sentinel-2B was launched in March 2017). The resolution of these data is 10 m^2 for most bands (e.g., red, green, blue, near-infrared—NIR) with other bands having a larger footprint (e.g., short-wave infrared 20 m^2; European Space Agency, 2017a, b).

All available Sentinel-1 and -2 data covering the Whakarewarewa – Arikikapakapa region of interest, in the research period January to August 2017, were used:

- 58 Sentinel-1 images, available in both VV and VH polarisations;
- 25 Sentinel-2 images.

All processing was performed in the Google Earth Engine processing facility (Gorelick, 2017). Sentinel-1 images were averaged to one image for the research period. All clouds in the Sentinel-2 data were filtered and then averaged to one image. Vegetation indices were calculated from the Sentinel-2 data. These were: Normalized Difference Vegetation Index (NDVI) from the NIR and red bands (e.g., Rouse et al., 1974); and Normalized Difference Water Index (NDWI) from the SWIR and NIR bands (Joint Research Centre, 2011).

The radar (VV, VH) bands and some multi-spectral bands (red, green, blue, NIR), including the derived indices (NDVI, NDWI) were used in a K-means clustering machine learning algorithm (Hall, 2009). This algorithm classifies all data into clusters with similar properties. It is an unsupervised algorithm, which means that no training data is needed beforehand. Interpretation of vegetation cluster types was based on expert knowledge and Google Earth.

Vegetative cover over the Whakarewarewa-Arikikapakapa area of interest has been broadly classified into five types (Figure 2D): grass, mix grass/shrubs, low lying shrub/trees, mixed trees including natives, and mixed trees including pines. Heaviest vegetation occurs in the southern parts of Whakarewarewa on the upper and lower northeast-facing slopes that are densely covered with mixtures of native forest and mixed exotic trees and scrub (Landcare Research). These include stands of conifers close to the ridge top. In and around the Whakarewarewa thermal features vegetation has been largely classified as low lying shrubs and trees, such as stunted scrub of mixed manuka and kanuka. Small grassy/shrubby areas are also identified. At Arikikapakapa, satellite imaging has identified the grassed golf course, with pockets of low lying shrubs and trees (mixed manuka and kanuka) that occur marginal to the geothermal lakes and mud pools.

6.3 Mineral Mapping

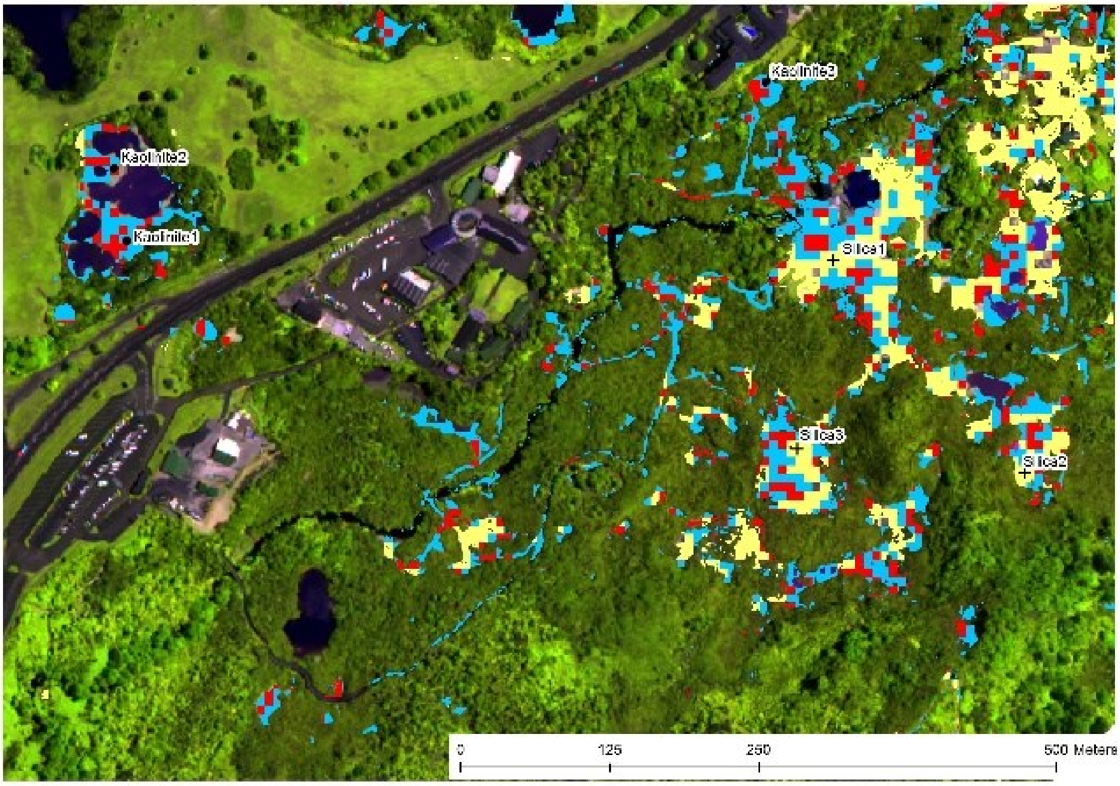
The WorldView3 satellite captures images in eight bands of visible to near infrared spectral range at 1.2 m^2 spatial resolution. In addition to these bands, eight bands are captured in SWIR range at 3.6 m^2 ground resolution. Due to US government restriction, WV3 SWIR data is down-sampled to 7.5 m^2 resolution. This resolution is superior to the ASTER sensor, which captures data in similar spectral range but at 30 m^2 resolution. Data from all sixteen bands were combined in one image for further processing to detect alteration minerals in Whakarewarewa area.

For the resulting mineral map of the area of interest we focused on four of the largest features: two sinter terraces associated with the Pōhutu and (extinct) Waikite Geysers, Frog Pond mud pool, and the Golf Course mud pool (Figure 2A). Each of these features are significantly larger than the WV3 SWIR resolving resolution of 56 m^2.

Initial results of the unsupervised classification were not able to distinguish between kaolinite and silica sinter due to high spectral variance in visible to near infrared (VNIR: 425 – 950 nm) . However, the last four SWIR bands (SWIR-5, -6, -7 and -8: 2165 –2330 nm) show a peculiar spectral response for both kaolinite and silica (Figure 3). It is therefore only the data from these four bands that have been used to classify kaolinite and silica sinter dominated pixels. The close-up WV3 image of Whakarewarewa-Arikikapakapa area (Figure 3) shows six locations with their spectral response of both minerals that clearly identifies their peculiar spectral response in the last four bands, despite significant non-distinguishing variations in the VNIR and lower SWIR bands.

We have categorized features into three categories: silica sinter dominated, kaolinite dominated, and kaolinite + water dominated (Figure 2E). The WV3 SWIR imaging distinguishes silica sinter from kaolinite at the four large features, and some smaller features. The Pōhutu and Waikite sinter terraces are mapped as sinter, with kaolinite (and kaolinite + water) occurring marginally (Figures 2E and 3). Smaller areas around the Waikite sinter apron contain mixtures of sinter and kaolinite. At the two mud pools, kaolinite and kaolinite + water are discerned at both the Frog Pond and the Golf Course mud pool (Figures 2E and 3).

Smaller features are also distinguished, such as the sinter associated with the Papakura geyser near Puarenga Stream. In the eastern parts of Whakarewarewa, areas of mixed sinter and kaolinite occur at Lake Roto-a-Tamaheke, a lake of mixed chloride-sulphate waters (Figure 2E). In Arikikapakapa, kaolinite and kaolinite + water categories rim small lakes and some smaller mud pools are recognized.



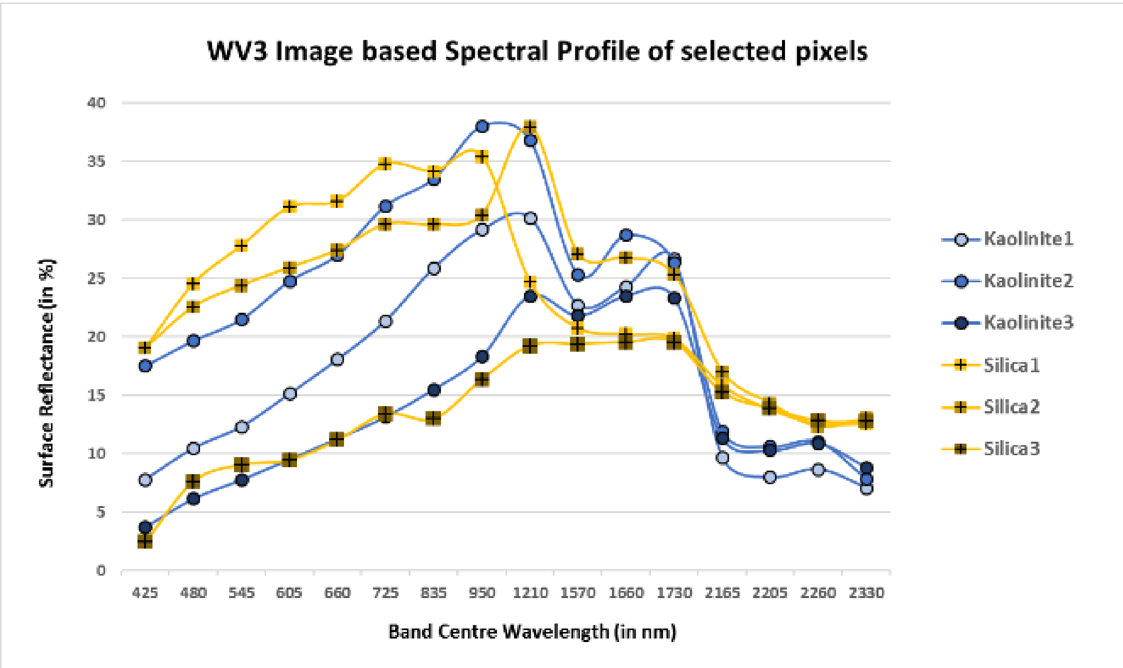


Figure 3. Top. Details of Figure 2E showing mineralogical classification of part of Whakarewarewa-Arikikapakapa. Silica (pale yellow), kaolinite dominant (red), and kaolinite – wet (blue). Bottom. The spectral response of the six spots highlighted in the above aerial photo. Despite the large spectral variation in the VNIR (425-950 nm) and lower SWIR bands (≤1730 nm), it is the spectral response of the higher three SWIR bands (i.e., SWIR-6, -7, -8 at 2205-2330 nm) that distinguish kaolinite from silica.

6.4 Photogrammetry Mapping

Photographic data collected by UAVs can be paired with structure-from-motion (SfM) photogrammetry, which offers a low-cost means of producing high-resolution 3D surface models. SfM photogrammetry uses algorithms to match corresponding ground features from multiple overlapping digital images and then calculates individual camera positions, orientations, focal lengths and relative positions of corresponding features. From these calculations, overlapping images are then used to construct a dense point cloud and a digital surface model (DSM) (Westoby et al. 2012). We tested the viability of SfM photogrammetry to measure water levels of geothermal pools for the purpose of rendering a potentiometric map of Whakarewarewa. This would provide insights into subsurface flow characteristics across a complex active geothermal area. Additionally, as a monitoring tool, it would provide information useful for highlighting any changes to the shallow hydrological system that might be natural and/or associated with geological events or impacts from human activities (Scott 2012).

Water levels of Whakarewarewa geothermal pools were measured using aerial photography collected from a UAV platform. Water level elevations were recorded by a ground team at the water edge of specific pools and stream sites. Photogrammetric point errors that generally occur at the center of pools were edited by disabling elevation points at the center of pools, prior to DSM generation (Macdonald et al. 2019). Water level elevation variation was compared between edited and unedited DSMs. Four methods using point and polygon data with edited and unedited DSMs were compared to evaluate their accuracy for measuring water level elevations from aerial photography. The most accurate method was used to generate a potentiometric map of Whakarewarewa Geothermal Valley (Figure 4).

The map shows a water level high about 15 m above Puarenga Stream that approximately corresponds with both the intersection of Pohaturoa and Te Puia Faults and the Ngāwhā Crater (site of a historical hydrothermal eruption) (Lloyd 1975). This area contains numerous small acid sulfate (steam-heated) springs as well several extinct neutral chloride spring features (silica sinter deposits), including the Waikite geyser sinter apron. Together, these features indicate that shallow groundwater at this location has changed historically, where it used to be a site of up-flowing geothermal fluid that utilized favourable permeable pathways, possibly along faults and through crater-fill breccias. The water level contours suggest that groundwater is still upwelling at this site, but not able to discharge to the surface, but flowing to the northeast towards Whakarewarewa Village and the Puarenga Stream beneath the two small hills, Te Puhunga and Te Whakarewarewa (Figure 4).

In summary, the use of remotely sensed data acquired by a UAV looks promising as a method to measure water levels of geothermal pools. Further development of this method is needed and should concentrate on sampling data from the edges of pools to avoid photogrammetric errors near the pool centers. The data collected during this project will serve as a baseline for future monitoring at Whakarewarewa Geothermal Valley.

Figure 4: Potentiometric map with water level contours (yellow lines) of the Whakarewarewa Geothermal Valley. See Figure 1 for this map location. Yellow dots represent measured water level sites, orange dots denoting locations of some additional 35 water level sites. Red triangles locate topographic highs, Te Puhunga and Te Whakarewarewa. Black dashed outline highlights the boundary of Ngāwhā Crater, whereas the red dashed lines represent faults suggested in Lloyd (1975).

7. REMOTE SENSING WHAKAREWAREWA-ARIKIKAPAKAPA: FUTURE PROJECTS

Future remote sensing project focusing on the Whakarewarewa-Arikikapakapa geothermal area will refine WV3 SWIR mineral mapping, in particular investigating the criteria for better distinguishing kaolinite and silica spectral profiles. We will apply our trained knowledge into the classification process. This could, for example, be done by first producing spectral mineral indices (Sun et al., 2017) that can subsequently be used in an expert-classification. Alternatively, spectra acquired in the field or taken from a spectral library could be used to examine spectral absorption features of image pixels that contain a mix of different minerals and vegetation. This will help to train a classifier and to correct for any bias towards certain materials.

Additional data has recently been collected over Rotorua City during an airborne hyperspectral survey, using an AisaFENIX hyperspectral sensor (370 – 2500 nm), with a spectral sampling interval of 3.4 nm (VNIR) and 5.7 nm (SWIR), and spatial resolution was ~2 m. This will refine mineral mapping, in particular by investigating the criteria for better distinguishing kaolinite and silica spectral profiles. The high spectral and spatial resolutions from aerial hyperspectral should improve distinctions between kaolinite, silica and rhyolitic pumice.

Moreover, band ratios calculated from airborne hyperspectral data are suitable for mapping subtle wavelength absorption features. Work is in progress to use different combinations of spectral band ratios for mineral group indices, mineral group contents and mineral group compositions. A mineral group index is sensitive to the presence of material type but doesn't specifically identify wavelength absorption depth and geometry. Band ratios pertaining to mineral group contents and mineral group compositions respectively accentuate absorption depth and absorption geometry.

8. CONCLUSIONS

Documenting, categorizing and monitoring the geothermal features at Whakarewarewa-Arikikapakapa establishes the baseline database to manage the resource. Mapping the geothermal area using remote sensing is a low-impact and safe method of establishing this database in a culturally respectful and appropriate manner, thus providing a valuable asset for understanding cultural sites and landscapes.

The latest technological remote sensing techniques, from across all platforms (satellite, aircraft and UAV), have been used to obtain a spectrum of scientific parameters (thermal ground, vegetation types, mineral occurrences, groundwater levels) useful for monitoring the 'health' of a geothermal area that is vitally important to the Tūhourangi-Ngāti Wāhiao culture, but also of national and scientific significance. The insights gained from these data provides a foundational scientific knowledge-base and a greater capacity for resource monitoring of both natural changes and impacts from human activities. Early determination of any changes allows for easier resource management and the long-term preservation of its cultural and environmental heritage that underpin the principles of kaitiakitanga (guardianship).

However, the data acquisition also requires deep consultation with local iwi/hapu to ensure alignment of research with statutory aspirations. A combination of community engagement, with its historical context and cultural knowledge-base, with the technological database, informs the resource management that leads to maximizing resource preservation for present and future generations. Our current and future activity should always be guided by the lessons of the past, as in the whakataukī, or proverb:

Me hoki whakamuri kia haere whakamua
(to move forward we must be aware of the past).

9. ACKNOWLEDGEMENTS

Thank you to the following: Blair Millar (Whakarewarewa Village Charitable Trust, Rotorua) for reviews that fine-tuned the manuscript; Samantha Alcaraz (GNS Science, Wairakei) for the graphics design; Harald van der Werff (ITC, University of Twente, Netherlands) for comments regarding the on-going workstreams using the WV3 dataset; Ringahora Huata (Whakarewarewa Village Charitable Trust, Rotorua); Andreas Markwitz (The MacDiarmid Institute).

10. REFERENCES

Bay of Plenty Regional Council. https://www.boprc.govt.nz/your-council/working-with-iwi/statutory-acknowledgements/

Biggs BG. 1966. Maori Myths and Traditions. In AH McLintock (editor), Encyclopaedia of New Zealand, 3 Volumes. (Government Printer: Wellington) II:447-454.

Burns B, Leathwick J. 1995. Geothermal vegetation dynamics. Science for Conservation, Dept. of Conservation, Wellington, NZ. pp. 1173-2946, 18.

Durance PMJ, Ashraf S, Rae AJ, Kereszturi G. 2017. Developing GNS's capability in multispectral satellite imagery as a tool for geothermal and mineral exploration. GNS Science Report 2017/26. 91p.

European Space Agency. 2017a. Copernicus – observing the earth. URL: http://www.esa.int/Our_Activities/ Observing_the_Earth/Copernicus/Overview4, Accessed 25 August 2017.

European Space Agency. 2017b. Sentinel online, spatial resolution. URL: https://earth.esa.int/web/sentinel/ user-guides/sentinel-2-msi/resolutions/spatial. Accessed 25 August 2017.

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment. doi:10.1016/j.rse.2017.06.031.

Hall M, Frank E, Holmes G, Pfahringer B, Reutemann P, Witten IH. 2009. The WEKA data mining software: an update. ACM SIGKDD Explorations Newsletter 11, 10. doi:10.1145/1656274.1656278.

Joint Research Centre. 2011. Normalised Difference Water Index Factsheet. URL: http://edo.jrc.ec.europa.eu/documents /factsheets/factsheet_ndwi.pdf. Accessed July 2017.

Landcare Research. https://whenuaviz.landcareresearch .co.nz/place/119254.

Wilson A, Nicholson T, Bignall G, Bradshaw D. 2015. Kaitiakitanga and The Next 10,000 Megawatts. Proceedings of the 37th New Zealand Geothermal Workshop, Taupo New Zealand.

Lloyd EF. 1975. Geology of Whakarewarewa hot springs. Wellington (NZ): Department of Scientific and Industrial Research. 24 p. (Department of Scientific and Industrial Research information series; 111).

Macdonald N, Reeves RR, Graham DJ, Brakenrig T. 2019. Obtaining water level data at Whakarewarewa Geothermal Valley using UAV photogrammetry. GNS Science Report 2019/14. (in prep).

Neilson G, Bignall G, Bradshaw D. 2010. Whakarewarewa a Living Thermal Village, Rotorua, New Zealand 2.p in: Proceedings World Geothermal Congress Bali, Indonesia, 25-29 April 2010. Bali, Indonesia: International Geothermal Association

Reeves RR, Scott BJ, Hall J. 2014. Thermal infrared survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields, GNS Science Report 2014/57. 28 p.

Reeves RR, Rae L. 2016. Changes in aerial thermal infrared signature over the Rotorua Geothermal Field, New Zealand: 1990–2014, Geothermics, Volume 64, 2016, Pages 262-270, http://dx.doi.org/10.1016/j.geothermics.2016.06.007.

Rouse JW, Haas RH, Scheel JA, Deering DW. 1974. Monitoring Vegetation Systems in the Great Plains with ERTS. Proceedings, 3rd Earth Resource Technology Satellite (ERTS) Symposium, vol. 1, p. 48-62.

Scott BJ. 2012. Guideline for mapping and monitoring geothermal features. Whakatane (NZ): Bay of Plenty Regional Council. 35 p. (Bay of Plenty Regional Council guideline; 2012(03))

Sun Y, Tian S, Baogang D. 2017. Extracting mineral alteration information using WorldView-3 data. Geoscience Frontiers, 8, 1051-1062.

Westerhoff RS. 2017. Satellite remote sensing for improvement of groundwater characterisation (Thesis, Doctor of Philosophy (PhD)). University of Waikato, Hamilton, New Zealand. Retrieved from http://hdl.handle.net/10289/10922.

Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM. 2012. ‘Structure-from-Motion’ photogrammetry: a low-cost, effective tool for geoscience applications. *Geomorphology.* 179:300-314.