Kaitiakitanga of geothermal ecosystems through joint scientific and matauranga-a-iwi approaches: Waiotapu case study

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Ngati Tahu-Ngati Whaoa Runanga Trust and GNS Science Report 2021/35
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NGATI TAHU - NGATI WHAOA RUNANGA TRUST

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ABSTRACT

Geothermal areas are unique environments that can include geothermal surface features, and exhibit unique flora and fauna that has adapted to these environmental conditions. Iwi have a strong historical and contemporary cultural association with geothermal resources, including cooking, bathing, trading and for spiritual purposes.

This report integrates geological, geophysical, geothermal surface feature and vegetation data with Ngati Tahu-Ngati Whaoa matauranga into a holistic knowledge-base combining indigenous knowledge and Western science regarding the Waiotapu Geothermal Field (New Zealand) to enhance knowledge and to support kaitiakitanga.

The Waiotapu Geothermal Field is the largest (by surface area) of the 29 high temperature geothermal systems in the Taupo Volcanic Zone, New Zealand. With over 400 mapped geothermal surface features (e.g., hot springs, pools, mud pools, and heated ground), the area supports a unique ecosystem that includes the largest population of *Cyclosorus interruptus* (a threatened fern species) of any New Zealand geothermal site.

Resources of the Waiotapu geothermal area have long been used by Ngati Tahu-Ngati Whaoa for purposes such as cooking and preserving food, bathing, treating health conditions, and washing clothes. Vegetation was also used to build waka and houses, and flax was harvested to make woven products (e.g., mats, clothing, rope) that were traded with other tribes and, in later times, Europeans. Geothermally altered rocks and clays from the Waiotapu area provided a unique resource for Ngati Tahu-Ngati Whaoa. One such rock, kokowai, was so highly valued by other iwi, it was considered to be worth the same as pounamu.

KEYWORDS

Ngati Tahu-Ngati Whaoa; Waiotapu; Waikite; geothermal ecosystems; geothermal surface features; matauranga-a-iwi

GLOSSARY

Maori word/s	English translation
Hapu	Subtribe/s
Kainga	Home or settlement
Kakahi	Freshwater mussel
Kaumatua	Elder person
Kokowai	Red ochre
Koro	Elder man
Korowai	Cloak
Koura	Freshwater crayfish
Kowhaiwhai	Type of Maori art
Kuia	Elder woman
Mahinga kai	Wild foods
Mana whenua	Customary authority over an area
Matauranga	Knowledge
Matauranga-a-iwi	Iwi knowledge
Maunga	Mountain
Maunga Kakaramea (Rainbow Mountain)	Mountain of Coloured Earth
Mauri	Life force or essence
Ngahere	Forest
Ngati Tahu-Ngati Whaoa Runanga Trust	Mandated iwi authority for Ngati Tahu-Ngati Whaoa
Pa	Fortified settlement
Pouwhenua	Geographical marker points
Piupiu	Grass skirt
Rahui	Prohibition order
Raranga	Maori weaving
Rohe	Tribal boundary
Rongoa	Medicine
Taonga	Treasure, treasures or treasured
Tapu	Sacred
Te Tihi o Ruru	The Owl's Perch
Tino rangatiratanga	Self-governance
Tohunga	Priest or learned person
Tuna	Eel
Tupuna	Ancestor or ancestors
Ukaipo	Birthplace
Urupa	Cemetery
Wahi tapu	Sacred site
Waka	Canoe
Whakairo	Carving
Whare	House

1.0 INTRODUCTION

The 29 geothermal fields of the Taupo Volcanic Zone (TVZ) (Figure 1.1) in the North Island of New Zealand provide freely available economic, biodiversity, and geodiversity benefits – collectively known as ecosystem services. Ngati Tahu-Ngati Whaoa has a historical, cultural and contemporary association with geothermal resources within their traditional rohe (tribal boundary) (Figure 1.2).

Many of the geothermal fields in the central part of the TVZ form a loose mosaic of sites linked by the Waikato River. Cultural knowledge resides with Ngati Tahu-Ngati Whaoa for geothermal areas in their rohe, which is generally not captured with western scientific studies.

The Waiotapu (and Waikite) Geothermal Fields are part of the larger Waikite-Waiotapu-Waimangu geothermal system (Figure 1.3) as defined by Waikato Regional Council. Although scientifically Waikite and Waiotapu are thought to be related, the Waimangu Geothermal Field is not considered to be related at shallow depths (see Section 3) and is managed by the neighbouring Bay of Plenty Regional Council. From a management perspective, Waikato Regional Council have the Waikite-Waiotapu-Waimangu geothermal system defined in their regional plan and have this categorised as a “Protected Geothermal System”. A “Protected Geothermal System” is “where the heat and fluid flows and geothermal features will be protected. Only existing and small-scale new uses including scientific investigation and remediation or mitigation of past adverse effects, are provided for within these systems”. This level of protection ensures development of the geothermal resource is minimised and that surface geothermal features are preserved.

Matauranga a Ngati Tahu-Ngati Whaoa is combined with modern scientific data from the Waiotapu-Waikite Geothermal Field (Figure 1.1) to enhance knowledge and to support kaitiakitanga. This is achieved by summarising existing publicly available scientific data with cultural data provided by Ngati Tahu-Ngati Whaoa. Ngati Tahu-Ngati Whaoa have also provided some of their history so the reader is able to understand how some matauranga that was historically shared by the elders of the tribe has become lost in recent times due to the people’s disconnection with some of their land. This situation came about due to government legislation developed and implemented throughout the 19th and 20th centuries. Matauranga was also provided through confidential interviews with several people from Ngati Tahu-Ngati Whaoa.

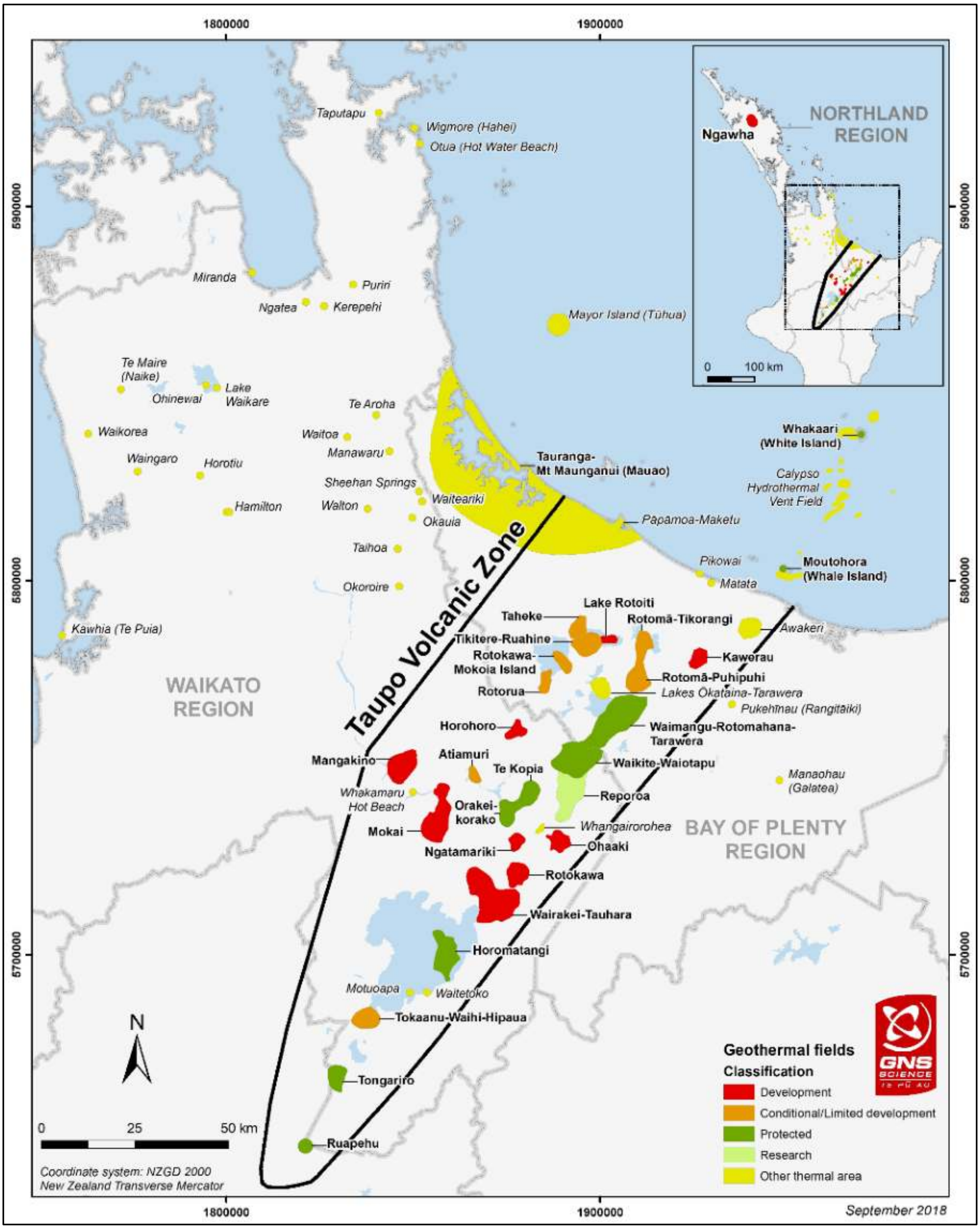

Figure 1.1 Geothermal fields of New Zealand (New Zealand Geothermal Association (NZGA) 2020).

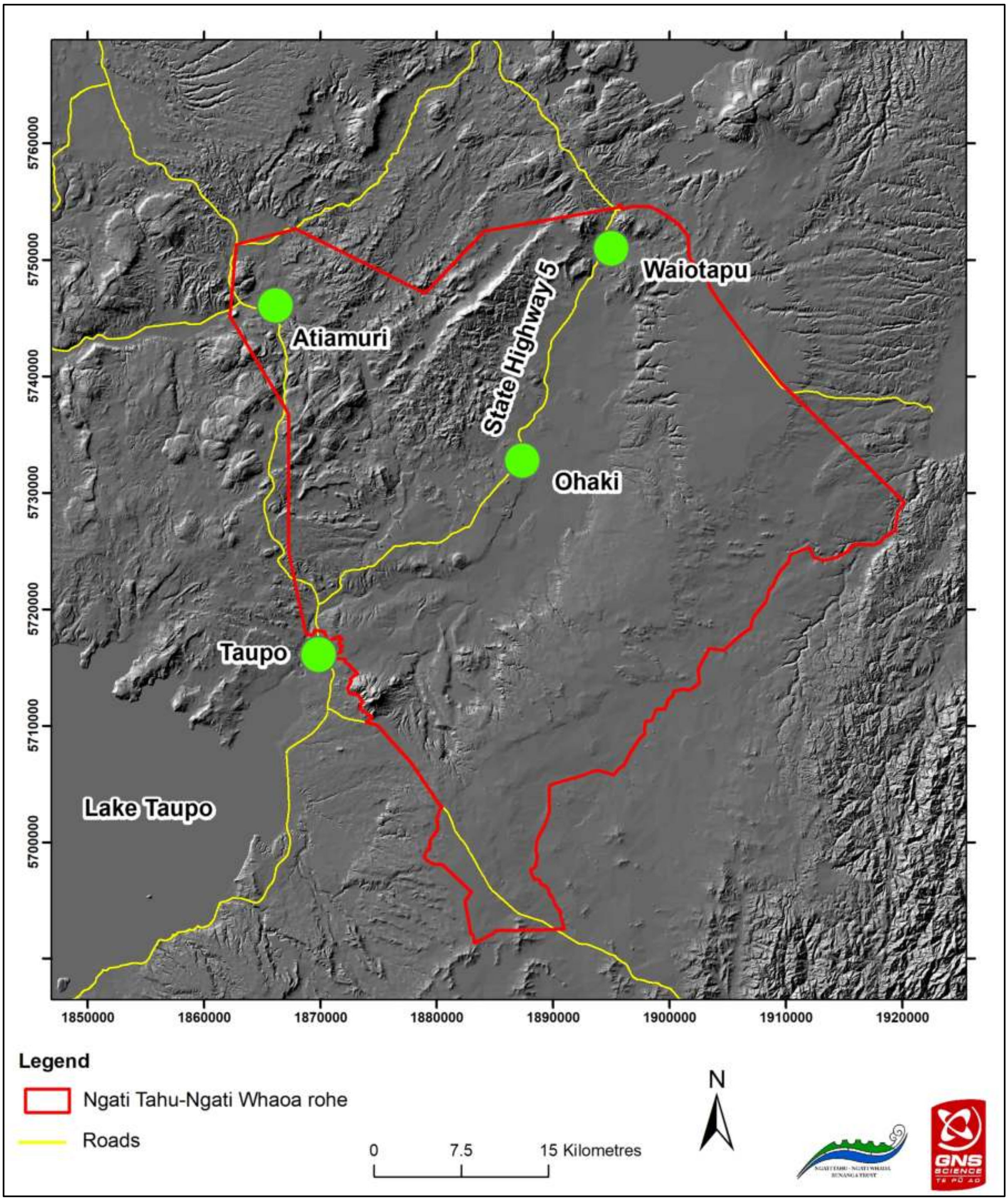

Figure 1.2 Ngati Tahu-Ngati Whaoa rohe (Te Puni Kōkiri–Kāinga 2020). Green dots represent locations on the map.

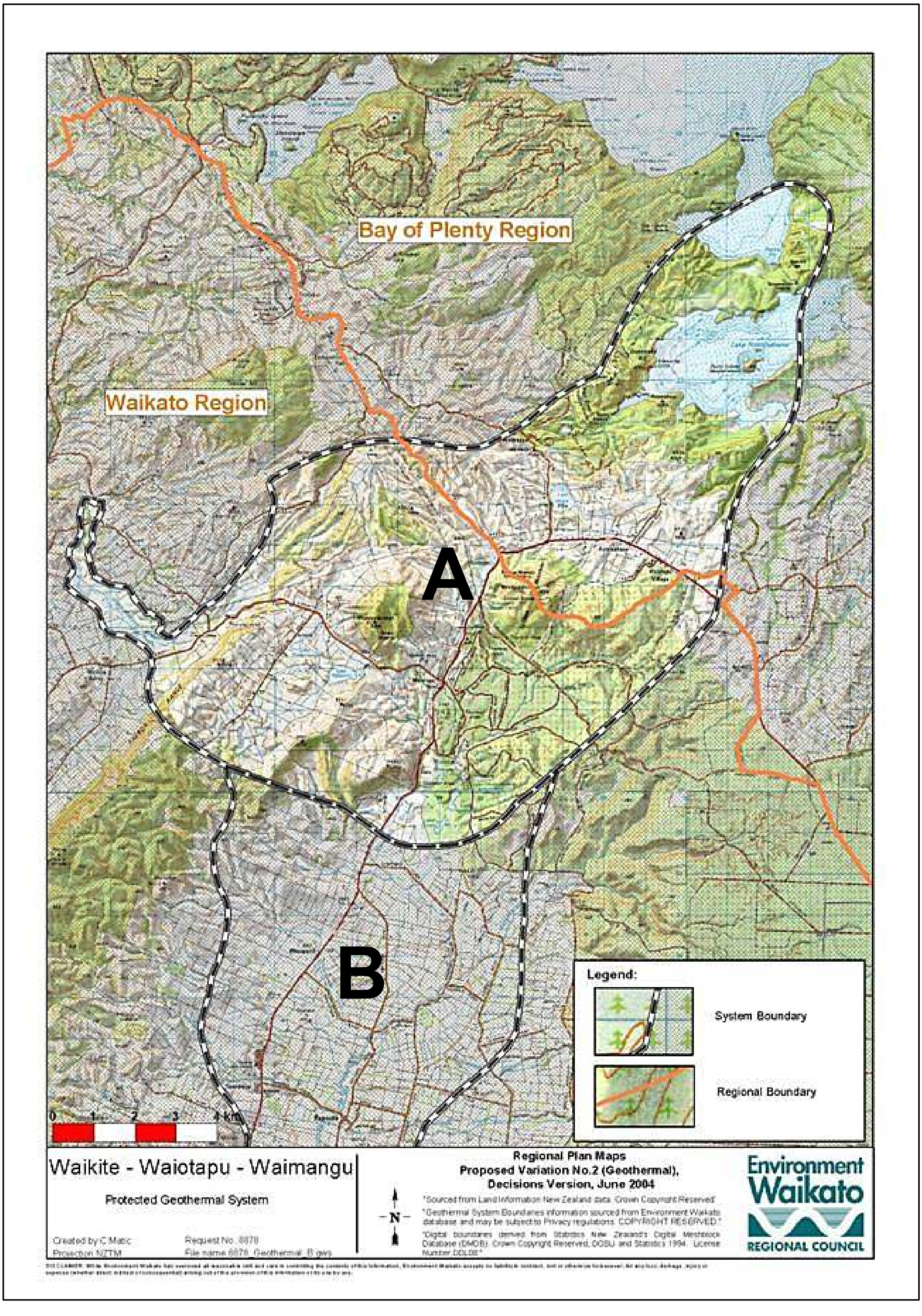

Figure 1.3 Spatial extent of the Waikato Regional Council Waikite-Waiotapu-Waimangu (Area A) protected geothermal system used for geothermal system management (from Waikato Regional Council 2021). The Reporoa geothermal system is also shown (Area B).

2.0 NGATI TAHU-NGATI WHAOA PERSPECTIVE

2.1 Background

From Huka Falls, we extend east across the Kaingaroa Plains to Ngapuketerua, Wairapukau and further onto Pekepeke. From here we extend to our northern pouwhenua at Maunga Kakaramea, turning west to the Paeroa Ranges and on to Orakei Korako, the birthplace and principal kainga (settlement) of our iwi. From Orakei Korako we extend further west to Pohaturoa, an ancient Pa site. These are the pouwhenua, the geographical marker points that describe the rohe (tribal boundary) of which Ngati Tahu-Ngati Whaoa are recognised as the iwi with mana whenua (customary authority).

Our people have occupied these lands since the arrival of our Tupuna Ariki (eponymous ancestor), Tahu Matua, around 1250 AD (some 100 years prior to the seven waka from Hawaiki). Our Tupuna (ancestor) Whaoa is some generations younger. Whaoa descends from Tahu Matua on his mother’s side, Hinewai, and he descends from Atuamatua on his father’s side, Paengatu. As a tribe, we derive our name from our ancestors Tahu Matua and Whaoa. Through successive generations of inter-marriage with neighbouring iwi, our tribal members also trace descent from ancestors who arrived on the Arawa, Mataatua and Tainui waka.

Prior to the arrival of European settlers to Aotearoa-New Zealand, Ngati Tahu-Ngati Whaoa was an autonomous, independent and self-governing confederation of hapu. As Ngati Tahu-Ngati Whaoa we exercised tino rangatiratanga (self-governance) over our traditional rohe. The historical hapu (subtribes) no longer form distinct communities within Ngati Tahu-Ngati Whaoa. In more recent times the descendants of our many tupuna have operated as a single tribal grouping known today as Ngati Tahu-Ngati Whaoa.

We became a river iwi, living sustainably off mahinga kai (wild foods) and other resources that our rohe provided. The close connection Ngati Tahu-Ngati Whaoa has with the Waikato River is illustrated by the significant number of places held sacred along the Waikato River from Huka Falls to Pohaturoa.

Ngati Tahu-Ngati Whaoa has a historical, cultural and contemporary association with geothermal resources within our traditional rohe. Geothermal areas were favoured by our tupuna for settlements, providing precious warmth and hot bathing, natural cooking and preserving, and sites for ritual purposes and healing. Large kainga and cultivations were often established around these taonga (treasures) such as at Orakei Korako, Ohaki and Waiotapu.

With the passing of the Geothermal Energy Act 1953, Ngati Tahu-Ngati Whaoa lost control of and access to some of our geothermal taonga. The geothermal fields within our traditional rohe include Rotokawa (Tauhara North), Tauhara (Tauhara North), Broadlands (Kaingaroa No.2), Ohaki (Tahorakuri), Ngatamariki (Tahorakuri), Reporoa (Paeroa East), Waiotapu (Paeroa East), Waikite (Rotomahana Parekarangi), Te Kopia (Rotomahana Parekarangi), Orakei Korako (Tutukau) and Atiamuri (Tatua West).

2.2 Context of this Report

Much of our tribal history pertaining to the Waiotapu and Waikite geothermal areas was passed down through many generations by our tupuna however this practice is not as common as it used to be leading to many stories being lost over time. During the last half of the 20th century urban migration affected the Maori populations of Waiotapu and Waikite as many Maori moved from the district to follow employment and tertiary training opportunities. This added to the disconnect of our lands from our people which began when land was confiscated for use by the Crown. Some of the stories contained in this report speak of our history with the Waiotapu and Waikite geothermal areas however many kaumatua (older tribal members) interviewed as part of this project only remember what they saw as they were growing up during the 1950s and 1960s, so these memories form the bulk of the iwi matauranga shared in this report. Due to reasons beyond the control of those collating this report, only one of the kaumatua interviewed for this project was able to share knowledge told to him by an earlier generation of kaumatua. This person also has significant expertise in the history of the Waiotapu and Waikite Geothermal Fields based on his own extensive research and physical study of these areas.

Maps (Figures 2.1 to 2.4) and Table 2.1 show features referenced by kaumatua that are discussed in this report.

Table 2.1 Locations of interest identified by kaumatua during interviews as relates to Figures 2.2 to 2.4.

Point Number	Names of Points Discussed in the Text
1	Hot pool
2	Mud pool
3	Mud pool that was used as a dump
4	Creek that was used for bathing
5	Lady Knox Geyser
6	The Spout hot pool
7	The Venus Pools
8	Historic Battlefield
9	Lake Ngakoro
10	Lake Orotu
11	Wetland associated with Lake Orotu
12	Lake Ngahewa
13	Wetland associated with Lake Ngahewa
14	Ministry of Works depot circa 1960s
15	Lake Rotowhero
16	Whakapapataringa
17	Hot pool used for washing clothes
18	Waiotapu School Camp (formerly Prison camp and Single Men's camp)
19	Waikokomuka Stream
20	Waiotapu Village site
21	Lake Ngapouri
22	Lake Tutaeinanga
23	Waikite Wetland
24	Otamakokore Stream
25	Armed Constabulary Camp circa 1871
26	Waiotapu School site
27	Te Tihi o Ruru

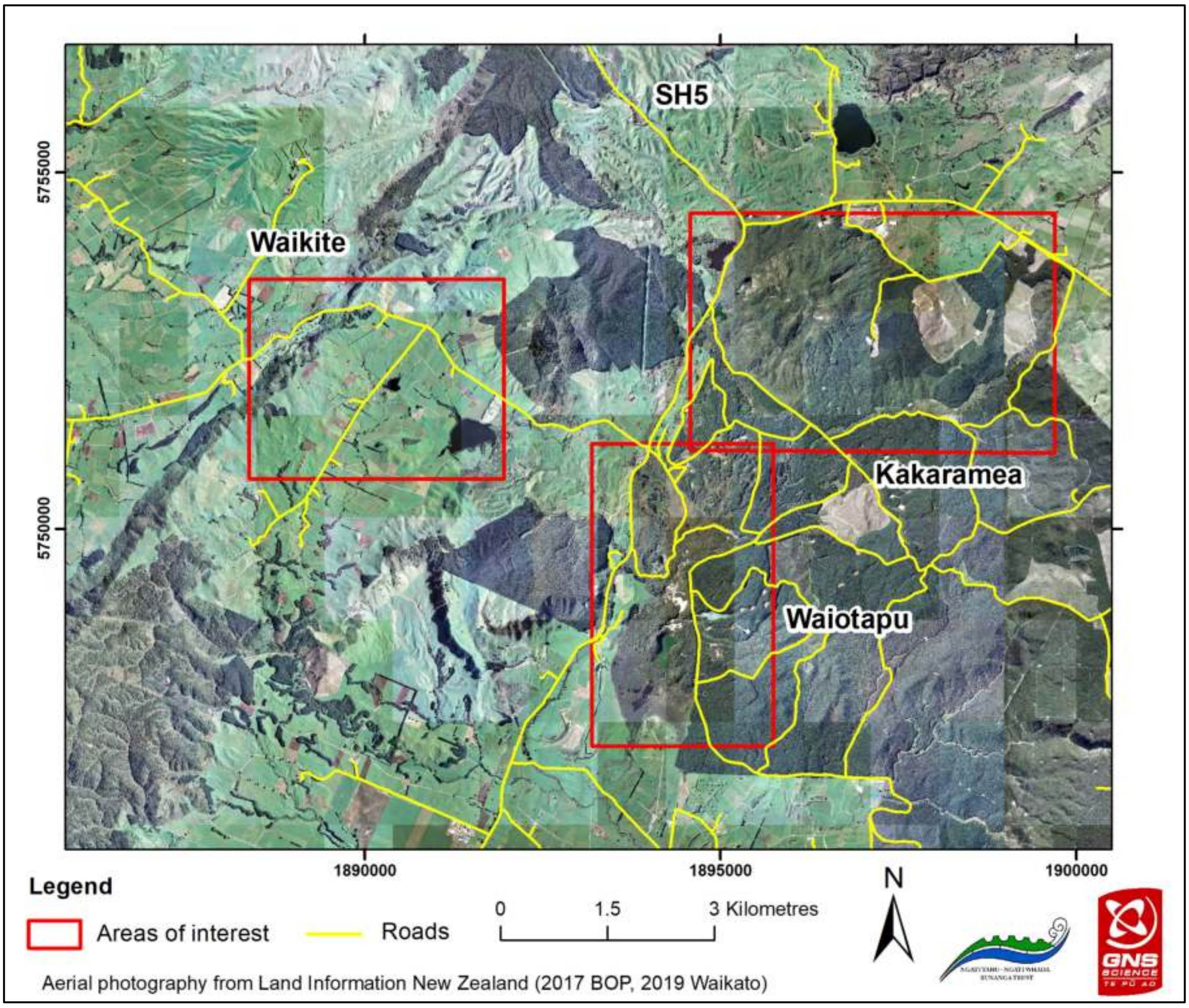

Figure 2.1 Map showing outlined areas of interest at Waiotapu, Kakaramea and Waikite discussed in the text. Enlargements of these areas are shown in Figures 2.2 to 2.4.

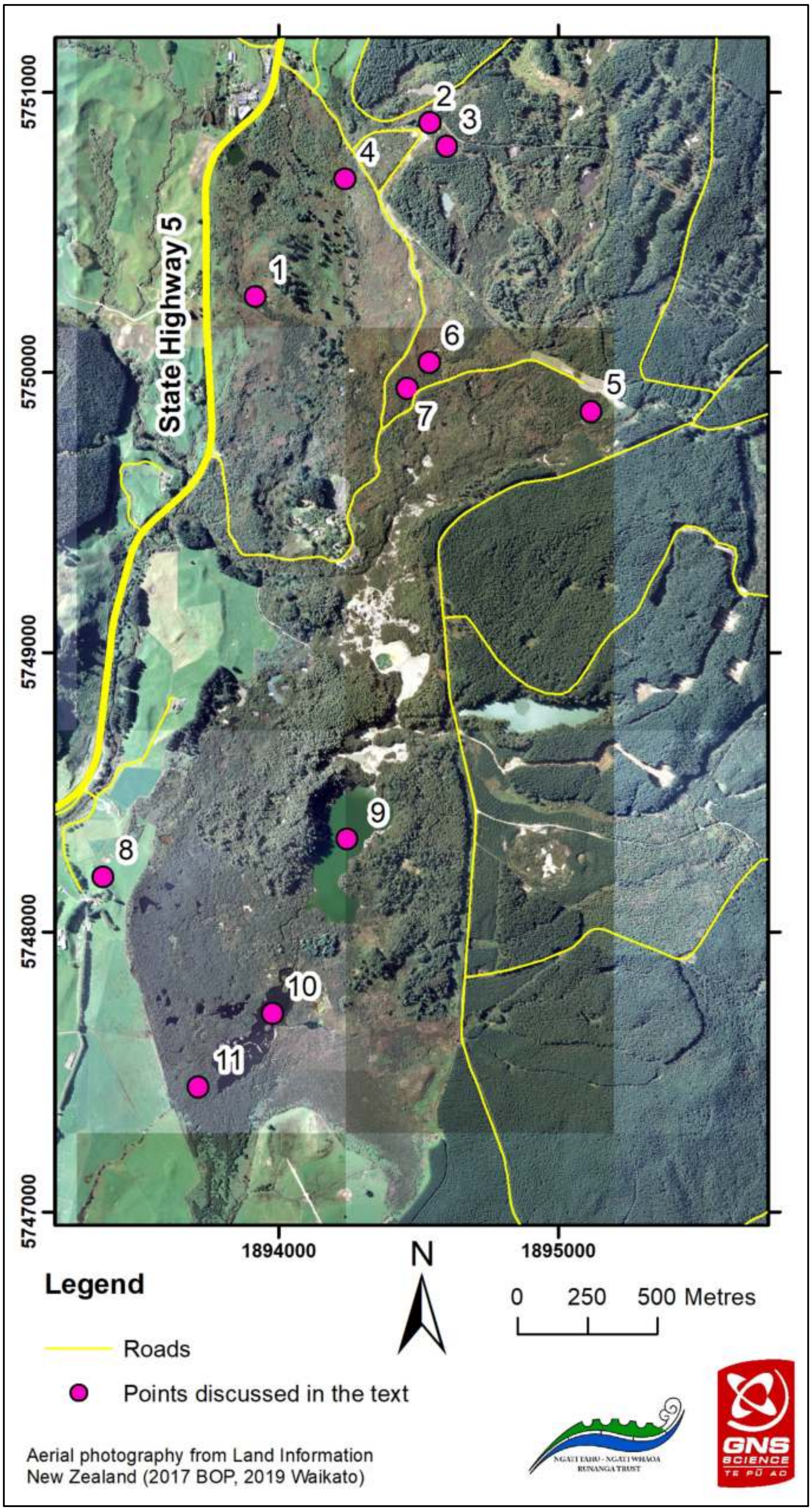

Figure 2.2 Waiotapu areas of interest.

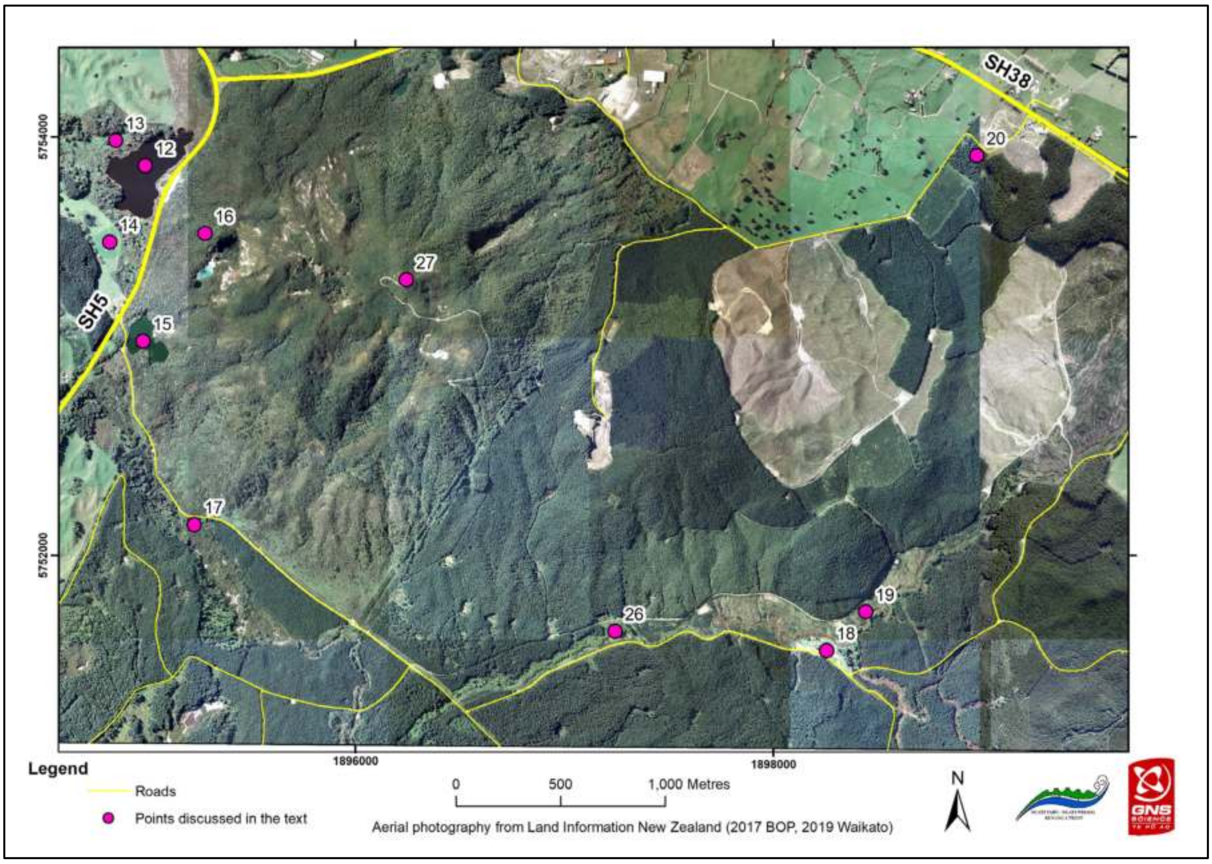

Figure 2.3 Kakaramea areas of interest.

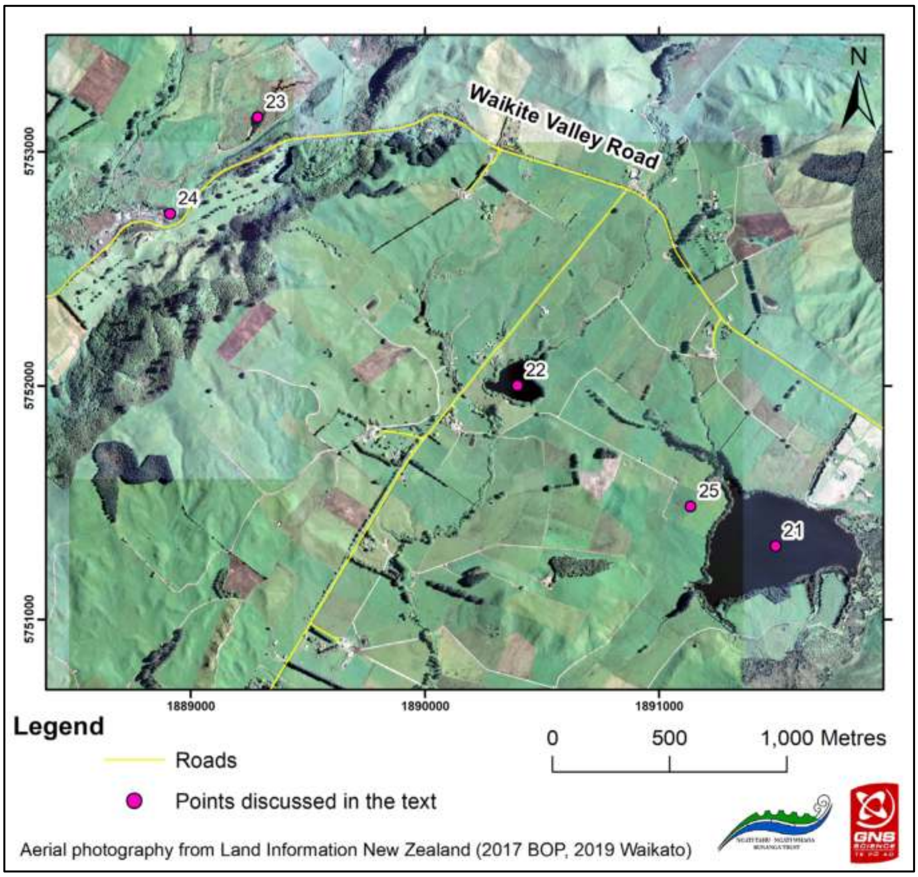

Figure 2.4 Waikite areas of interest.

2.3 Pre-European History of the Waiotapu and Waikite Geothermal Area

2.3.1 Maunga Kakaramea

Maunga Kakaramea (also known as Rainbow Mountain) (Figure 2.5, point 27 on Figure 2.3) is an iconic peak for the Ngati Tahu-Ngati Whaoa people and its traditional history reinforces tribal identity, solidarity and continuity between generations. The geothermal activity on and around the maunga is part of the Waiotapu Geothermal Field.

Maunga Kakaramea means “mountain of coloured earth” which is reflective of its bare brown, orange and red steaming slopes. Red ochre (kokowai) was and still is a precious article of trade which is directly associated with the geothermal area around the maunga. It was gathered at certain times of the year from the maunga before being sun-dried, which was the first step in the long preparation process. Its chief application was a mix of shark oil that was applied to the face and body of the highly ranked at major ceremonial occasions. The same mix would be applied to those of high rank before going into battle. Red ochre was also used as a dye for raranga (weaving), painting of kowhaiwhai patterns and whakairo (carvings). Today red ochre use is limited to colouring in the arts of weaving and whakairo.

Historically Maunga Kakaramea was used as a place of refuge during battle for the Ngati Tahu-Ngati Whaoa. Our people came to occupy Maunga Kakaramea following an attack on them by a chief named Rahurahu. Rahurahu was ultimately defeated at Maunga Kakaramea by Tahu-Ngati Whaoa and other allied tribes and from that point on our iwi continued to reside there.

Also referred to as Maunga Kara, the mountain was a burial ground for the Ngati Tahu-Ngati Whaoa people. Many urupa (cemeteries) are located at the foot of the maunga and are the final resting places for a number of Tahu-Ngati Whaoa people. The mountain also hides caves that were used as urupa. These urupa are wahi tapu (sacred) places and there are many other sites of significance on the maunga such as Komutumutukioruahine which was the name of a palm located on the summit of the mountain.

Other caves on the maunga were used as kainga as the maunga also provided the people with valuable food resources. Some of the foods the maunga and its fresh waterways provided were fern roots, eels (tuna), freshwater crayfish (koura), ducks and other waterfowl.

The summit of Maunga Kakaramea was known as Te Tihi o Ruru-The Owl’s Perch (point 27, Figure 2.3) as it provided expansive views over the rohe and beyond. This made it an ideal stronghold as a pa. On the western side of Maunga Kakaramea was another stronghold where many battles were fought, known as Whakapapataringa (point 16, Figure 2.3). The area is cone-shaped and is visible from the State Highway. A kaumatua shared a story (Ngati Tahu-Ngati Whaoa Runanga Trust (NTNWRT) 2021) that was passed on to him about how Whakapapataringa was covered in ditches which spiralled downwards allowing warriors to shoot at attackers below from many different angles therefore stopping them from climbing the hill itself.

The mauri of Maunga Kakaramea represents the essence that binds the physical and spiritual elements of all things together, generating and upholding all life. All elements of the natural environment possess a life force and all forms of life are related. Mauri is a critical element of the spiritual relationship of Ngati Tahu-Ngati Whaoa with Maunga Kakaramea.

Figure 2.5 View of Maunga Kakaramea showing some coloured sand. Department of Conservation Rotorua Office 2013 shared with NTNWRT 2013.

2.3.2 Waiotapu

The Ngati Tahu-Ngati Whaoa people have had a very strong presence within Waiotapu and Maunga Kakaramea for generations. The name Waiotapu translates into English as “Sacred Waters” which in itself reflects the iwi connection to this area. It is believed that Waiotapu was not commonly accessed by those not of high rank so only tohunga (priests or learned persons) and those akin to chief status would have been able to enter the area now known as the tourist park “Wai-o-tapu Thermal Wonderland”.

Many battles were fought in and around the Waiotapu area. In one of his books on the history of the Te Arawa people, Don Stafford describes how the Ngati Tahu living at Waiotapu joined with Arawa war parties to fight the Tuhoe. The combined armies crossed the Kaingaroa Plains. Retaliation by the Tuhoe saw their army separate themselves at the Rangitaiki River, one going to Rerewhakaaitu while the other section went to Waiotapu, where they attacked and defeated the Ngati Tahu people living at Paeroa and Te Kopia (Stafford 1967).

The kaumatua interviewed (NTNWRT 2021) for this project gave more detail in respect of this battle by saying that the southernmost geothermal lake within the Waiotapu Reserve, Lake Orotu (point 10, Figure 2.2), was a main area of settlement and was where this battle most likely took place. This was supported by a map he provided the interviewer that shows a battlefield area (Figure 2.6). The battlefield is also marked on Figure 2.2 as point 8.

The kaumatua commented that while he had identified some physical remains of settlement when he walked through the area many years ago, he had not formally written down or recorded these findings. The map denotes other known surface features of the geothermal area and their Maori names. He went on to explain how food and other resources were abundant in the area surrounding Lake Orotu, which is geothermal, but where unnamed freshwater tributaries feed into the Waiotapu Stream, which changes from geothermal to fresh water (point 11, Figure 2.2). Koura, tuna and birds were plentiful as were ferns (providing sustenance with their roots), raupo and flax. With the geothermal surface features providing warmth, a means to cook and preserve food, and bathing options that also had healing properties, this made settlement in the area ideal.

The original forests in the Waiotapu area provided an abundance of kai, such as fern root and birds, as well as rongoa (medicine) and native trees for making waka and various other materials for making tools and whare (houses). Various locations also provided microclimates for planted cultivations including the growing of kumara.

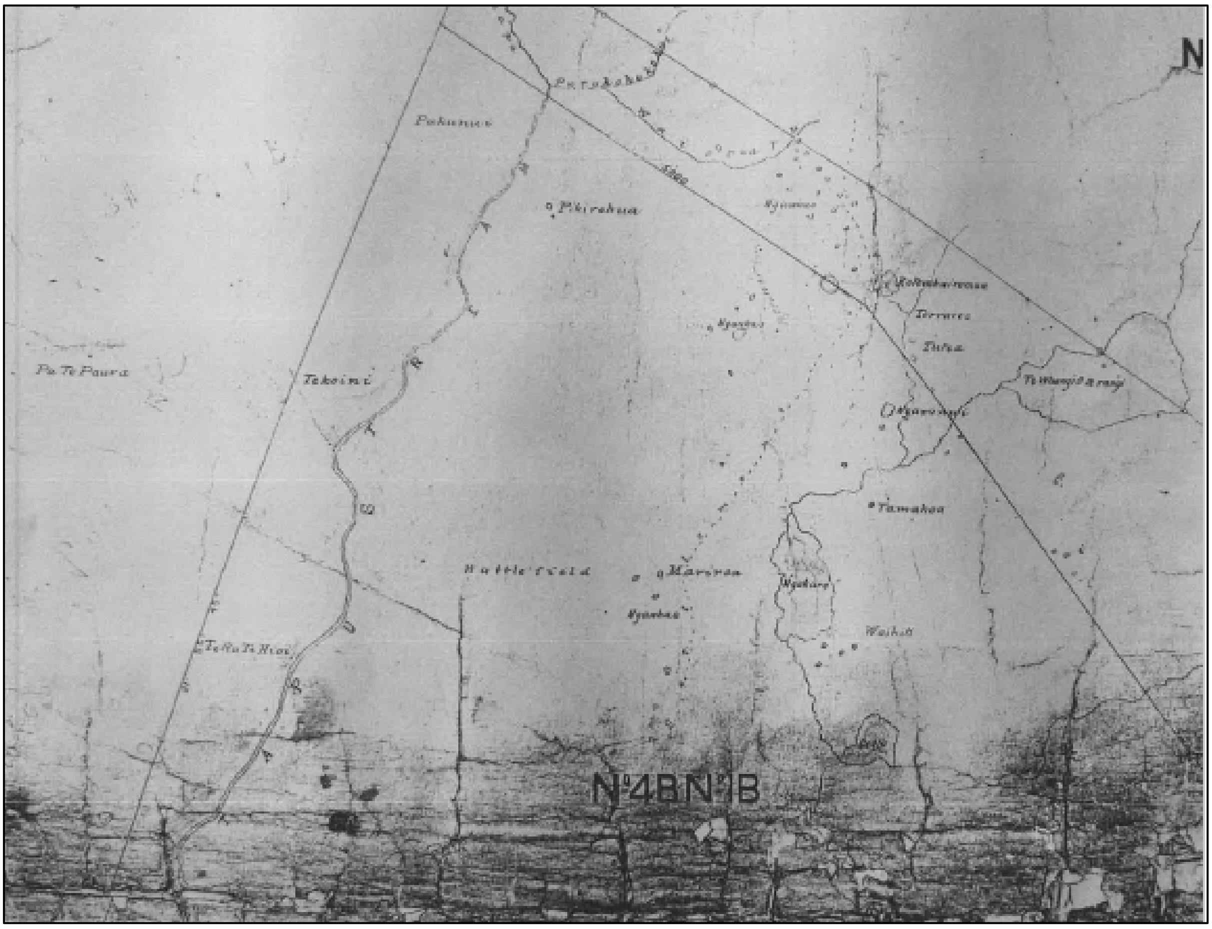

Figure 2.6 Battlefield area (Fletcher 2021).

2.3.3 Waikite

The Waikite thermal area was also important as it formed part of the trail to Orakei Korako, the tribe’s ukaipo or birthplace, via the Paeroa Ranges which incorporates the Te Kopia Reserve. People would travel to and from Orakei Korako to Waiotapu and Maunga Kakaramea, staying at established settlements or pa along the Paeroa Ranges. These trails also provided links to the rest of the rohe in the east, west and south. Extensive wetland areas also existed in the Waikite Valley and a known site was where the Otamakokore Stream bubbles out of the ground to form a geothermally influenced wetland (point 23, Figure 2.4). This wetland provided the same food, flax and raupo opportunities as those surrounding Waiotapu and Maunga Kakaramea so were regularly utilised by those whanau travelling through the area or domiciled nearby.

2.4 Recent History

The Waiotapu Reserve was a kainga for many tribal members and this habitation continued up until the mid-late 1960s when the last family left the area. The first European history and contact within this area was believed to have occurred in the 1840s, when the odd traveller would pass through the area, recording details of their visit in diaries and letters. During the time of unrest lead by Te Kooti in the 1860s and 1870s, armed constabulary camps were established throughout the rohe. One of these camps was located near the Waikite Geothermal Field (point 25, Figure 2.4), at Lake Ngapouri. Lake Ngapouri (point 21, Figure 2.4) was valued as a mahinga kai site where tribal members would gather kokopu, koura and kakahi (freshwater mussels).

2.4.1 Tourism

The iwi has promoted Waiotapu as a tourist destination since those first visits in the 1840s. An article in The Cyclopedia of New Zealand (c2016) lists the principal sights of Waiotapu under Maori management. Also mentioned is that the government held 4,000 acres in the immediate neighbourhood of the Waiotapu hotel (Figure 2.7), which opened in 1896 across State Highway 5 from the existing hotel. The hotel was very much the social centre of the area at the time. Not only was it a stopover for coaches, but it also contained a small store and the Post Office.

The government owned land was originally targeted for tourism, but instead was either forestry planted or converted into a Lands and Survey farm which remained in operation until recent times when it was sold in smaller lots to a range of private owners. Those areas deemed unsuitable for either farming or forestry because of the active, unstable geothermal ground were handed over to the Government Tourist Department and developed as a tourist attraction. The area has many unique geothermal features including the Champagne Pool (Figure 2.8), the Devil's Bath and the Lady Knox Geyser. These features are still viewed today by many visitors throughout the world when they visit the thermal park known as Wai-o-tapu Thermal Wonderland. The thermal park is contained within the Waiotapu Scenic Reserve and although this land was taken from the iwi through government legislation, ownership of 125 hectares of the Reserve was recently transferred to the NTNWRT through the Affiliate Te Arawa Iwi and Hapu Claims Settlement Act 2008.

Figure 2.7 The original Waiotapu Hotel built in 1896 and destroyed by fire in 1931 (Photo from Residents of the Reporoa District 1983).

Figure 2.8 The Champagne Pool at Wai-O-Tapu Thermal Wonderland. Photo provided by NTNWRT.

2.4.2 Land Title

The next known contact was with those who surveyed the area in the 1880s after Native Land Court sessions were held regarding ownership. Maunga Kakaramea and Waiotapu were considered originally part of Kaingaroa No.1 block but the area was later split off into what became Paeroa East. The Waikite Geothermal Field was and still is part of the wider Rotomahana Parekarangi 6A block (Figure 2.9).

The following is an excerpt from the preamble contained in the aforementioned settlement Act which explains how this and much more of the iwi's land was taken by the Crown.

> "The Crown introduced the Native Land Court (the Court) into the central North Island in 1867, without consulting with the Affiliate[1], to convert customary title into title derived from the Crown. Some of the Affiliate engaged with the Court to gain secure titles to assist leasing of land and secure their claims from other groups. Others objected to the Court. The Crown received complaints about the cost of hearings, survey changes, and applications initiated without the consent of the owners. From 1873, the Crown focused on the acquisition of Maori land to facilitate Pakeha settlement in the central North Island. The Crown was aware of widespread resistance to land sales amongst the Affiliate and initially proposed to restrict negotiations mainly to the lease rather than the sale of the land. By August 1874 the Crown had opened, but not completed, lease negotiations for almost 650,000 acres and purchase negotiations for 400,000 acres of land within the Affiliate area.
>
> In the 1880s the Court adjudicated over much of the land in the area that the Affiliate exercised customary interests, including many of the blocks the Crown had brought under negotiation in the 1870s. The combined effect of actions such as: the use of payments before title was determined, occasionally aggressive purchase techniques employed by the Crown, and the use and implementation of monopoly powers over land dealings, meant that the Crown failed to actively protect the interests of the Affiliate in the land it wished to retain. This left some of the Affiliate virtually landless.

[1] Affiliate refers to all iwi and hapu included in the Affiliate Te Arawa Iwi and Hapu Claims Settlement Act 2008.

The Crown acquired land of particular significance to the Affiliate through public works and scenery preservation legislation. In the 19th century, land was compulsorily acquired for public works purposes, including roading and railway. In the 20th century, land was taken for internal communications, electricity generation, scenic reserves, forest plantation and an aerodrome. Over time, through purchases and public works takings, the Affiliate lost ownership of some important geothermal lands and wahi tapu."

As previously mentioned, part of the Waiotapu Scenic Reserve (Figure 2.10) was returned to Ngati Tahu-Ngati Whaoa, via the NTNWRT, after the passing of the Affiliate Te Arawa Iwi and Hapu Claims Settlement Act 2008. The Runanga land is currently leased by Te Pumautanga o Te Arawa Trust, which was established to manage the assets negotiated by the affiliate iwi and hapu who signed the settlement act. The assets themselves were returned to iwi with mana whenua over each particular area.

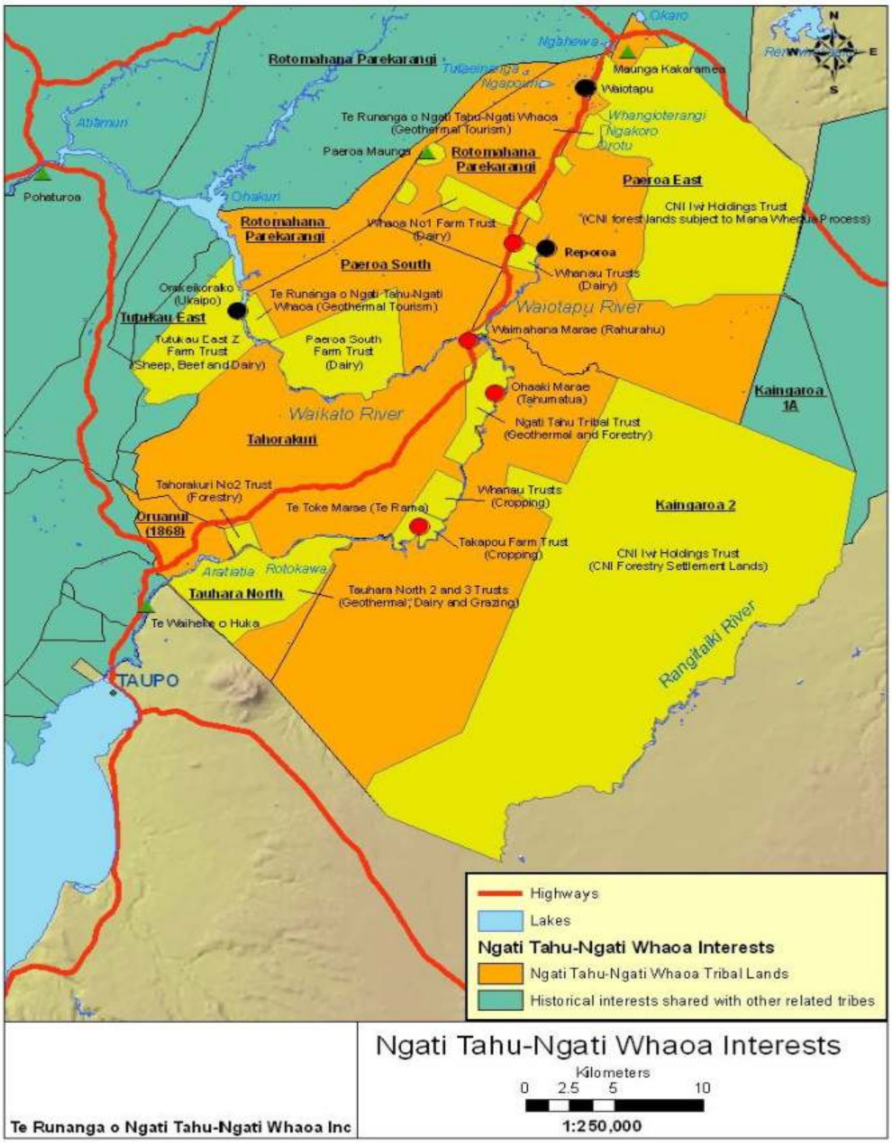

Figure 2.9 Map showing historic and contemporary Ngati Tahu-Ngati Whaoa Maori Land Blocks (NTNWRT 2019).

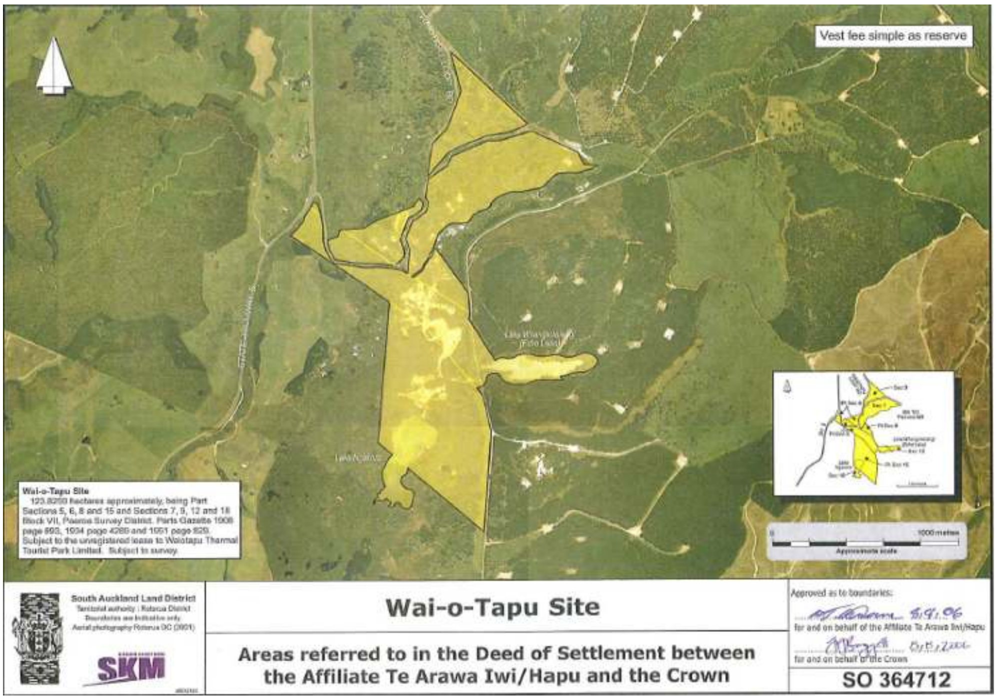

Figure 2.10 The Affiliate Te Arawa Iwi/Hapu Deed of Settlement Schedule 7: SO plans (2008).

2.4.3 Forestry

In 1901 the Waiotapu area became the site of the first exotic forestry planting in the country. This was seen favourably by iwi as it provided much needed employment but when the first plantings were ready for harvest in the 1920s to 1930s the land was taken from the iwi by the Government under the Waste Lands Act 1858.

The first forestry plantings were done by prisoners after they had cleared the scrub off what was known as the “Pumicelands”. The Pumicelands were so named as the area was covered in pumice after the Tarawera eruption in 1886 and the main vegetation following on from that was hardy, regenerating scrub plants. Prisoners were housed in a purpose-built camp (Figure 2.11) on the bank of the Waikokomuka Stream, not far from Kerosene Creek (point 18, Figure 2.3). Prison labour continued to plant the forest until 1920 when the camp was abandoned and another temporary camp was set up further in the forest for returned servicemen, who continued the planting regime until 1936. The prison camp later became the single men’s camp for forestry workers. It could not be established when the camp was repurposed to house workers other than prisoners, nor when it stopped being used for this purpose. However, kaumatua (NTNWRT 2021) remembered it still being used as a single men’s camp in the 1950s and 1960s so it likely changed to its current format as a school camp in the late 1960s or early 1970s. The camp (Figure 2.11) is still in use by school groups and other interest groups to this day and many local Maori who attended school in the Reporoa area in the 1970s and 1980s have fond memories of the camp.

The government established the New Zealand Forest Service in 1919 to manage the growing plantation. As the plantation grew in size, more men were needed to plant and then harvest the trees as well as mill the trees into usable timber. This coincided with the depression era so men, and later whole families, moved closer to the area for work. Iwi living locally were an already established labour source however as the plantation continued to grow more men were needed than were available locally. A village with housing for families was established on Rainbow Road behind what is now the Runanga office (point 20, Figure 2.3) and other villages in the wider Kaingaroa area provided housing for the growing work force. Many local Maori families moved into these villages as the housing came with all the modern amenities of the time, which was the start of the movement away from traditional uses of some of the geothermal surface features.

By the start of the Second World War the forest had grown to cover thousands of acres, spreading from Waiotapu onto the Kaingaroa Plains, and became known as the Kaingaroa Forest. Also by this time, some land at Waiotapu and the Kaingaroa Plains that was originally converted to pasture was found to be unsuitable for this purpose as water was scarce, grazing was poor and stock suffered from "bush sickness", caused by a lack of trace elements in the soil, especially cobalt, so this land was also converted to forestry. During the Second World War years, planting continued but on a smaller scale as the work was done by local Maori women because most fit and able men had gone to war. A kaumatua interviewed for another project (NTNWRT 2015) shared how she was brought up by her grandparents as her father went to war and her mother worked planting trees in the Kaingaroa forest for the Forest Service. By 1962 an article written by Mr. R Nellbeck (Nellbeck 1965), a visiting silviculture manager from Sweden, noted that the Kaingaroa Forest covered 350,000 acres of which 270,000 acres had been planted.

Many of our iwi members lived in the Waiotapu and Kaingaroa villages until the Waiotapu village was disbanded in the late 1980s when the government privatised the Kaingaroa Forest. Although the land was earmarked for return to iwi via the Treaty of Waitangi settlement process, our whanau who lived in Kaingaroa village fought with the government to transfer the management of the village to those who wished to remain living there. This was achieved in 1987 and many of our whanau continue to live there as they were able to purchase their homes but not the land the homes stood on. The government vested the land back to iwi ownership through the Central North Island Forests Land Collective Settlement Act 2008 and Ngati Tahu-Ngati Whaoa, through our mana whenua status, hold interests in many of the land blocks included in this settlement. Privatisation also initially brought redundancy to iwi workers and some chose to move out of the district to pursue other career or work opportunities. However, forestry skills were still required and those who remained in the area went on to find work in the private forestry sector. Because of this, there has now been at least three generations of our people working in forestry roles both inside and outside our rohe.

Planting many species of exotic trees changed the landscape forever and many native plants were lost to the area. To this day some of those early planted exotic species continue to cause environmental concern with self-seeding wilding conifer species colonising areas held tapu (sacred) to the tribe. Much of the work carried out by Department of Conservation (DOC) and the Runanga in and around the Waiotapu and Maunga Kakaramea Scenic Reserves has a strong focus on the control, or ideally the eradication, of wilding pine species to allow regenerating native species to re-establish themselves wherever possible.

Figure 2.11 Waiotapu Prison Camp 1901. Photo provided by NTNWRT. Waiotapu Camp today (Waiotapu Camp 2021).

2.5 Use of Resources at Waiotapu and Waikite

The Ngati Tahu-Ngati Whaoa people made use of many natural resources in the Waiotapu and Waikite Geothermal Fields. This included the geothermal surface features, naturally coloured sands and clays and the flora and fauna that flourished there.

2.5.1 Fauna (Animals) Found in or Near Geothermal and Fresh Water That Were Used as Food

Up to the contact period tuna, koura, ducks and other birds were the staple proteins in our people's diet and all were abundant around Waiotapu, Maunga Kakaramea and Waikite freshwater wetland areas. Wetlands and lakes provided ideal habitats for birds and aquatic species. Geothermal wetlands and lakes in these areas also provided ideal habitat for ducks however due to the geothermal influence on the water, no aquatic food species were available.

Rahui (prohibition orders) were extensively used throughout both types of wetlands and lakes to allow for the sustainable management of birds as well as flora. In the 1600s one of these places was marked with a human head, which was not an uncommon practice, and served as a reminder of the fate of anyone who chose to ignore the rahui. In the early 1900s trout were introduced to Lake Taupo and they quickly spread throughout the Waikato River and its tributaries. These too became a food source for our people and a koro remembers catching brown trout in the Waikokomuka Stream at Waiotapu in the 1960s (point 19, Figure 2.3).

2.5.2 Fauna (Animals) Found on the Land That Were Used as Food

With the introduction of pigs and deer to the landscape, these quickly became favoured sources of protein for the iwi as they provided a change from birds and native fish. Pigs and deer were and still are abundant within the Waiotapu area and are also found in the Te Kopia Reserve, of which the northern end is located next to the Waikite Geothermal Field. Dama wallabies have also become prolific in both areas and are not valued as a food source but are instead considered a significant pest to the health of the ngahere (forest) in both areas causing as much damage as possums. For this reason, discussions are underway with both Waikato and Bay of Plenty Regional Councils as to options for eradication of this exotic species before they spread further south.

2.5.3 Flora (Vegetation)

As mentioned above, streams, wetlands and lakes (containing either fresh or geothermal water) existed throughout the Waiotapu and Waikite geothermal areas. These were not only homes for wildlife but also provided ideal growing conditions for flax and raupo. Ferns also grew in these conditions and their roots provided a staple carbohydrate when other options such as kumara were scarce or unavailable. Eating fern roots was replaced with potatoes once they became widely available through the arrival of European missionaries and settlers. Many threatened or at-risk native fern species grow amongst the geothermal wetlands as they prefer the warmer temperature that comes with the warm ground and water.

2.5.3.1 Weaving

Ngati Tahu-Ngati Whaoa was an iwi known for their proficiency in weaving, using particular materials sourced from native plants for each of the woven products such as whariki (mats), korowai (cloaks) or piupiu.

Flax (Phormium tenax), or harakeke as it is known in Maori, was particularly abundant in the Waiotapu and Waikite areas, especially near the wetlands of the Otamakokore Stream, Lake Ngahewa and Lake Orotu, but was also found in other wetland and lake areas within the tribe's rohe (boundary). Flax was commonly used in weaving all manner of products from clothing to rope, food storage containers, baskets and mats.

In post-European times, flax was gathered and milled or traded locally before being exported overseas for making linen or ropes. New Zealand flax was highly valued by the early European traders from the time of Captain Cook because its superior quality made it the best to use for ship's ropes as it handled sea conditions better than other types of flax rope. In the early 1800s, dressed, or scrapped, flax was traded for muskets, which were then used to protect the people from other marauding tribes. Large amounts of flax were gathered and prepared for trade which, according to one kaumatua story (NTNWRT 2021), lead to some people starving as they neglected their crops in favour of this work. Flax mills tended to be located near abundant flax supplies and it is known that at least one existed in the Waikite Valley and another is thought to have been located in the Waiotapu area. One kaumatua spoke (NTNWRT 2021) of a colleague whose Maori grandmother owned the last flax mill in the Waikite Valley, located five miles from the Waikite Wetland. After the second world war, wetlands at the southern end of the Waiotapu geothermal area and on the Waikite geothermal area were drained so that the land could be converted to pastoral farming. This destroyed the habitat for flora and fauna in both areas so flax is no longer as prevalent in either place. However, in recent years DOC re-established the wetland at Waikite (point 23 on Figure 2.4, Figure 2.12), and many native flora species, including some endangered geothermal ferns, are beginning to thrive in the restored environment. Endangered birds are also thought to be returning to the wetland however there has not been an ecological study completed to quantify this.

DOC have also assisted the landowner in the restoration of the wetland surrounding Lake Ngahewa (the lake is point 12 and the wetland is point 13 in Figure 2.3) and this is now recognised as one of the preferred flax gathering areas for weavers in the Rotorua and Reporoa districts.

Raupo (Typha orientalis) (Figure 2.13) also had many uses although none of the kaumatua interviewed were able to share any stories of this. However, New Zealand history tells of raupo being used as food, medicine, roof thatching and to make poi, sails and waka. In fact, the photo of a Ngati Tahu-Ngati Whaoa whanau (Figure 2.14) shows them standing beside their cottage made of raupo. Considering its abundance in both geothermal areas it is almost certain that the iwi also used it for these purposes as well.

Figure 2.12 Waikite Wetland 2018 (Cashmore 2021).

Figure 2.13 Raupo (Typha orientalis) (New Zealand Plant Conservation Network 2021).

Figure 2.14 A Ngati Tahu-Ngati Whaoa whanau in their raupo cottage located behind the Hotel circa early 1900s (Residents of the Reporoa District 1983).

2.5.3.2 Rongoa (Medicine)

Many native species were used as rongoa (medicine), including kawakawa (Piper excelsum), koromiko (Hebe stricta) and raureka (Elaeocarpus dentatus). The most potent rongoa were collected from where the sun shone directly on the leaves. Other remedies were derived from wild herbs such as the leaf and root of dock (Rumex obtusifolius) which was used as a skin poultice and a blood purifier, and dandelion (Taraxacum officinale) which was used for sores. One kuia interviewed (NTNWRT 2021) talked about her mother gathering rongoa at Waiotapu. Five-finger, or whauwhaupaku (Pseudopanax arboreus) (Figure 2.15), and koromiko (Hebe stricta) (Figure 2.15) grew very well in the area. Five-finger acted as a diuretic, removing excess fluid from the body and koromiko was used to settle upset stomachs.

The kuia also knew of many other native species that were used by her mother or other iwi members as rongoa but she was not aware of any others being gathered from Waiotapu. This is most likely due to the introduction of the forestry plantation as the native species could not compete for sunlight or were damaged by logging operations so are no longer found in the area. A koro remarked on this fact during his interview as he could only remember a few native plants being gathered for food as the landscape was dominated by exotic trees rather than native species.

Figure 2.15 Five-finger (Pseudopanax arboreus) (University of Auckland 2021). Koromiko (Hebe stricta) (Conservation Volunteers New Zealand 2021).

2.5.3.3 Food

Herbs and other vegetation in the area were not only used as rongoa but also formed part of a balanced diet and some are still eaten today. Puha (Figure 2.16), prickly puha (Figure 2.16) or sow thistle (Sonchus asper and Sonchus oleraceus) were two common herbs readily available after harvested forestry areas were burnt off to clear the land of slash before being replanted. This activity was common from the start of forest harvesting up until the 1970s to 1980s but is not considered good environmental practice and was discontinued many years ago. Nevertheless, puha is one of the first plants to reappear on open ground and is much loved by most members of the iwi so was a welcome addition to the diet in previous times. One koro remembered that the wider iwi would come to gather puha from the area after a burn-off. He also remembered everyone coming to gather watercress (Nasturtium officinale) from the Waikokomuka Stream that flowed past the singles men's camp (point 18, Figure 2.3), which was just past the old Waiotapu School. (point 26, Figure 2.3).

Since the prison camp was established, many exotic fruit trees were planted in the Waiotapu area by either the prisoners or families who settled in the village or surrounding area. Many kaumatua (NTNWRT 2021) remembered picking apples, pears and cherries from the trees as well as gathering blackberries and raspberries. Mint was also introduced in the early years of European settlement and a koro commented that it was particularly abundant along the banks of the Waikokomuka Stream (point 19, Figure 2.3). One kaumatua (NTNWRT 2021) also spoke fondly of collecting rosehips from wild roses which were eaten or used to make jam, jelly or cordial. Other foods the koro remembered gathering as a child were orange and blue coloured berries, which were unable to be positively identified, and the hearts or nuts of thistles (again, identification as to exactly which variety is unknown) and cabbage trees (Ti kouka).

Figure 2.16 Puha (Sonchus oleraceus) (Massey University 2020).

Prickly Puha (Sonchus asper) (Photo by Bendle 2021).

2.5.4 Geothermal Surface Features

2.5.4.1 Ngawha (Hot Pools)

Geothermal surface features are taonga (treasures) to our people. Many ngawha (hot pools) were used for cooking, bathing and spiritual purposes. Many of the kaumatua interviewed remember bathing in the hot pools and streams in the Waiotapu geothermal area however some of the pools were unable to be located during recent site visits, possibly due to the modification of the area for road improvements and forestry planting. Some of the hot pools that do still exist are now covered in weeds as the area is no longer frequented. This might be due to access impediments such as, the gate blocking access to the Lady Knox Geyser (point 5, Figure 2.2) where once popular swimming holes such as the Venus Pools (point 7, Figure 2.2) and the Spout (point 6 on Figure 2.2, Figure 2.17) are located, or because the iwi no longer live in the local vicinity. One kaumatua who grew up beside the old Ministry of Works depot (point 14, Figure 2.3) near Lake Ngahewa remembers bathing in the Spout and Venus Pools regularly (NTNWRT 2021). The Venus Pool was a particular favourite as it had a small pool where three to four people could sit comfortably and get acclimatised to the heat before getting into the larger pool, which was quite a lot hotter than the smaller one. As a child he was told it was bottomless and children had to hang onto a ledge beside the pool. This sparked the imagination of what could lay in the depths such as a taniwha (dragon) which definitely encouraged obedience. During one such visit in the 1960s, the kaumatua, his siblings and his mother were enjoying a bath when a tourist arrived and started taking photos of them in the water. He was duly sent off by a very angry mother who took great exception to her family being filmed performing such a private ritual. Another kaumatua also remembers going with her parents to the Venus Pool as her parents found it soothed their aching bodies after a hard day's work (NTNWRT 2021). She was told to hang on to the ledge in the big pool or she would end up in China. The water chemistry of Venus Pool is discussed in Section 3.4.2.

Another hot pool mentioned during an interview was accessed in the early 1960s by driving a short distance off State Highway 5 (point 1, Figure 2.2). The water feeding this small pool then flowed through a man-made pool built over the stream, before returning into the stream. The man-made pool was used for bathing and washing clothes as it was fed by a continuous stream of clean water. The small pool was used to scald pigs and chickens (immersing chickens in hot water for a very short time made them easy to pluck).

The Spout was another favoured pool that many kaumatua remembered fondly. This pool has a waterfall at one end so after using clay from the bank as soap, you could wash it off under the waterfall. The Spout has also become a little known but popular tourist attraction but it is seldom visited by tribal members as access is impeded by a gate managed by the lessee of the Tourist Park.

Another story from a kaumatua told of a pool near Lake Rotowhero (point 15, Figure 2.3) that was used by the whanau (families) in the area to wash clothes, which is no longer in use for this purpose due to the introduction of washing machines (NTNWRT 2021). When questioned, the kaumatua thought this particular pool (point 17, Figure 2.3) was used for the washing as the water may have been cleaner and clearer than others in the vicinity (the others nearby were a "bit greeny").

Since the introduction of exotic food species such as pigs and deer (and more recently wallabies), this area has been hunted by tribal members in order to supplement the family's diet. Hot pools throughout the area are still used regularly to scald the hair off pigs either by submerging them in the pool then scraping the hair off or historically, as shared by a kaumatua, by soaking a flour or sugar sack in the hot water then draping that over the pig to soften the skin before scraping the hair off (NTNWRT 2021). Wild pork was often boiled with either watercress or puha and potatoes, and is a meal that is still enjoyed by many to this day.

Hot water and hot mud were available in certain areas around Waiotapu and Waikite. One kaumatua recalls his father being employed by the Ministry of Works to build or maintain many of the roads in the area (NTNWRT 2021). When the men were doing the earthworks for the Waikite Valley Road, the child would fetch hot water from the Otamakokore Stream (point 24, Figure 2.4) to make tea to have with lunch. He remembered that the water was so hot there was no need to boil it and the tea could be brewed immediately. It was also favoured as it did not have a sulfur taste where some other hot water streams did. At Waiotapu there were certain holes in the bank on the side of the Old Waiotapu Road where eggs could be placed and in ten minutes they were "boiled" and ready to eat. These same holes were used to heat food as well so the men would put their lunch in a muttoncloth, place it in the hole and 10 minutes later it would be hot and ready to eat.

Figure 2.17 “The Spout” hot pool (NZ Hot Pools c2015).

2.5.4.2 Mud Pools

The mud pools in the area (points 2 and 3 on Figure 2.2, Figure 2.18) have long held a fascination for tourists who would visit and take photos of the plopping mud. This provided opportunity for tamariki (children) living in the vicinity to entertain the visiting tourists in return for money, as this was also their backyard playground. A kaumatua who grew up very near the Waiotapu mud pools recalls putting mud into jars and selling it to the tourists who would arrive by the bus load or performing traditional songs for a koha (donation) (NTNWRT 2021). Mud from the pools and surrounding some ngawha was also used medicinally to treat skin ailments and arthritis.

The mud pools were also used in a far less environmentally-friendly way as the same kaumatua recalled seeing one of the mud pools (point 3, Figure 2.2) used as a rubbish dump in the 1960s by the two government entities based in the area at the time, Ministry of Works and the New Zealand Forest Service. All manner of obsolete machinery and equipment were taken to the edge of the mud pool where they would then fall or be pushed into the pool and disappear forever. Other rubbish was also disposed of in the same manner and signifies the depth the mud pools must be if a whole grader or truck could disappear.

Figure 2.18 Mud pools at Waiotapu. Photos provided by NTNWRT.

2.5.4.3 Coloured Sands

Geothermal features were also where people would find coloured sands and clays. Maunga Kakaramea translates as “Mountain of coloured earth” (Figure 2.5) which helps explain how the following stories came about. Small bottles of coloured sand taken off the side of the maunga were sold as mementos of the area and one kaumatua shared a story of how her brother worked collecting sand off the maunga for the people operating the tourist centre at the time, which was then bottled or used to make pictures out of before being sold to tourist visitors (NTNWRT 2021). Her brother also assisted with starting the Lady Knox Geyser (point 5, Figure 2.2) by pouring soap flakes into it, which continues to the present day and guarantees that tourist visitors can see a geyser erupting at the same time every day. Another kaumatua remembers owning a picture of a geyser spouting which was made from sand (NTNWRT 2021). The lady who made the picture would also make lamp stands out of beautiful old bottles which she would fill with sand.

2.5.4.4 Clays

Other stories shared were about paru or black clay. One kaumatua remembers watching her mother-in-law collect the paru so she could dye the piupiu (e.g., Figure 2.19) she made (NTNWRT 2021). After a piupiu was made, parts of the piupiu that needed black highlights was scraped before soaking it in a bath of paru, after being primed in a bath of tutu (Coriaria arborea), manuka (Leptospermum scoparium) and blue gum (Eucalyptus globulus). After the paru was washed off the scraped parts would be dyed black (Figure 2.19). This correlates with another kaumatua’s recollection of how he had seen paru used by his mother (NTNWRT 2021).

Paru was also used in pre-European times to colour rock carvings and one kaumatua remembers seeing such art work near Tihoi on the western shores of Lake Taupo (NTNWRT 2021), however there are no sites documenting where this artwork exists within the two geothermal areas discussed in this report.

As previously mentioned, the Ngati Tahu-Ngati Whaoa people were actively engaged in commerce and trade. Food such as kereru, tuna and fish, as well as mineral commodities such as kokowai (red ochre or haematite) (Figure 2.20) were used for customary trade with other iwi. Kokowai in particular was often carried in backpacks to the east coast to trade with Ngati Kahungungu in exchange for pounamu. Kokowai could be dug from the ground or gathered from geothermal waterways around Maunga Kakaramea and Waiotapu. The right to dig kokowai could be purchased and at the time it was considered to be so valuable that one iwi member traded his wife in exchange for an ochre source near a thermal stream at Waiotapu. Before the kokowai could be used and regardless of where it was gathered, it was first prepared by being placed in the sun to dry, which took a long time and needed to be turned regularly, before being ground into a fine powder.

Figure 2.19 A piupiu showing the black lines that were traditionally dyed with paru (WorthPoint 2021).

Figure 2.20 Kokowai in its natural state. Photo from Te Ara with permission from Te Papa Tongarewa the Museum of New Zealand.

3.0 GEOSCIENCE

This section details the geology (rocks), geophysics (thermal and rock properties), thermal features, and chemistry of geothermal fluids in the Waiotapu area and presents a conceptual model for the Waiotapu-Waikite geothermal system. We also document the vegetation in the area that can be exclusive to thermal areas.

3.1 Regional Geological-Geothermal Setting

The Waiotapu Geothermal Field is one of 29 high temperature (>225°C) geothermal systems in the TVZ (Figure 3.1). The TVZ is a volcanically active region with numerous volcanic centres that extend ~250 km from Whakaari (White Island) to Ruapehu and active for the past ~2 million years (e.g., Wilson et al. 1995; Houghton et al. 1995; Wilson and Rowland 2016). Volcanism in the TVZ is dominated by large caldera-forming (collapsed) volcanoes (e.g., Lake Taupo) and cone-shaped stratovolcanoes (e.g., Mount Ngauruhoe). The volcanoes generate many different volcanic rocks types that include lava flows, ash deposits and pyroclastic deposits. Pyroclastic rocks are the product of fast, laterally-moving (up to 700 km/hr) clouds of hot gas and volcanic rock generated after the collapse of an erupted ash plume. Volcanic rocks are further classified based on their composition and minerals. The two main rock types in the TVZ are andesite (erupted from stratovolcanoes) and rhyolite (typically erupted from calderas). Rhyolite has more silica and the magma traps greater amounts of gas resulting in significantly larger and more violent eruptions generating widespread pyroclastic deposits. Dacite is rare and a rock type created by the mixing of andesite and rhyolite molten magmas prior eruption.

Geothermal systems in the TVZ occur in thick sequences (0.5 to >3 km) of volcanic rocks that are interlayered with minor lake (lacustrine) and river (alluvial) sediments. Both volcanic and sedimentary rocks overly a significantly older basement of metamorphosed sedimentary rock (sandstone and mudstone) of Mesozoic (>65 million years) age (Wilson et al. 1995). Magmas (molten rock) trapped at depth provide heat for the geothermal systems that consist of a large circulating cell of hot water (e.g., Figure 3.2). The deep fluid consists of meteoric (rain) water modified through interaction with the rocks and includes minor fluid and gases derived from the magma.

3.1.1 Geology of the Waiotapu Area

In the Waiotapu area, Maunga Kakaramea and Maunga Ongaonga are the most prominent land features (Figure 3.3). Both are volcanic dacite domes, which form a relatively small volume of volcanic rocks in the TVZ (~5 km^3; Figure 3.1; Reid and Cole 1983). Maunga Kakaramea, “mountain of coloured earth” is named after its distinct pink to dark red and greyish-white exposed rocks (Figure 2.5). The red colouration is from iron-oxide minerals (such as haematite) whereas the bleached greyish-white is from quartz and clay minerals (such as kaolinite). These minerals are the product of the interaction of hot geothermal steam with the rocks. The slopes of the maunga remain thermally active with steaming ground, but the amount of thermal activity here has lessened over the last 150 years (since 1870s; Hedenquist and Browne 1989).

Many different rock types (formations) occur in the Waiotapu area. Their surface occurrences are shown in Figure 3.3 and the different formations are summarised in Table 3.1. Exposed rocks mainly consist of flat lying pyroclastic deposits together with minor alluvial and lacustrine sediments plus domes of dacite and rhyolite lava (Grindley 1959; Lloyd 1959; Steiner 1963; Nairn 1973; Hedenquist 1983; Hedenquist and Henley 1985; Leonard et al. 2010). Pyroclastic rock deposits, known as ignimbrites, extensively cover the landscape, filling valleys and thinly mantling ridges. If the pyroclastic deposit is hot enough, the particles can fuse together on emplacement to produce hard, sheet-like deposits known as welded ignimbrite. When cooler, they form non-welded ignimbrites or deposits comprised of loose rock fragments (e.g., pumice breccias).

In the Waiotapu area there are at least 11 different ignimbrite units mapped (Figure 3.3; Table 3.1) (Leonard et al. 2010). These are distinguished based on crystal abundance, mineral types, types of included rock fragments (and abundances), degree of welding and their relationship to other rock types. The ignimbrites are sourced from at least five different volcanic centres, all from outside the Waiotapu area; some volcanic centres are known, and others are uncertain (Leonard et al. 2010; Downs et al. 2014). These volcanic centres have been active at different times and are commonly the source of multiple eruptions.

The oldest ignimbrite is the Akatarewa Formation ignimbrite (950 ± 50 Ka / thousand years) but the source is not known (Downs et al. 2014). The Waiotapu Formation ignimbrite is younger (710 ± 50 Ka) and is sourced from Kapanga Volcanic centre (Figure 3.1). Matahina Formation (322 ± 7 Ka) ignimbrite is from the Okataina Volcanic Centre, Mamaku Formation ignimbrite (~280–290 Ka) from the Rotorua Volcanic Centre and Kaingaroa Formation ignimbrite (281 ± 21 Ka) from the Reporoa Volcanic Centre (Downs et al. 2014). Unconsolidated pumice comprising the Taupo Pumice Formation forms the youngest ignimbrite, and was sourced from the Taupo Volcanic Centre (Figure 3.1) and erupted during the 232 ± 5 CE Taupo eruption. Between the layers of ignimbrite are layers of tuff and reworked (eroded) volcaniclastic material in addition to lacustrine sediments.

Interspersed within the ignimbrite sequence are volcanic lavas that form Maunga Ongaonga (825 m elevation), Maunga Kakaramea (743 m elevation), and Trig 8566 (592 m elevation) (Figures 3.3 and 3.4). Both Maunga Ongaonga and Maunga Kakaramea are dacite domes, whereas Trig 8566 is a rhyolite lava. Dacite lava from Maunga Ongaonga is dated at 154 Ka and the Trig 8566 rhyolite at 490 ± 3 Ka (Leonard et al. 2010; Downs et al. 2014).

The subsurface geology of the Waiotapu area is known from seven exploratory geothermal wells (Figure 3.4) drilled by the Ministry of Works between 1956 and 1959 to depth ranges of 450 to 1,100 m. An eighth 600 m deep well drilled in 1980, is located 2 km northeast of Maunga Kakaramea (Steiner 1963; Hedenquist and Browne 1989; Wilson et al. 2010). The subsurface geology is shown in Figure 3.5. These exploratory geothermal wells have intercepted at shallow levels many of the same rocks exposed at surface (e.g., Taupo Pumice Formation, lacustrine / fluvial sediments, Waiotapu Ignimbrite), but also other older ignimbrites sourced from the Mangakino Volcanic Centre (Ahuroa Ignimbrite: 1.18 ± 0.02 Ma; Ongatiti Formation ignimbrite: 1.21 ± 0.04 Ma; Wilson et al. 2010), and also the Ngakoro Andesite (~800 to 900 m below surface; Figure 3.5). The andesite is only known from these exploration wells and the source not known.

The Waiotapu area is dissected by several faults (Figure 3.3). Faults are fractures along which the ground has been displaced and are created by earthquake / tectonic activity. Structurally, the area is dominated by north-northeast oriented faults (Figure 3.3) that are parallel to the major structural trend of the TVZ (Leonard et al. 2010; and references therein). Major faults include the Paeroa Fault and the Ngapouri Fault. The Paeroa Fault extends for 30 km and in places is comprised of several closely spaced faults. Along parts of the Paeroa Fault there has been up to 500 m of vertical displacement exposing much deeper rocks in the exposed scarp of the upthrown block (Berryman et al. 2008). The Ngapouri Fault is a branching fault off the Paeroa Fault (Downs et al. 2014). Thermal features often occur aligned along the structural features, those at Waikite occur near the Paeroa Fault along a smaller fault possibly linked with the Paeroa Fault at shallow depths (Nairn 1973). Many hydrothermal eruption vents (described below) coincide with the Ngapouri Fault (Figure 3.4) (Hedenquist and Browne 1989).

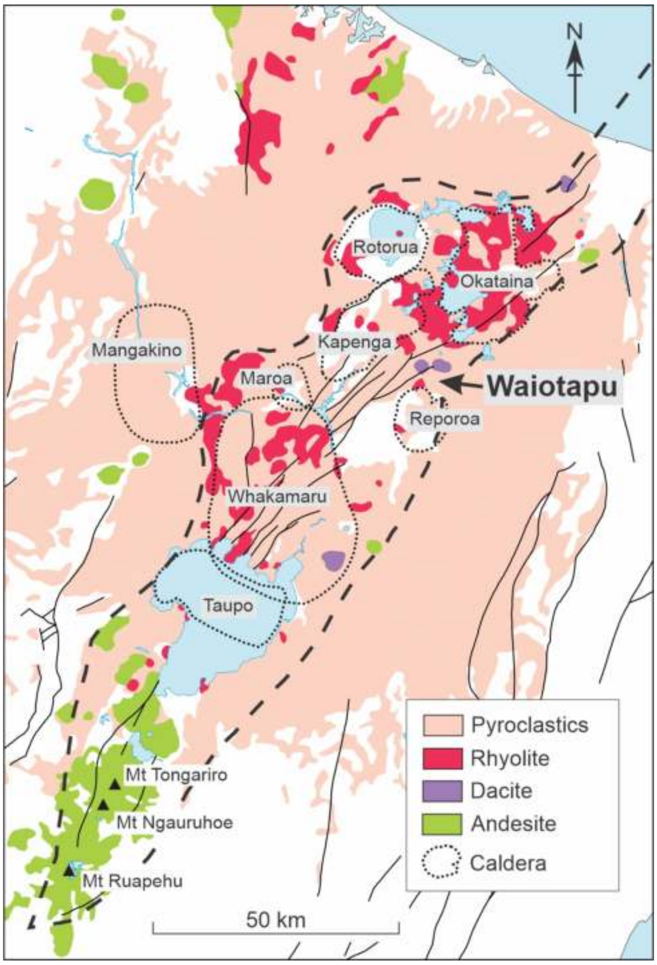

Figure 3.1 Simplified geology map of the TVZ (dashed outline) showing the location of major volcanic centres (calderas) and location of the Waiotapu Geothermal Field (Leonard et al. 2010).

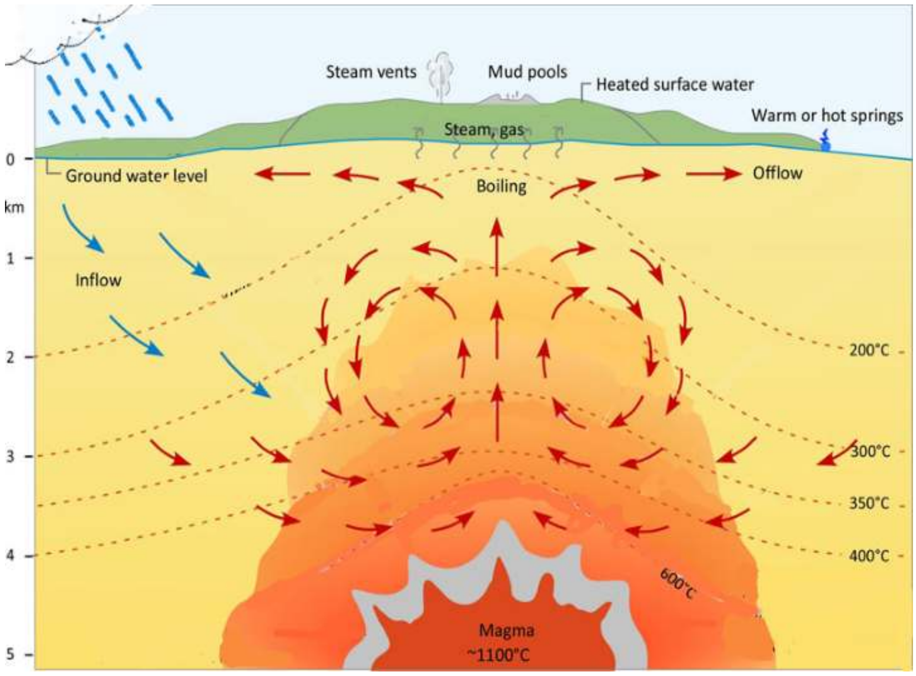

Figure 3.2 Conceptual model of a geothermal system with a magma heat source and water circulation pattern (Saemundsson 2014).

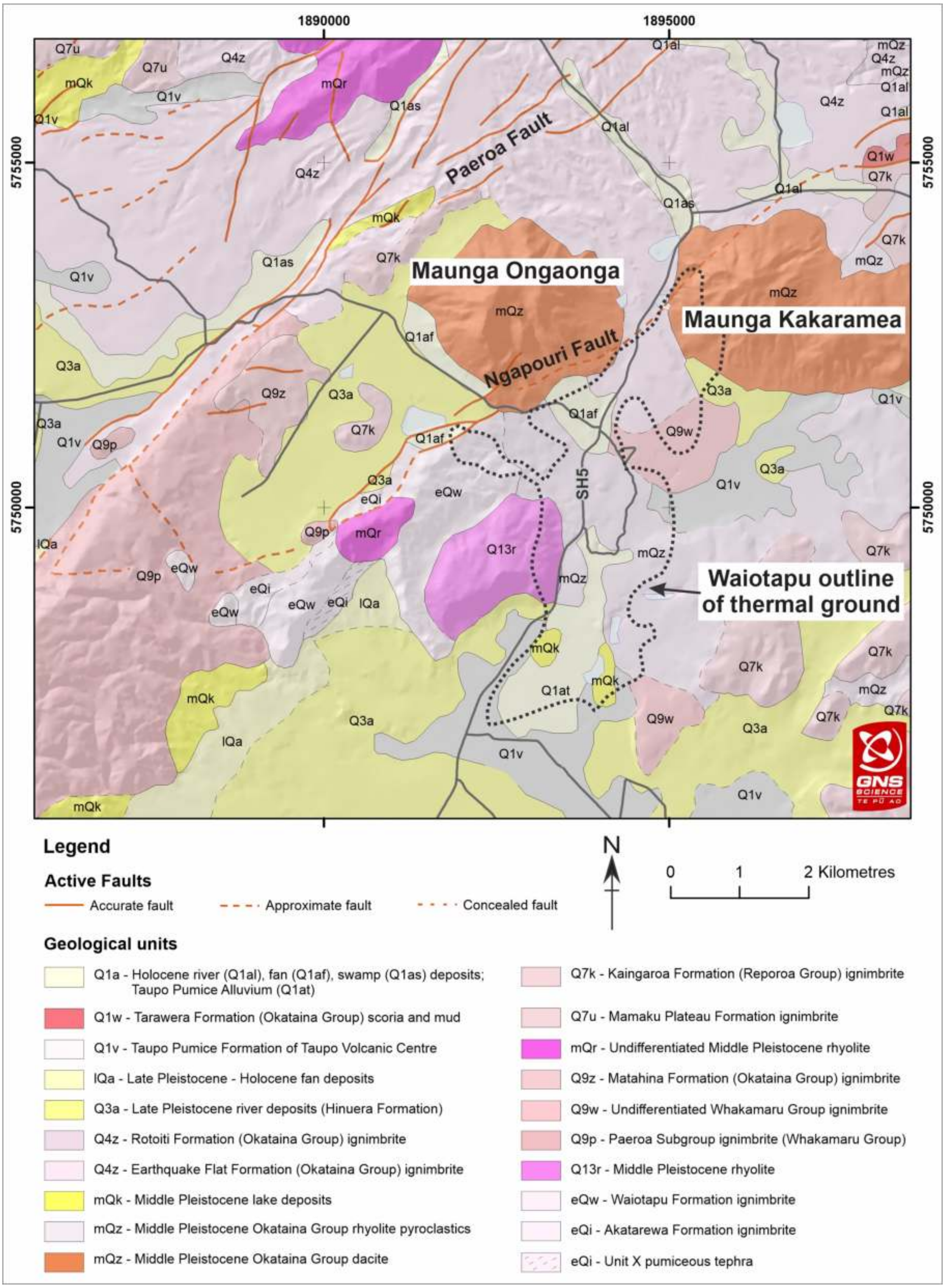

Figure 3.3 Surface geology map of the Waiotapu area showing different rock types overlain on shaded topography (Leonard et al. 2010). Active faults are also shown.

Table 3.1 Summary of rock units exposed at the surface in the Waiotapu area (data from Leonard et al. 2010 and reference cited therein). They are ordered from youngest to oldest. Ma = millions of years.

Unit Code	Stratigraphic Unit	Main Rock Type	Unit Description	Group	Volcanic Source Centre	Youngest Age (Ma)	Oldest Age (Ma)	Dating Method
Q1a	Holocene alluvium	Sand / silt	Alluvial gravel, sand, silt, mud and clay with local peat; includes modern riverbeds	Tauranga Group		0.000	0.012	
Q1w	Tarawera Formation	Mud	Scoriaceous lapilli (Scoria) and ash with some variable mud (erupted lake sediments); includes reworked sands and gravels	Okataina Group	Okataina Volcanic Centre	0.000	0.000	1886 (witnessed)
Q1v	Taupo Pumice Formation	Ignimbrite	Non-welded pumice breccia / ignimbrite and reworked pumice deposits from the 181 AD Taupo eruption	Taupo Group	Taupo Volcanic Centre	0.002	0.002	Radiocarbon
lQa	(Undifferentiated)	Sand / silt	Alluvial and colluvial (unconsolidated material at base of hillslopes) fan deposits of poorly sorted gravel, sand and clay	Tauranga Group		0.000	0.128	
Q3a	Hinuera Formation	Sand / silt	Alluvial deposit of layered pumice sand, silt and gravel with minor peat beds	Tauranga Group		0.012	0.027	Radiocarbon
Q4z	Earthquake Flat Formation	Ignimbrite	Non-welded rhyolite ignimbrite commonly with high crystal content and includes minor fall deposits	Okataina Group	Okataina Volcanic Centre	0.061	0.061	
Q4z	Rotoiti Formation	Ignimbrite	Non-welded rhyolite ignimbrite usually with moderate to high crystal content and includes widely dispersed fall deposits	Okataina Group	Okataina Volcanic Centre	0.061	0.061	
mQk	(Undifferentiated)	Silt	Silty, lacustrine sediments commonly diatomaceous (micro-fossils) with pumice, crystal and rhyolite rock fragments	Tauranga Group		0.128	0.524	
mQz	(Undifferentiated)	Ignimbrite	Non-welded to highly welded ignimbrite with minor fall deposits	Okataina Group	Okataina Volcanic Centre	0.128	0.524	
mQz	(Undifferentiated) Maungaongaonga dacite	Dacite	Dacite (dome) with pumiceous and breccia carapace (Maunga Ongaonga and Maunga Kakaramea)	Okataina Group	Okataina Volcanic Centre	0.128	0.524	

Unit Code	Stratigraphic Unit	Main Rock Type	Unit Description	Group	Volcanic Source Centre	Youngest Age (Ma)	Oldest Age (Ma)	Dating Method
Q7k	Kaingaroa Formation	Ignimbrite	Crystal- and generally pumice-poor ignimbrite with vapour-phase-altered top and includes minor fall deposits	Reporoa group	Reporoa Volcanic Centre	0.220	0.240	Ar-Ar
Q7u	Mamaku Plateau Formation	Ignimbrite	Pink to purple-grey welded and locally columnar jointed ignimbrite. Vapour phase altered and includes minor fall deposits	Ohakuri-Kapenga-Rotorua-Reporoa	Ohakuri, Kapenga, Rotorua volcanic centres	0.229	0.251	Ar-Ar
mQr	(Undifferentiated)	Rhyolite	Rhyolite lava with pumiceous and breccia carapace		Ohakuri, Kapenga, Rotorua volcanic centres	0.128	0.524	
Q9z	Matahina Formation	Ignimbrite	Unwelded to welded columnar jointed ignimbrite	Okataina Group	Okataina Volcanic Centre	0.315	0.329	Ar-Ar
Q9w	(Undifferentiated)	Ignimbrite	Complex sequence of partly welded, crystal-rich ignimbrites	Whakamaru Group	Mangakino Volcanic Centre	0.343	0.353	Ar-Ar
Q9p	Paeroa Subgroup	Ignimbrite	Three layered partly welded, crystal-rich ignimbrites	Whakamaru Group	Mangakino Volcanic Centre	0.343	0.353	
Q13r	(Undifferentiated)	Rhyolite	Rhyolite lava with pumice and breccia carapace		Ohakuri, Kapenga, Rotorua volcanic centres	0.487	0.493	Ar-Ar
eQw	Waiotapu Formation	Ignimbrite	Highly welded, crystal-poor, jointed, grey to brown ignimbrite with long distorted glassy fiamme		Mangakino Volcanic Centre	0.650	0.770	Ar-Ar
eQi	(Undifferentiated) 'Unit X'	Tuff	Crystal-lithic tuff / breccias with tuffaceous sandstone, siltstone and pumice tuff		Mangakino Volcanic Centre	0.524	1.810	
eQi	(Undifferentiated) Akatarewa unit	Ignimbrite	Poorly-welded pumice-rich ignimbrite		Mangakino Volcanic Centre	0.950		

The different rocks typically have formation names. However, there are some units that do not have official formation names (undifferentiated) with an informal name (i.e., Maungaongaonga dacite). Fiamme are lens shaped flattened pumice fragments that occur in welded ignimbrites. Ar-Ar = argon-argon dating method for determining the age of a rock. The age range is for the unit seen throughout the TVZ, but in specific area can have a set age. For example, Maungaongaonga dacite has a reported age range of 0.128–0.524 Ma but dacite lava from Maunga Ongaonga is dated at 0.154 Ma.

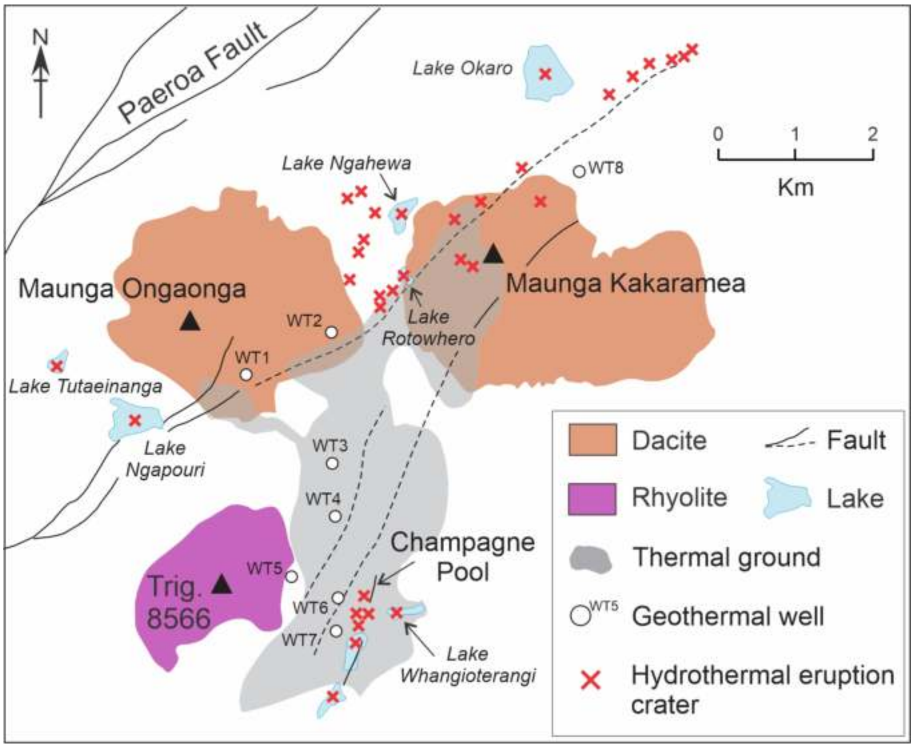

Figure 3.4 Locations of hydrothermal eruption craters and geothermal exploration wells in the Waiotapu area (modified from Hedenquist and Henley 1985). The grey shaded region outlines that area of thermal ground exposed at the surface.

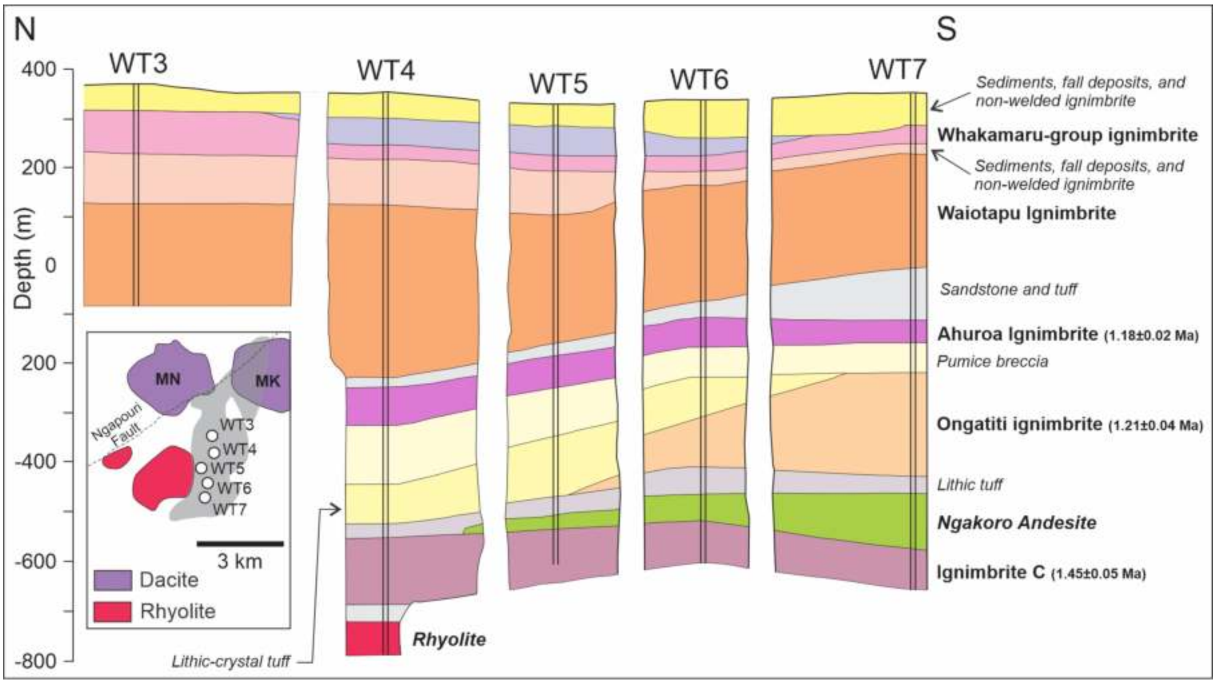

Figure 3.5 Cross-section for rock units intersected in geothermal wells WT3 to WT7, Waiotapu (modified from Wilson et al. 2010). Inset map shows surface location of the exploration geothermal wells in relation to surface geothermal features (grey area) and the dacite domes of Maunga Ongaonga (MN) and Maunga Kakaramea (MK).

3.1.2 Hydrothermal Eruption Breccias and Collapse Craters

In the Waiotapu area, there are many hydrothermal eruption breccias that have formed due to past and present geothermal activity. A hydrothermal breccia is a deposit of mud and clay with rock fragments of varying size that has formed via a violent steam eruption. The ejected fragmented rock material partly fills the source vent and blankets the surrounding area. The thickness of the breccia deposit and the size of rock fragments decrease away from the source vent with the vent often occupied by a pool or small lake filled by hot or cold water. Champagne Pool, Lake Okaro, Whangioterangi, Ngahewa, Rotowhero, Tutaeinanga and Ngapouri all occupy craters created by hydrothermal eruptions (Figures 3.4 and 3.6).

These and numerous other hydrothermal eruption craters (Figure 3.4) and associated breccia deposits have been recognised in the area with craters ranging from ~50 to ~700 m in diameter (Lloyd 1959; Hedenquist and Henley 1985). The Champagne Pool is the product of a hydrothermal eruption and is filled by hot alkali chloride waters (75°C) that occupy a sub-circular eruption crater / vent which is ~65 m in diameter and 62 m deep (Figure 3.6A). Breccia erupted from the Champagne Pool (Figure 3.6B) forms an oval-shaped deposit apron around the pool, and is 4 m thick at 30 m from the vent and nearly 1 m thick 200 m from the vent. This breccia and the resultant pool formed ~900 years ago (Hedenquist and Henley 1985).

Immediately north of the Champagne Pool is an area of altered steaming ground that has numerous craters, 5 to 30 m in diameter and 5 to 8 m deep. These craters are not eruption craters but collapse craters that form from acidic steam condensates dissolving the rock. Collapse craters are distinguished from hydrothermal eruption craters by the absence of ejected breccia aprons surrounding the crater (Hedenquist and Henley 1985; Browne and Lawless 2001). The most recent formed in 1968. Many are active features that continue to enlarge, but others are filling-in due to wall collapse.

3.1.3 Traditional Mineral Resources

Hydrothermal mineral alteration of the dacite rocks has resulted in the formation of Kokowai (or red ochre), which is visible as the red coloured rock surfaces on the slopes of Maunga Kakaramea. The red colouring is hydrothermal clay stained red by iron oxide minerals (haematite), a product of hydrothermal mineral alteration caused by geothermal steam.

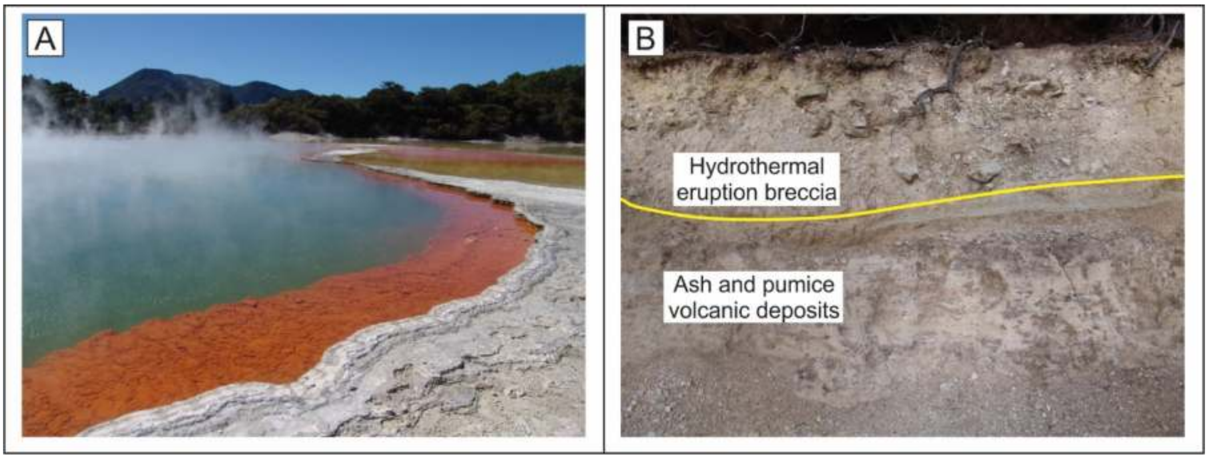

Figure 3.6 A) The Champagne Pool is the crater formed by a hydrothermal eruption ~900 years ago. It is a 62 m deep pool of hot alkali chloride water. B) A hydrothermal eruption breccia deposit directly adjacent to the Champagne Pool that formed during the hydrothermal eruption. It consists of large rock fragments supported in a mud matrix and overlies volcanic ash with pumice deposits. Images M.P. Simpson.

3.2 Geophysics of the Waiotapu- Waikite Area

This scientific discipline as applied to geological applications, uses properties of the earth such as its gravity, magnetic, and electrical fields, natural surface heat flow and radioactivity, to study physical processes and physical properties of the Earth, and space. This discipline can be applied at different scales ranging from very localised surveys through to planetary-scale depending on the issues to be resolved.

High-temperature geothermal fields (such as Waiotapu) make ideal targets for geophysical studies. Hot water and steam rising from depth result in conditions that are very different from non-geothermal areas. This can include increased heat flow which can be seen at the surface, (but also through warm groundwater bores) and mineral alteration of the rocks. Interaction of water or steam with the rocks changes their mineralogy (e.g., formation of clays) and this can change their electrical, electromagnetic, density and magnetic properties. Geophysics can also provide information on the larger geological structures that constrain the geothermal system. For example, techniques such as magnetics can provide information on where geothermal fluid has flowed. Volcanic rocks contain magnetite, which is a magnetic mineral, but this mineral is destroyed by interaction with hot fluids resulting in demagnetised (not magnetised) zones that can outline the geothermal system. This section summarises key geophysical surveys in the Waiotapu area.

3.2.1 Resistivity

Resistivity is the measure of how a specified material (in this case, rocks) resists the flow of an electric current. Alteration minerals (e.g., clays) and the presence of saline fluids (such as geothermal water) in pore spaces are two factors that can change rock resistivity. This can result in low-resistivity anomalies centred over high-temperature geothermal systems. These types of anomalies have been well documented and are fundamental in assisting geoscientists to help define the extent of geothermal systems in New Zealand (e.g., Risk et al. 1970, Bibby et al. 1992, Bibby et al. 1984). A number of electrical techniques are available (e.g., Schlumberger, bipole-dipole) that are designed to investigate the resistivity of the rocks at different depths and target structures.

Bibby et al. (1994) present the results (and a discussion of the limitations) of two Schlumberger resistivity survey over the Waiotapu / Waimangu / Waikite / Reporoa areas. These have estimated penetration depths of 300 to 700 m. Risk et al. (1994) also reports a resistivity (bipole-dipole) survey investigating the deep (estimated penetration depth to a few kilometres) resistivity structure of the Waiotapu area. However, ambiguities in the results of this survey (e.g., low resistivity due to geothermal activity verses low-resistivity background geology) make the results difficult to interpret at depth.

Results of the Schlumberger resistivity traverses throughout the TVZ (including the surveys above) have been summarised by Stagpoole and Bibby (1998a and b) and are presented in this report (Figures 3.7 and 3.8). Resistivity traverses enable lateral changes in the resistivity at approximately the same depth to be identified and can provide boundary control of the geothermal areas at relatively shallow depths (depending on the electrode spacing).

Key features of the resistivity surveys in the Waiotapu area (from Bibby et al. 1994) include:

- The extent of the low resistivity area associated with geothermal surface features is the largest found in the TVZ.
- The Waimangu, Waiotapu and Reporoa Geothermal Fields are enclosed all within the same 30 Ω-m low resistivity anomaly.

- The boundaries of the geothermal fields (e.g., Waiotapu, Reporoa, Waimangu) are probably masked by subsurface flows of geothermal water.
- The resistivity data suggests that geothermal surface features at Waikite are probably as a result of an outflow from the Waiotapu Geothermal Field.

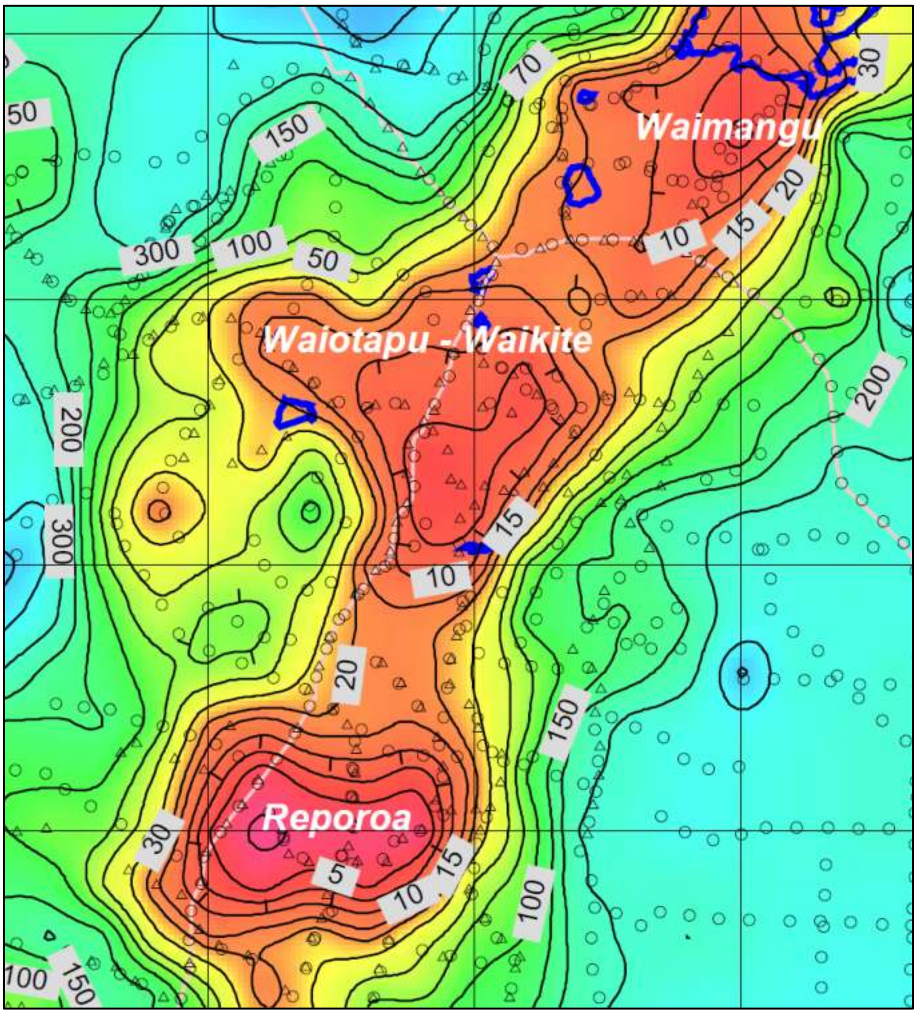

Figure 3.7 Schlumberger apparent resistivity survey over the Waiotapu/Waimangu/Waikite/Reporoa areas at AB/2 = 500 m (modified from Stagpoole and Bibby 1998a). This provides estimated resistivities at approximately 300 m depth. Note that apparent resistivity contours are not at a linear scale. For scale, grid lines are 5 km apart.

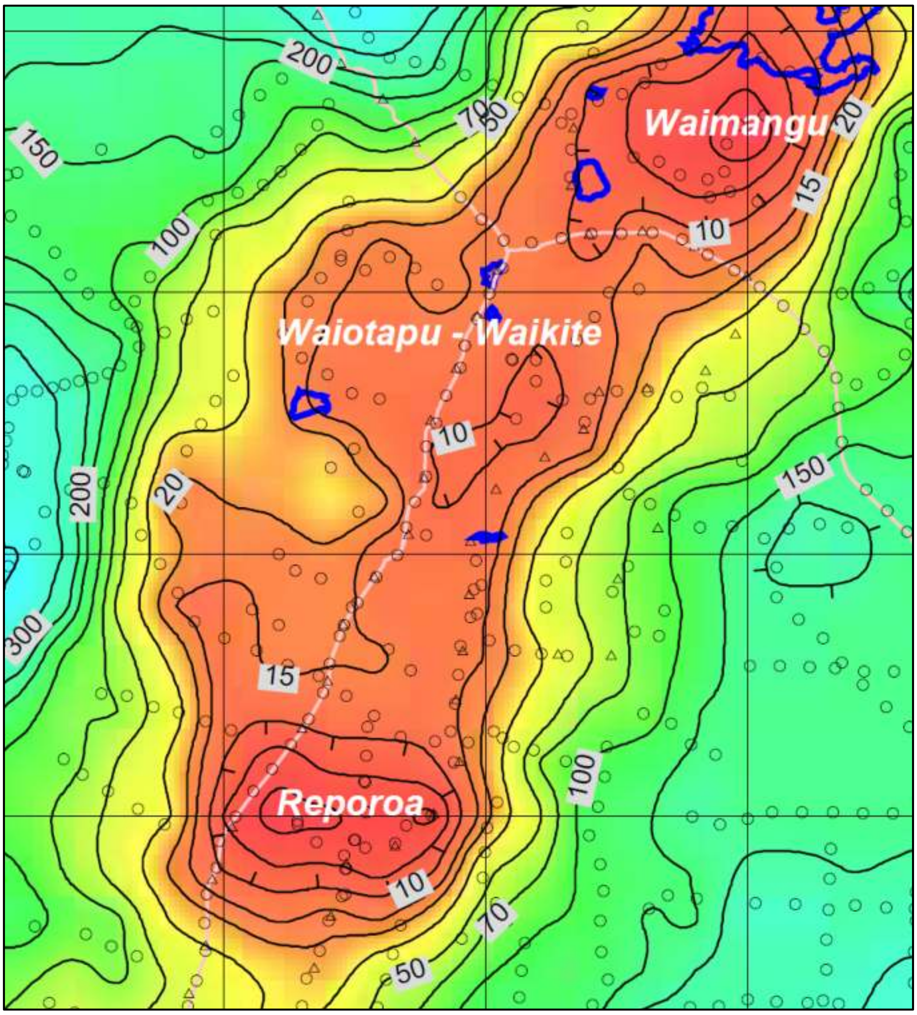

Figure 3.8 Schlumberger apparent resistivity survey over the Waiotapu/Waimangu/Waikite/Reporoa areas at AB/2 = 1,000 m (modified from Stagpoole and Bibby 1998b). This provides estimated resistivities at approximately 700 m depth Note that apparent resistivity contours are not at a linear scale. For scale, grid lines are 5 km apart.

3.2.2 Magnetotellurics

The word “magnetotellurics” has two parts – “magneto” for magnetic and “telluric” for earth currents. This translates to meaning a method that measures magnetic and electrical fields that are found in the Earth and can be used to measure resistivity in the subsurface.

Magnetotellurics (MT) is an electromagnetic technique used to infer the earths resistivity structure by measuring alternating magnetic fields and their respective inducted electrical currents in the earth. Investigation depths range from about 300 m to >10 km depending on the frequencies and the quality of data that is measured. Although most MT surveys use the natural variations in the earth’s magnetic field as the source signal, it is possible to “make” signal using specialist equipment. This variation, called Controlled-Source Audio-frequency Magnetotellurics (CSAMT), uses only the higher frequencies (>10 Hz) and is designed to investigate the near-surface (100–1,000 m) only. The MT/CSAMT technique is used widely for geothermal, hydrocarbon and mineral exploration. It has been used extensively on commercially developed geothermal fields in New Zealand to map the 3D nature of the geothermal reservoir and inform drilling targets for geothermal power production (e.g., Heise et al. 2008, Boseley et al. 2010).

Although no comprehensive published MT/CSAMT survey has been done in the Waiotapu area, several studies in the region are worth mentioning. Heise et al. (2016) presents the results of a northwest/southeast oriented MT survey that covers the Rotorua city – Waimangu area, to the north of Waiotapu. Immediately to the south, Walter (2014) presents an MT survey of the Reporoa Caldera. The few MT sites measured in the Waiotapu area were used to help constrain the Reporoa MT model. Ingham (2005) presents a deep (up to 10 km) MT survey along a line approximately 125 km long from Murupara to Tirau. The profile contains only 18 sites, so a detailed analysis of the Waiotapu area is not presented.

Bromley (1993) used a CSAMT and resistivity survey to investigate a possible hydrological link between the Waikite and Te Kopia Geothermal Fields along the Paeroa Fault. The survey showed a possible link based on a low resistivity zone at about 600 m depth that correlates with a zone of hydrothermal alteration and fractured rhyolite tuffs in a nearby borehole. This shows that the extent of geothermal fluids may extend beyond currently mapped geothermal field boundaries and will need to be considered when managing these geothermal systems. Further work is required to confirm the potential link between Waikite and Te Kopia.

3.2.3 Magnetics

Magnetic surveys are a geophysical method to image anomalies in the earth's magnetic field caused by magnetic source bodies within the sub-surface. The total magnetic field measured at a point of the earth is a combination of the earth's magnetic field (regional field) and those caused by local rocks (local anomalies). Magnetism in local rocks can be caused by ferromagnetism (magnetic minerals in the rock that create their own magnetic field) and remnant magnetism (magnetism of the rock that is "frozen" into the rock at the time of formation). In geothermal areas, it is possible for magnetised rocks to become demagnetised due to the destruction of magnetic minerals caused by the interaction with hot water or steam.

Magnetic surveys are usually collected over large areas so that maps of magnetic intensity can be made. This is usually done using specialist equipment attached to an aircraft to fly lines over the area of interest. This results in large datasets that need to be processed. Magnetic data can be modelled to derive rock magnetisation models whereby rock type, structure and areas of hydrothermal alteration can be interpreted. However, like most geophysical modelling, there are many models that fit the data and usually a best model is presented based on the data, other data (such as geology and other geophysical datasets) and the author's experience.

A key factor that influences these measurements is the inclination of the earth's magnetic field (which depends on the magnetic latitude, Figure 3.9). This needs to be considered in the data processing so that magnetic anomalies can be accurately identified. This is generally done by applying a mathematical correction to the data known as "Reduced to Pole" (RTP), which adjusts the data as if the measurements were taken in a vertical magnetic field (as occurs at the north and south magnetic poles). The RTP correction ensures that magnetic anomalies occur directly beneath the anomaly as presented on the map.

Hochstein and Soengkono (1997) present a summary of airborne magnetic surveys in the TVZ and should be referred to for historical surveys. Soengkono (2015) presents a revised magnetic map for the eastern part of the TVZ based on high resolution airborne data collected in 2005.

Soengkono (2015) presents data reduction (Figure 3.10) and 3D modelling (Figures 3.11, 3.12 and 3.13) of high-resolution magnetic data along selected lines. Key findings of this work in the Waiotapu area include:

- The Waiotapu Geothermal Field only has a moderate intensity of hydrothermal demagnetisation that mostly occurs at depth (from approximately 1 km deep).
- A northwest/southeast trending low-magnetisation zone occurs between -1,100 and -2,600 m below sea level (RL) from the western part of the Waiotapu area to Waikite (Figure 3.11). This may represent a demagnetised zone as part of a larger structural feature such as a caldera edge.
- The above demagnetised zone appears not to follow the direction of the Ngapouri Fault Zone. This is not what might be expected if the fault zone was the permeable path for supplying geothermal fluids from depth.

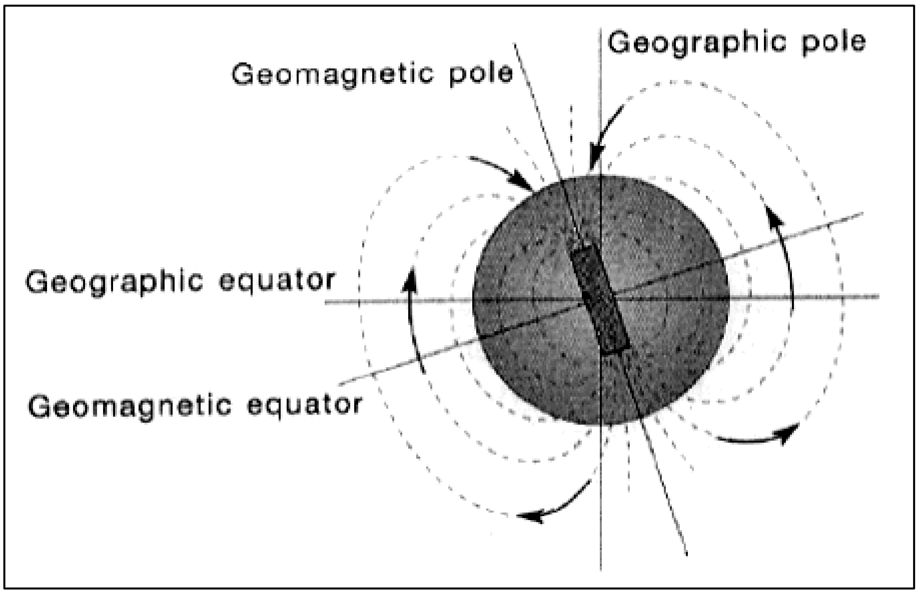

Figure 3.9 Generalised magnetic model of the earth (from Universidad Nacional de Colombia (UNAL) 2019). Dashed lines are equipotential magnetic field lines (lines of equal magnetic potential). Note the change in angle of these lines at the poles (90 degrees at the magnetic poles) compared to the geomagnetic equator (0 degrees). This angle is the inclination of the magnetic field.

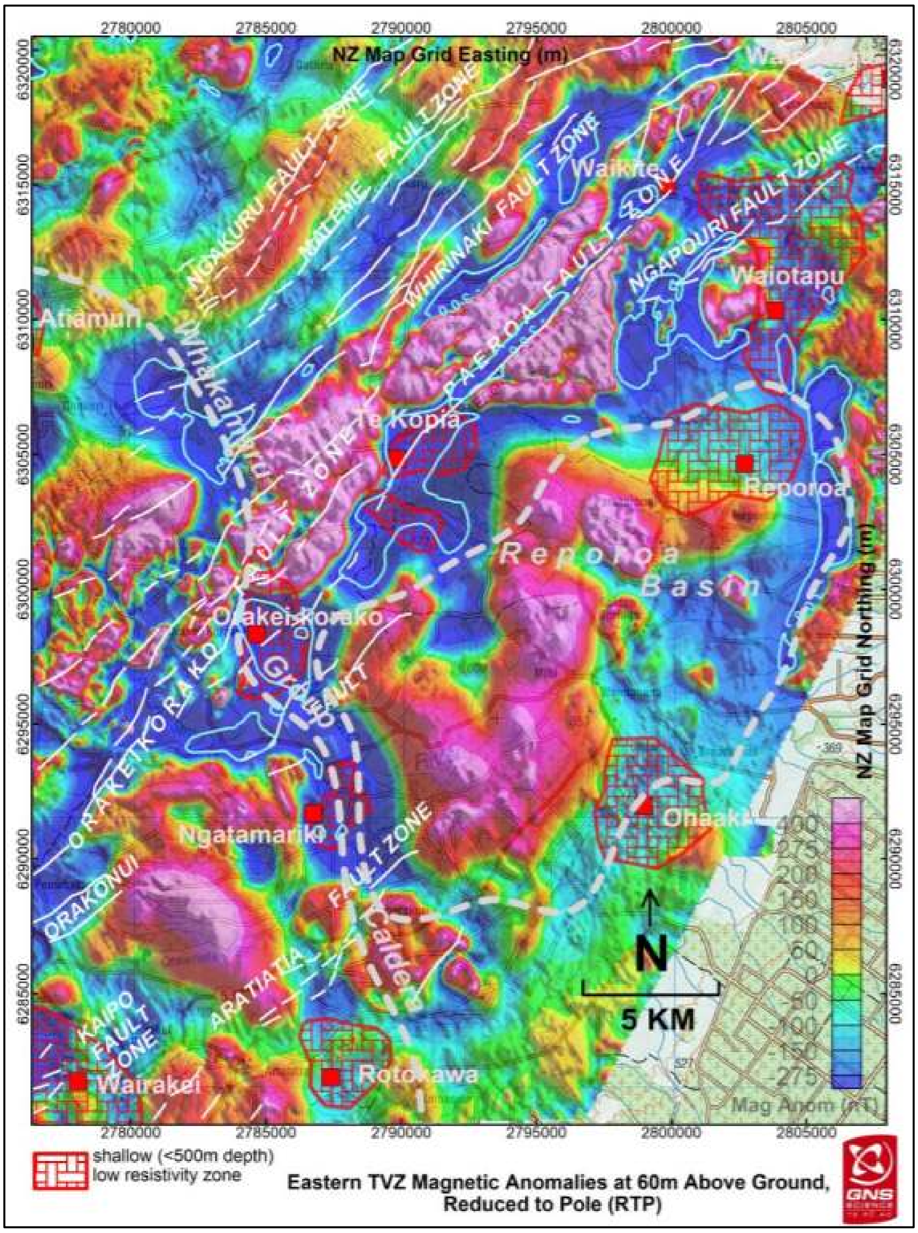

Figure 3.10 Eastern TVZ magnetic anomalies (from Soengkono 2015).

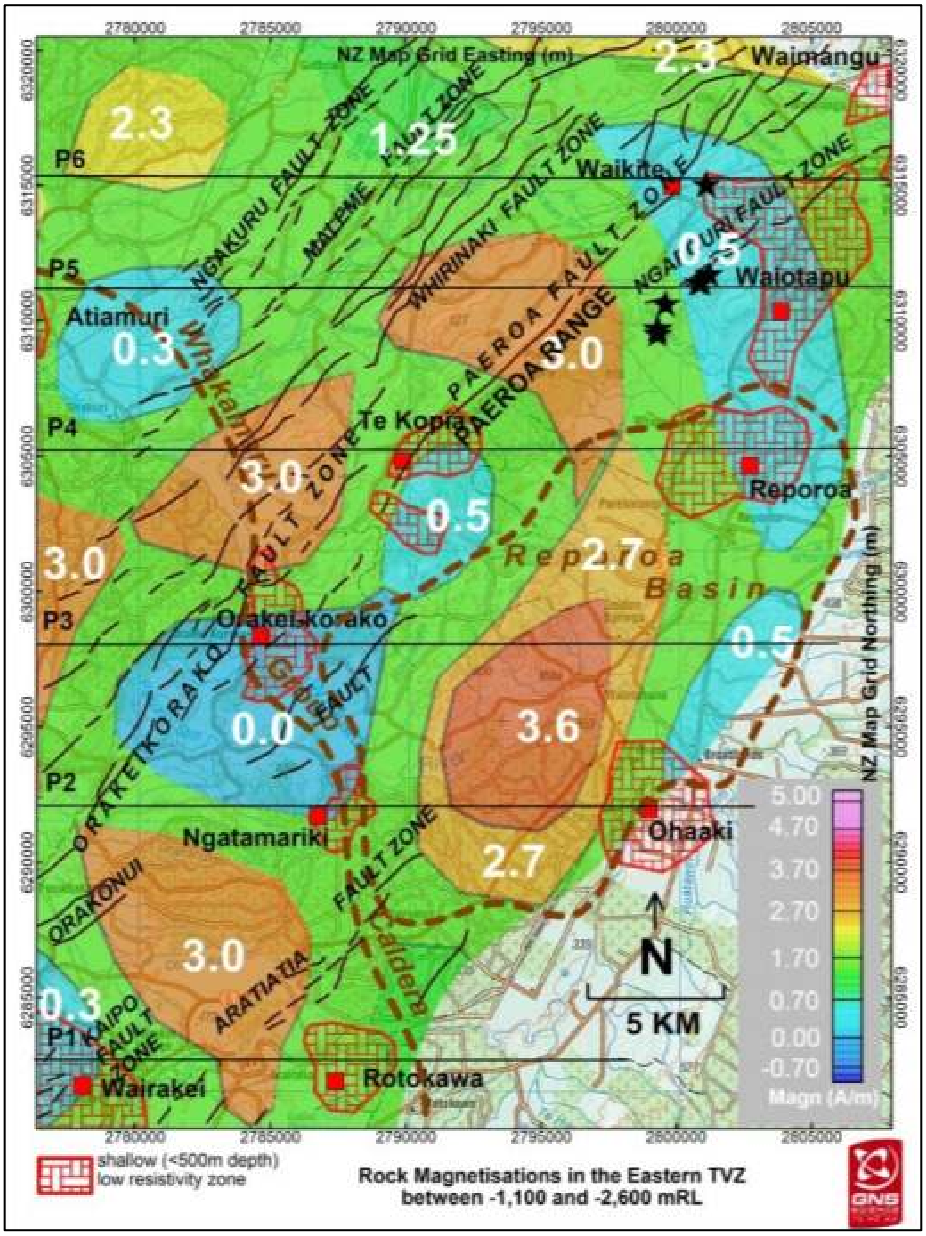

Figure 3.11 Modelled rock magnetisation at approximately -1,000 to -2,600 m RL (from Soengkono 2015). Solid black stars near south-western edge of Ngapouri Fault Zone represent surface locations of reversely magnetised rocks (Grindley et al. 1994).

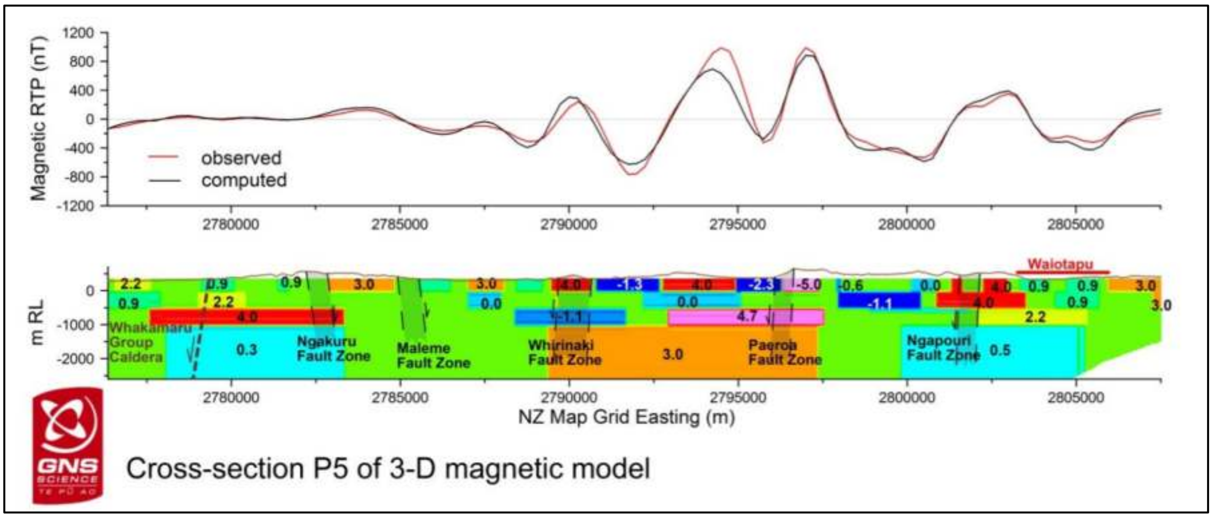

Figure 3.12 Modelled magnetisations along Profile P5 (See Figure 3.11 for location). Magnetisation is in A/m (from Soengkono 2015).

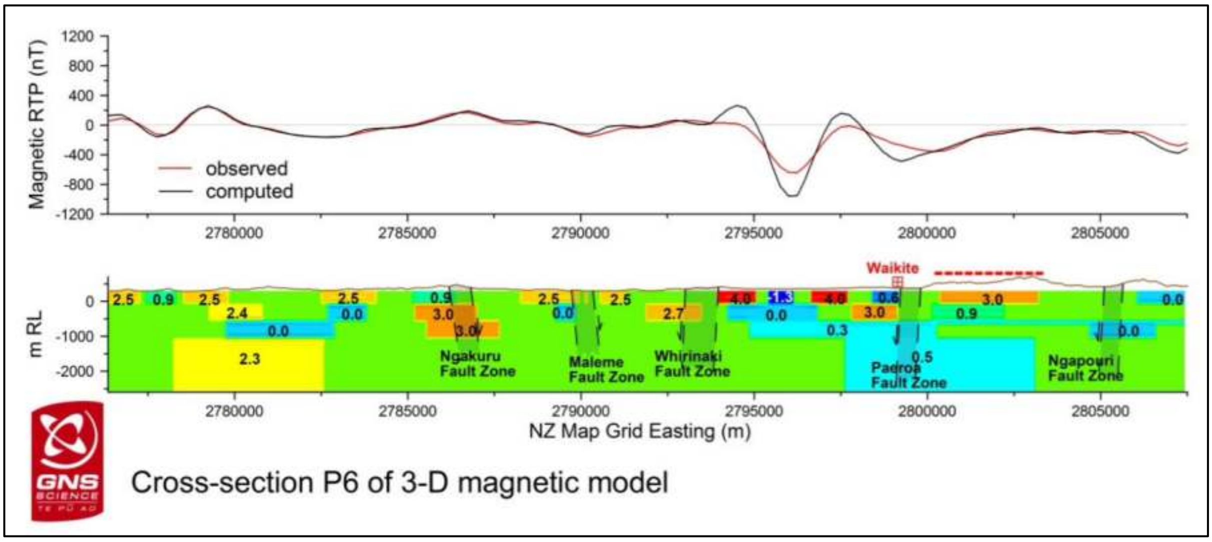

Figure 3.13 Modelled magnetisations along Profile P6 (See Figure 3.11 for location). Magnetisation is in A/m (from Soengkono 2015).

3.2.4 Heat Loss

Estimating heat loss from a geothermal field provides an indication of thermal activity present in the geothermal system at depth. Geothermal surface features (such as hot springs, pools and hot ground) occur where geothermal fluids discharge at the surface. Changes in the activity of the geothermal surface features over time can indicate changes that may be occurring within the geothermal reservoir due to either natural or anthropogenic (human) causes. Measurements of heat loss can be used as a proxy to monitor the combined / collective heat discharge from large areas. Heat loss monitoring can reveal when and where large-scale changes in the thermal regime (aquifer pressure and temperature) are occurring within a geothermal system.

Estimating heat loss over an area is invariably difficult to calculate. Factors that will affect calculations include climatic conditions during the survey, the method used (discussed below), and, the ability or otherwise to make measurements at every geothermal feature (due to health and safety, and/or, time constraints). Heat loss over an area is estimated by adding up the separate contributions of each thermal feature. Components that need to be considered in geothermal areas include:

- Heat loss from pools through evaporative and radiative processes.
- Heat loss from streams and hot springs.
- Heat loss from heated ground.
- Heat loss from fumaroles.

Measurements required to estimate heat loss for the above thermal features can include water temperature, water flow rates, surface area of the pools, climatic data (e.g., air temperature, wind speed), ground temperatures, ground temperature profiles with depth, calorimeter measurements and water chemistry (to use the mass-balance methods).

Benseman et al. (1963) estimates that the natural surface heat flow from the central Waiotapu area is approximately 560 MW (for context, equivalent to the power usage for approximately 540,000 homes) which includes an estimate of 20 MW from the Maunga Ongaonga area (Lloyd 1963). This is mostly based on estimates from water discharges, evaporation and heated ground. Bibby et al. (1995) summarise the pre-1995 heat flow assessments of the Waiotapu area. They estimate the heat flow from the Waiotapu Valley is between 195 MW and 300 MW using the chloride heat flux method (a method that uses water chemistry). This method underestimates heat flow (compared to the Benseman et al. 1963) because it is possible not all the chloride water makes its way into the surface (i.e., may be involved in recirculating).

The Waikite thermal area is largely aligned northeast-southwest, and discharges into the Otamakokore Stream. Healy (1952) and Glover et al. (1992) both estimate heat loss to be about 40 MW using mass/temperature and chloride fluxes. However, these estimates do not include conductive or evaporative heat losses which can be significant. Healy estimated heat loss from the main springs, middle and northern groups of features to be 81 MW. Harvey et al. (2016) also estimates heat loss from Waikite to be approximately 86 MW, thus presenting a relatively consistent total heat loss estimate for this area.

The quantified natural heat loss from the combined Waiotapu and Waikite geothermal areas are significant in a New Zealand context because their combined heat loss is the second highest geothermal system in New Zealand (Figure 3.14). Only the Waimangu-Rotomahana geothermal system loses heat faster than Waiotapu-Waikite. Both systems are classified as “protected” under their respective regional plans administered by both the Bay of Plenty Regional Council and Waikato Regional Council, indicating that changes to heat flow over time must be due to natural changes. The high heat flow manifests as significant areas of surface thermal activity that has resulted in these systems having the largest geothermally influenced ecosystems in New Zealand.

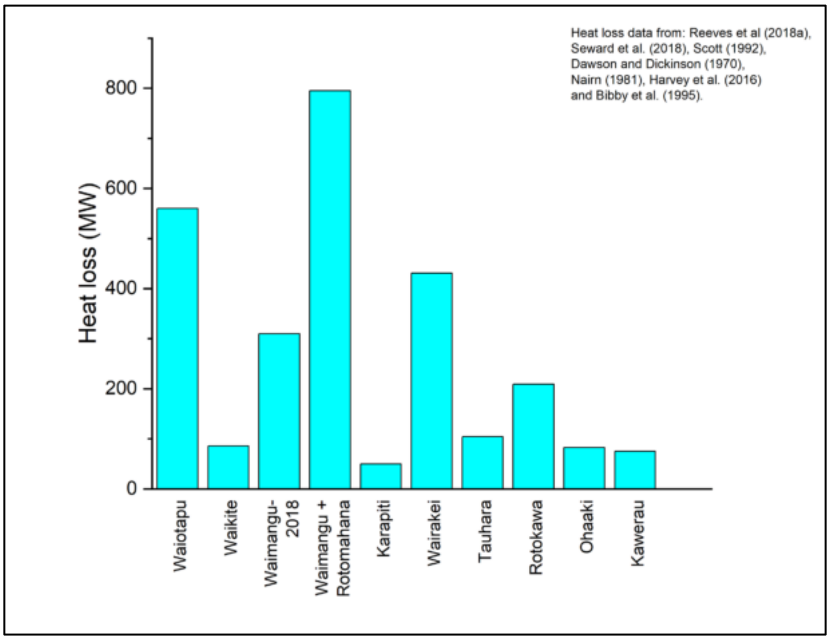

Figure 3.14 Heat loss estimated for Waiotapu and Waikite and other New Zealand geothermal fields.

3.2.5 Thermal Infrared Surveys

Aerial thermal infrared (TIR) surveys of geothermal areas have been used for identifying and monitoring surface geothermal features for over 28 years in New Zealand (e.g., Mongillo 1994; Mongillo and Bromley 1990; Reeves and Macdonald 2018). The technique is based on the principle that objects having temperatures above 0° Kelvin (-273.15°C) emit TIR radiation with energy dependant on temperature. The differences in thermal (heat) activity between hot/warm geothermal surface features (e.g., hot pools, springs, mud pools) compared to background temperatures (e.g., pasture, forest) in geothermal areas enable these features to be readily identifiable, and in some cases, enable temperatures to be obtained. A key limitation of the technique is that the thermal photographs that get taken only measure TIR radiation from objects that can be seen by the camera. It cannot see below the ground surface, and objects between the ground and the camera can affect the TIR image (e.g., steam that absorbs TIR radiation).

Aerial TIR data is generally collected by mounting a specialist camera to an aircraft that can detect the thermal bands of the electromagnetic spectrum rather than the visible parts as would be recorded by a normal camera. There are generally three ways of collecting Aerial TIR data:

- Satellite. Some satellite imagery contains the thermal bands that can be used to identify thermal features. Unfortunately, publicly available TIR imagery is relatively course (ground pixel size of approximately 30 m x 30 m) making detailed assessments of geothermal areas impossible. This data is not discussed in this report.
- Aircraft. This could include a light aircraft or helicopter. This method enables large areas to be covered (e.g., geothermal field – scale) in relatively short amounts of time. Typical ground pixel sizes for these surveys range from 0.7 m to 2 m.
- Unmanned aerial vehicles (UAVs). UAVs (or sometimes known as drones) enable smaller areas to be flown quickly and can provide ground pixel sizes down to the centimetre scale. Caution should be used when using this data as although high-resolution data can be collected, mosaicking images (i.e., joining images to make a single map) can be problematic at high resolutions and require many ground control points to be reliable.

Mongillo (1994) presents the first aerial TIR survey of the Waiotapu and Waimangu Geothermal Fields from a light aircraft. The TIR images had a 3 m x 3 m ground pixel size over the study area. This survey was able to identify geothermal features, seeps and springs in the Waiotapu area. This survey did not cover the Waikite area.

Reeves and Sanders (2019) conducted an aerial TIR survey over the Waiotapu Geothermal Field in 2019 (Figure 3.15) with a published ground pixel size of 2 m x 2 m. This survey uses a different technology (Helicopter with an advanced TIR camera), resulting in higher ground resolution, wider temperature range (the previous survey was limited to a maximum temperature of about 80°C), and provides a TIR file suitable for geographic information systems (e.g., for mapping applications). The imagery clearly showed higher temperature anomalies associated with geothermal activity.

Harvey et al. (2016) presents an aerial TIR survey of the Waikite Geothermal Field and uses this data to estimate heat loss (see Section 3.2.4). The TIR imagery was collected over a two-week period using a TIR camera attached to a UAV. Images were mosaicked resulting in high-resolution visual and TIR images (Figure 3.16).

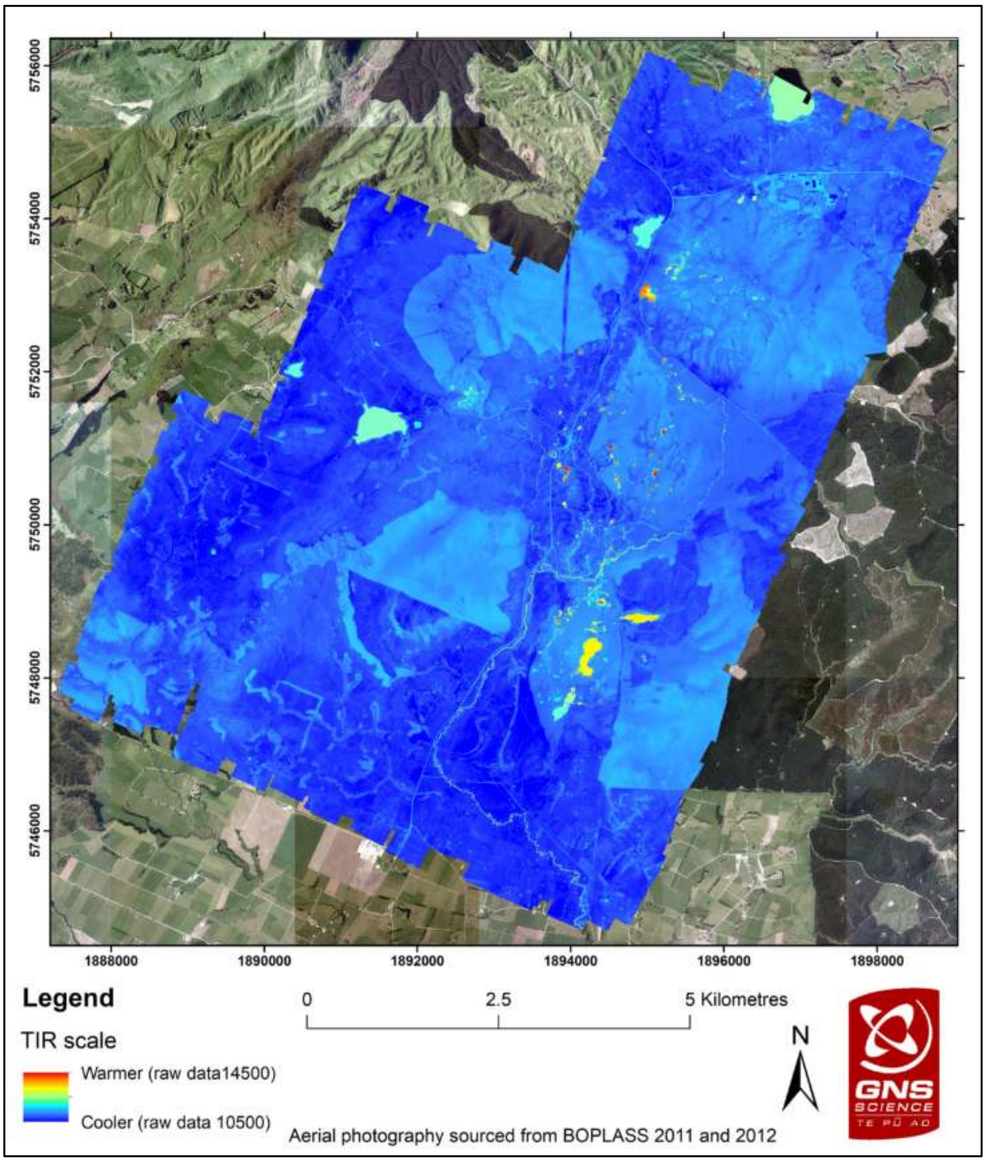

Figure 3.15 False colour 2019 TIR image of the Waiotapu Geothermal Field (from Reeves and Sanders 2019).

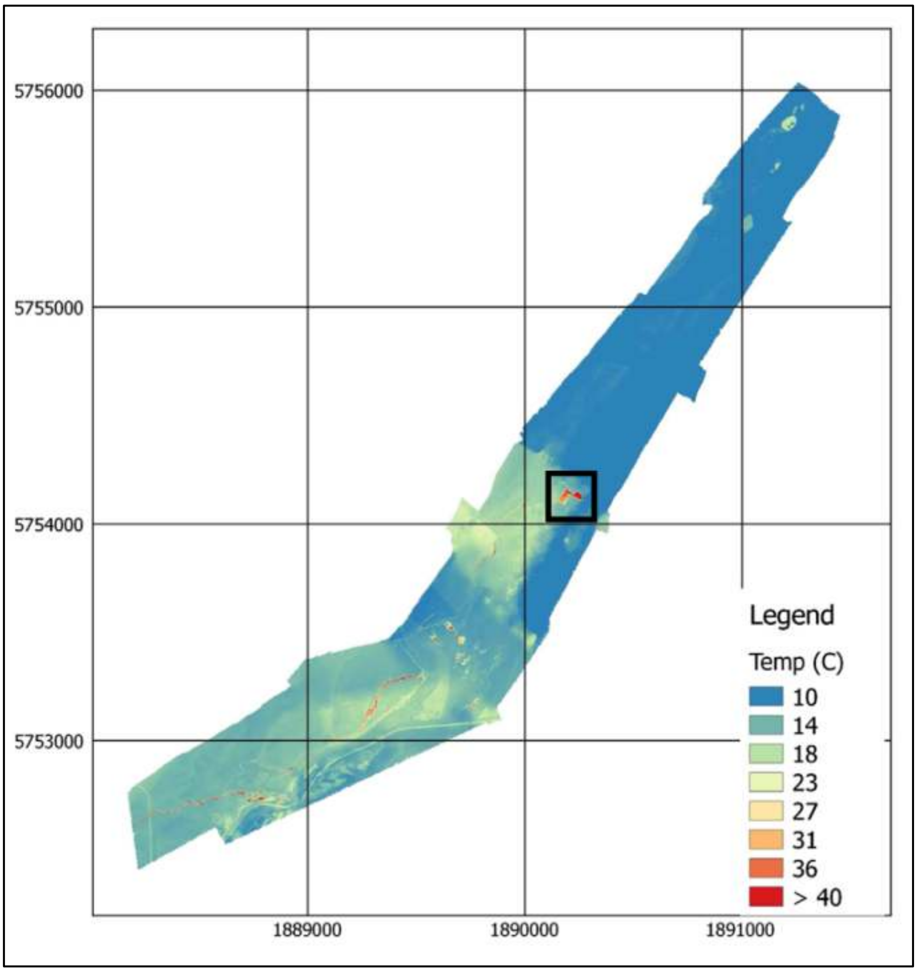

Figure 3.16 False colour image of the 2015 TIR image of the Waikite Geothermal Field (from Harvey et al. 2016). For scale, grid lines are 1 km apart.

3.2.6 Geophysics Summary

A lot of geophysical data and interpretations are available for the wider Waiotapu area. These studies range from regional studies (such as magnetics, MT and resistivity) through to more localised studies (e.g., TIR, heat flow). These studies provide insight into the larger geothermal processes and structures that help us understand what is happening below, and at the ground surface.

3.3 Geothermal Surface Features

Different types of geothermal surface features occur over New Zealand geothermal fields. These include geysers, springs, mud pots (or pools) and heated ground. The surface expressions of geothermal fields have intrinsic value that include tourism, cultural values and ecosystem support (e.g., thermotolerant vegetation). Increasing demands on optimising resource utilisation and land use can impact geothermal surface features in areas where development or land use change is occurring.

Scott (2012) divides active geothermal surface features into 12 key types (Table 3.2). The features are grouped by energy of the feature and by the types of fluids/processes that form the feature. This can range from high-energy, primary fluids (the fluids from deep in the geothermal system that make it to the surface) discharging as geysers, through to the low-energy heated ground caused by conduction of heat to the surface by either boiling or warm water under the ground. Figure 3.17 presents a conceptual model of the different types of geothermal fluids and processes that can take place in geothermal fields resulting in the types of geothermal surface features that can typically be seen. Key factors that will influence the type of surface feature include geothermal fluids interacting with groundwater, boiling of geothermal fluids and the types of permeable pathways that enable geothermal fluids to flow to the surface.

This section summarises key work that has been published on the surface features at Waiotapu and Waikite and focusses on the active geothermal feature types described in Table 3.2. Hydrothermal eruption craters are not discussed here since they have been detailed previously in Section 3.1.2, though many are now sites through which thermal waters discharge.

Table 3.2 Schematic representation of the key active geothermal surface feature types (after Scott 2012).

Discharge energy				
High	1. Geysers	4. Intermittent or active hydrothermal eruption craters	7. Mud geysers	10. Fumaroles
↕	2. Flowing springs	5. Mixed springs	8. Ejecting mud pots	11. Steaming ground
Low	3. Non flowing pools	6. Mixed pools	9. Mud pools	12. Heated ground
	Primary geothermal fluid	*Mixed/diluted geothermal fluid*	*Mixed/diluted steam heated fluid*	*Steam Fed*
Geothermally-influenced aquatic habitat				
Geothermal habitat on heated/acid dry ground				
Habitat dependent on geothermally-altered atmosphere overlays all types (warm air, frost-free)				

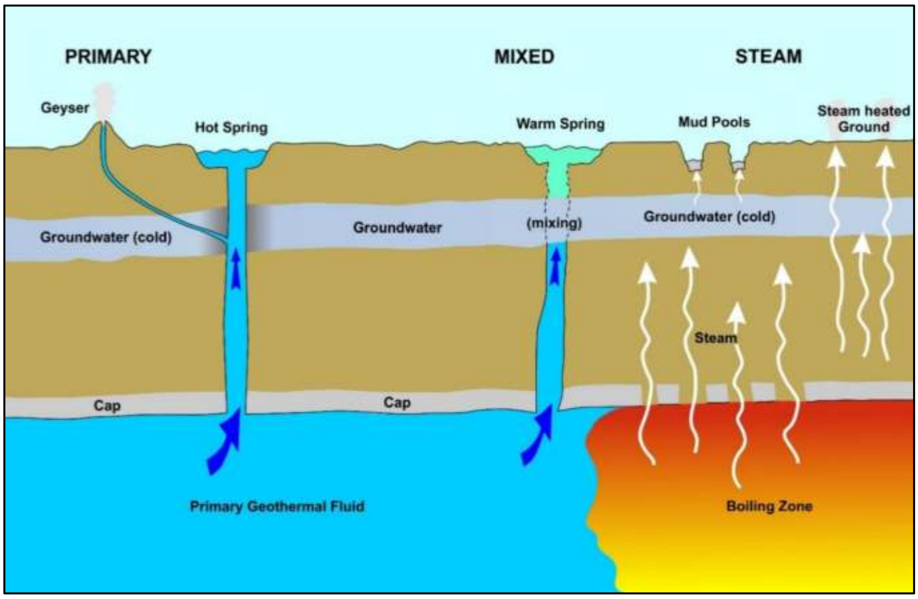

Figure 3.17 Schematic relationship between the various types of geothermal surface features and processes that support them (from Scott and Bromley 2018). Hot springs / pools like the Champagne Pool tap fluids from the primary geothermal fluid. Mud pools like those on Loop Road (Waiotapu) form from acid steam condensates with the steam sourced from boiling primary geothermal fluid at depth.

3.3.1 Mapping

Lloyd (1963) and Benseman et al. (1963) provide the first detailed scientific mapping of geothermal surface features in the Waiotapu area. This includes documenting spring and pool locations, water flows, water temperatures, water chemistry (in some cases) and estimating the extents of heated ground (largely based on ground temperature measurements). As with any mapping, the authors were limited to areas they could safely access. Advancements in technology mean that modern aerial TIR imagery (such as presented in Reeves and Sanders 2019) can be used as a method for mapping hot ground (assuming it is not covered in vegetation) because the TIR camera can clearly identify the warm/hot ground in contrast to the cooler, non-geothermal background ground temperatures.

A database of surface geothermal features for Waiotapu/Waikite is compiled in Appendix 1 from publicly available data (this data is available from the Thermal Springs of NZ Project from the online GNS Science Geothermal and Groundwater Database (Geothermal and Groundwater Database 2005–)). Limitations and methods of this dataset are discussed in Reeves et al. (2021), but include:

- assuming that features have been correctly mapped;
- assuming that features have been categorised into the correct feature type;
- assuming that no changes to the catalogue have occurred since the features were mapped.

Table 3.3 summarises the number of features by feature type. Geothermal surface features at Waiotapu and Waikite are largely mixed and steam-type features, with very few primary features. In general, thermal features associated with acid condensate waters dominate to the north, whereas mixed chloride-sulfate springs are more common to the south. Chloride waters from the Champagne Pool, that occupy a hydrothermal eruption vent, have the highest chloride content and best represent undiluted, but boiled reservoir fluids (Hedenquist and Browne 1989). Champagne Pool discharges fluids at 75°C and its outflow has produced the extensive Primrose silica sinter terrace (~220 x 90 m) (Figure 3.18).

The mixed geothermal surface features can be divided into two categories (note that this distinction is not made in the database because this would require each feature to have a chemical analyses):

1. Acid-sulfate features – e.g., mud pots / pools, acidic pools and springs. The acid-conditions associated with these mixed-type features occur largely at Waiotapu. Other characteristics of these environments include hydrogen sulfide odour, sulfur deposits and collapse craters caused by “acid eating / dissolution” of rocks at and above the water table.
2. Bicarbonate type features (e.g., springs, pools). These features represent geothermal fluids that have high carbon dioxide (CO_2) concentrations dissolved in the water that have typically been diluted with groundwater. These types of waters generally lie in outflow areas of New Zealand geothermal systems. These features are generally seen at Waikite.

The Hakereteke Stream receives geothermal water from Lake Rotowhero (next to Maunga Kakaramea) and numerous seeps in this area as it flows through the Waiotapu geothermal area, to the Waikato River. The stream is also known as “Kerosene Creek”, for the smell and the oil-like sheen sometimes seen on the water in the Waiotapu area. Molecular fingerprinting shows that the oil sheen in the stream is derived from organic-rich sediments in the area that have undergone a high rate of heating that has accelerated the generation of petroleum (Czochanska et al. 1986).

One of the traditional (and current) uses of hot pools for Ngati Tahu- Ngati Whaoa is to use them to singe the fur off pigs in preparation for cooking. Hot pool temperatures need to be approximately 68°C to do this effectively without cooking the pig. Given this hotter temperature, this largely restricts this type of use to the hotter primary type pools/springs which are relatively limited in number (Table 3.3) in the Waiotapu/Waikite geothermal area.

Table 3.3 Summary of mapped feature types at the Waiotapu and Waikite Geothermal Fields.

Feature Type	Number
Geyser	4
Primary flowing spring	10
Primary non-flowing pool	24
Mixed flowing spring	153
Mixed non-flowing pool	39
Mud pool	44
Mud pots	9
Heated ground	52
Steaming ground	22
Fumarole	15
Hydrothermal eruption crater	33
Total number of mapped features	405

Figure 3.18 Photograph of Primrose Terrace with Champagne Pool in the background. Photograph by Lloyd Homer and provided by GNS Science.

3.3.2 Monitoring Data

This section summarises published monitoring data for the surface geothermal features at Waiotapu and Waikite. Two on-going monitoring programmes at Waiotapu and Waikite are identified:

1. Waikato Regional Council monitor 20 geothermal sites at Waiotapu (note that some of these sites include multiple locations at some features) and seven sites at Waikite (Appendix 2). This monitoring is conducted as part of a long-term (started in 1993) state of the environment monitoring programme that monitors selected geothermal surface features throughout the Waikato region. Monitoring typically includes measurements of water temperature, pH and water chemistry. Wilson (2019) summarises and provides a high-level comparison between geothermal fields of the Waikato region using a statistical approach. The only time-series trend mentioned in Wilson (2019) is the Waiotapu Geyser that shows a decreasing trend in temperature between 2015 and 2018, although no qualification to the data is discussed.
2. GeoNet (https://www.geonet.org.nz/) is a partnership that builds and maintains the primary geological hazard monitoring system for New Zealand. As part of this monitoring, water quality samples are collected from selected volcano and geothermal sites. GeoNet monitor Te Manaroa Spring (Waikite) and Champagne Pool (Waiotapu). Data for Te Manaroa Spring from 2008, and, spot samples for two other sites are presented in Appendix 1. Monitoring results for these features are discussed in Section 3.4.1.

Reeves et al. (2011 and 2018b) summarise changes in hydrology at Waikite in response to rehabilitation of a geothermally influenced wetland between 2009 and 2016. Remedial actions included diverting a stream back through the drained wetland, installing a weir to increase water levels, plantings, fencing and pest control. Monitoring data from selected geothermal features, streams (Appendix 1), vegetation, and groundwater show that the actions were successful in increasing the wetland area and distribution of threatened geothermal fern species, however, the increase in water level did reduce the volume of geothermal inputs flowing into the wetland (via seeps in the wetland area), and it is not clear if the increase in the water level affected chemistry and/or temperature at two nearby hot springs.

Power et al. (2018) summarise methods and findings of sampling 925 geothermal springs/streams for a microbiological biogeographic survey (1000 Springs survey) throughout New Zealand between 2013 and 2015. Sampling enabled microbiology, water chemistry and physical properties of the springs to be measured. This includes 52 samples from Waiotapu and 15 samples from Waikite. This study found that pH drives diversity and community complexity within geothermal springs at temperatures <70°C. They also identified specific taxa associations and demonstrated that fluid chemistry signatures can be indicative of community composition. The paper focuses on the larger dataset, and specific findings about Waiotapu and Waikite are not discussed in detail. Chemical, microbiological, on-site measurements and a photograph from each sampling site are available from the 1000 Springs website (One thousand springs 2019) but were unavailable to be included in this report.

3.4 Geothermal Fluid Chemistry

Interpretation of geochemical analyses can provide insight into the ongoing processes of a geothermal system and how the chemistry of the various fluids are modified. Boiling, mixing and condensing gas change the chemistry of the fluids and determining the fluid compositions is key to understanding how the geothermal system is interacting with the rocks (alteration, precipitation, dissolution) and other water sources (e.g., groundwater).

There are three main end-member fluid types that occur in most New Zealand geothermal systems and these are: 1) near-neutral pH chloride waters, 2) bicarbonate / CO_2-rich steam-heated waters, and 3) steam-heated acid-sulfate waters / condensates (Henley and Hedenquist 1986). These waters can mix together to create hybrid waters (e.g., mixed sulfate-chloride) or they can mix with and be diluted by varying amounts of meteoric ground water (Table 3.4). Due to the diverse composition of the waters the Ngati Tahu-Ngati Whaoa people determined they had different properties and were used to treat different ailments.

The different water types occupy different parts of the geothermal system and at surface form distinctive thermal features. Figure 3.19 presents a schematic model for a typical New Zealand geothermal system showing the thermal structure and distribution of the main water types (Henley and Ellis 1983; Henley and Hedenquist 1986). Near-neutral pH chloride waters form a central plume of upwelling fluids and have variable amounts of chloride (400 to 2,200 ppm), and dissolved gases (Giggenbach 1995). The main gases are carbon dioxide (CO_2; <100 to 10,500 ppm) and hydrogen sulfide (H_2S; 10 to 245 ppm). This fluid type is inferred to be heated by a deep magma (melted rock at 5 to 6 km depth) that further contributes gases and some elements to the fluid. As the chloride water rises it can boil resulting in steam generation and gas loss. Where chloride waters discharge at surface they appear as clear boiling or near-boiling springs, pools and geysers typically with associated deposits of silica sinter. These chloride waters can occupy craters created by hydrothermal eruptions (e.g., Champagne Pool).

Acidic steam-heated acid-sulfate waters can develop above, and on the margins of the chloride-water upflows (Figure 3.19). This water type forms above the water table from the condensation of steam and gases derived from boiling chloride waters with the oxidation of hydrogen sulfide (H_2S) gas forming sulfuric acid (H_2SO_4; Schoen et al. 1974). The acidic fluid can dissolve the rocks and are associated with areas of steaming ground that may have fumaroles with or without sulfur. Acidic rock dissolution and steam-heating can form mud pools and in extreme cases can lead to large volumes of rock dissolution to create collapse craters. Since chloride and other non-volatile elements are not transported by the steam, the steam-heated water will lack or have very low concentrations of chloride.

The third water type, bicarbonate / CO_2-rich steam-heated waters can occur on the margins of the geothermal field and above the chloride water plume. They originate via the condensation and absorption of CO_2 released during boiling into cooler ground waters (Mahon et al. 1980; Hedenquist and Stewart 1985; Hedenquist 1990).

Table 3.4 Different fluid types, source, associated thermal features and associated hydrothermal minerals for geothermal fields of the TVZ (modified Henley and Hedenquist 1986).

Fluid Type	Cl (ppm)	Source	pH	Temperature (°C)	Thermal Features	Hydrothermal Minerals
Chloride	400–2,200	Deep circulating modified ground water	Near neutral 6.0–7.5	200–300+	Boiling spring, geyser (silica sinters)	Quartz, chlorite, illite, pyrite, calcite, epidote, albite, adularia
Steam-heated acid-sulfate	Nil	Surficial condensates	Highly acidic <2–3	100–130+	Boiling mud pools (dissolution craters)	Kaolinite, sulfur, alunite, opal, pyrite
Steam-heated CO_2-rich	<100	Condensation of steam and gas into marginal and shallow groundwaters	Weakly acidic 5–6	<100–180	Warm-hot spring (travertine)	Smectite, mixed-layered clays, zeolites, calcite, siderite
Mixed chloride + acid-sulfate	100–500	Surface and near surface mixtures	Highly acidic 2–4	<100–130	Warm-hot spring	Smectite, mixed-layered clays, zeolites

Cl = chloride which is a principle element of chloride waters, ppm = parts per million. pH is a measure of fluid acidity; neutral pH at 25°C is 7. Acid fluids have a lower pH value (1) and alkaline fluids a higher pH value (14).

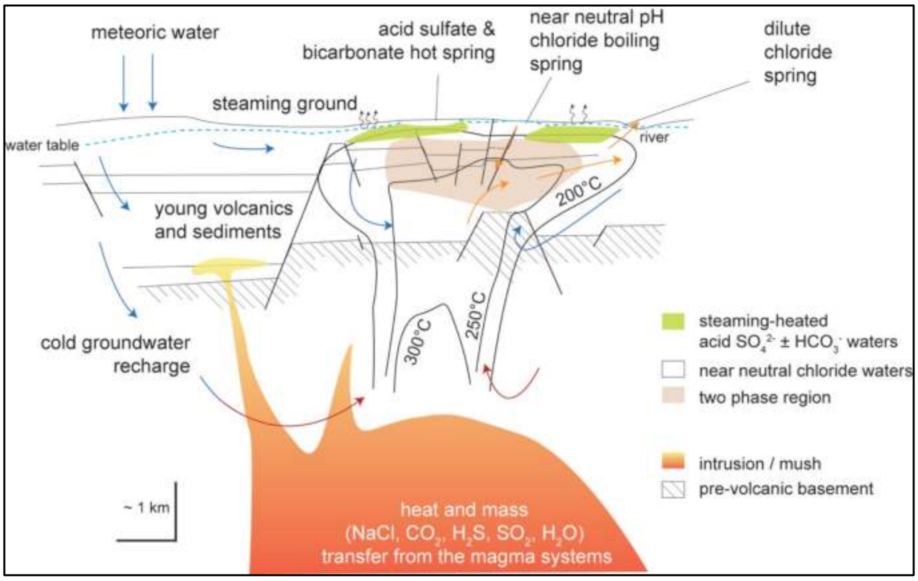

Figure 3.19 A schematic cross-section showing the principle features and the hydrologic and chemical structure of a typical TVZ geothermal system (Henley and Ellis 1983; Henley and Hedenquist 1986; Hedenquist 1990).

3.4.1 Fluid Chemistry of Waiotapu and Waikite

The chemistry of geothermal waters at Waiotapu have been analysed and reported by Grange (1937), Lloyd (1959), Wilson (1963), Hedenquist (1983; 1991), Hedenquist and Browne (1989), Giggenbach et al. (1994), Pope et al. (2004; 2005), Pope and Brown (2014). Waikite geothermal water chemistry is reported in Sheppard and Robinson (1980), Cody and Klyen (1991–1992), Glover et al. (1992), and Reeves et al. (2011 and 2018b). The chemistry of two features from Waiotapu and Waikite have been annually monitored as part of a wider, on-going chemical survey by GeoNet. In addition, since 1995 the Waikato Regional Council has collected temperature, pH, and observation data for selected Waiotapu and Waikite geothermal features (Littler 2015; Wilson 2019). Published water chemistry data used in this report is summarised in Appendix 1.

The chemistry of the geothermal fluids at Waiotapu and Waikite has mainly been determined from surface features (e.g., springs, pools), but also for fluids discharged from the seven exploratory wells that were drilled between 1956 and 1959 (reported in Hedenquist and Browne 1989; and reference therein). While there is general broad field-wide coverage of thermal feature chemistry there are only a small number of features for which there are repeated measurements over time. Appendix 1 presents temperature, pH and observational data for many thermal features with repeated measurements and chemical analyses. The fluid chemistry of representative thermal features for Waiotapu and the discharges from the seven geothermal wells are summarised in Tables 3.5 and 3.6 respectively. Table 3.7 summaries the fluid chemistry for representative springs and pools from Waikite.

Geothermal springs and pools at Waiotapu have diverse fluid types and can be grouped as chloride, acid sulfate, mixed sulfate-chloride, and mixed bicarbonate-chloride, and are diluted by varying amounts of meteoric groundwater. The range in composition of the different fluid types can be represented on a ternary diagram (Figure 3.20) using relative concentrations of chloride (Cl), bicarbonate (HCO_3) and sulfate (SO_4), the principal anions (atoms or molecules with a negative charge) of a geothermal water. Neutral pH chloride springs cluster near the chloride apex, with high sulfate (acid sulfate, mixed sulfate-chloride) and bicarbonate waters (mixed bicarbonate-chloride) plotting towards the SO_4 and HCO_3 apexes, respectively. Springs and pools classified as acid are those with a pH <4 (Hedenquist 1991).

At Waiotapu, springs and pools with acid sulfate or mixed acid sulfate-chloride waters are common throughout the field and range in temperature from near boiling to ambient. For the acid sulfate-chloride springs and pools, the ratio of sulfate to chloride is variable (Figure 3.20) but is highest (i.e., with greater sulfate) for springs in the northern part of the geothermal field. Chloride springs and pools with near neutral to slightly alkaline pH waters are by comparison rare and restricted to areas of lower elevation within the central and southern areas of the Waiotapu Geothermal Field and along streams. Champagne Pool is the best example of a chloride thermal feature and discharges chloride waters with the highest chloride concentration (1,898 mg/kg). Springs discharging bicarbonate waters are rare and principally occur along the shore of Lake Ngakoro towards the southern margin of the geothermal field. By contrast, springs and pools at Waikite only discharge mixed bicarbonate-chloride fluids with low chloride content (Figure 3.20B; Table 3.7). The high HCO_3/Cl ratio of the waters from the Waikite area is typical of peripheral waters forming at the margins of upflowing chloride waters (Sheppard and Robinson 1980; Cody and Klyen 1991–1992; Glover et al. 1992).

Chemistry data is available for seven of the eight Waiotapu wells (Table 3.6), as well WT2 was never discharged (Hedenquist and Browne 1989; and reference therein). Wells WT-4, WT-6 and WT-7 have measured temperatures that generally follow the boiling point for depth profile (the boiling temperature of the fluid will increase with depth due to increasing pressure of the water column) with a maximum temperature of 295°C near the base of WT-7 (1,000 m below surface). By contrast, measured temperatures for the northern wells WT-1, WT-2 and WT-3 (450 and 435 m deep) show inversions (i.e., where it is hottest at shallow depths). Chemical analyses corrected for steam loss indicate the wells all discharge chloride waters with between 673 and 1,600 mg/kg chloride; well WT4 has the highest chloride content. Chemical modelling of the well discharges coupled with those from the Champagne Pool (1,898 mg/kg Cl) suggests that the principal reservoir feeding the wells has an endmember chloride content of about 1,400 mg/kg chloride at 230°C and 300 to 400 m deep. The compositional range for chloride waters in the wells (Table 3.6) can be accounted for by the dilution of this reservoir water by varying amounts of 160°C steam-heated bicarbonate water. Assuming this fluid has boiled from 300°C, the deeper (>1 km depth) fluid would have about 1,100 mg/kg chloride (Hedenquist and Browne 1989).

Table 3.5 Chemical composition of representative springs, Waiotapu Geothermal Field. Chemistry in mg/kg (ppm).

Spring / Lake	Date	Temperature (°C)	pH	Li	Na	K	Rb	Cs	Mg	Ca	B	HCO_3	SiO_2	SO_4	H_2S	Cl
R.B. Hakereteke	3.78	99°	2.2	0.08	32	7	0.01	<0.01	0.80	4.0	<2	-	308	338	-	6
L.B. Hakereteke	3.78	74°	2.5	1.3	118	23	0.22	0.16	1.80	12.0	3.9	-	354	340	-	176
N. Waiotapu Pub	3.78	96°	7.2	2.8	314	34	0.40	0.50	0.06	11.0	6.5	18	196	86	-	482
Mud Volcano	3.78	27°	2.8	3.0	312	33	0.26	0.30	3.40	20.0	6.5	-	415	365	-	451
SE. Waiotapu Pub	7.6.83	82°	7.6	3.3	356	26	0.37	0.53	0.06	10.3	5.3	35	227	131	-	509
Venus Pool	3.78	48°	3.7	3.6	370	31	0.35	0.49	0.40	6.9	7.1	-	261	154	-	562
Lady Knox Geyser	25.3.83	98°	7.8	1.1	265	19	-	-	0.80	11.2	4.2	157	263	40	7.6	340
E. Lady Knox	7.6.83	95°	6.4	5.3	697	69	0.91	1.12	0.09	23.4	12.6	31	189	87	-	1,141
L.B. Waikokouka	25.3.83	99°	7.9	3.7	572	75	-	-	0.60	10.8	10.5	42	393	133	10	865
Postmistress Pool	7.6.83	94°	8.5	3.8	494	17	0.3	0.69	0.01	8.5	7.2	54	197	57	-	707
NE. Tearooms	17.3.83	94°	7.2	5.1	539	37	-	-	0.08	10.8	7.9	118	271	71	10.9	784
NE. Tearooms	17.3.83	66°	2.6	4.3	483	28	-	-	0.53	21.1	6.9	67	243	464	5.1	692
SW. Tearooms	1.12.83	67°	6.7	4.8	488	37	0.48	0.69	0.60	12.0	7.4	-	193	130	-	703
Adj. Weather Pool	17.3.83	99°	2.1	4.8	570	68	-	-	1.20	18.6	10.3	11	341	756	4.6	914
Rainbow Crater	17.3.83	80°	2.5	3.0	518	92	-	-	10.40	68.2	-	160	381	938	29.4	766
Crater 9	17.3.83	99°	2.0	5.1	612	80	-	-	1.10	20.6	11.7	23	306	634	6.1	986
Adj. Champagne Pool	17.3.83	63°	5.0	8.0	1,054	145	-	-	0.17	33.9	24.7	280	344	300	21.1	1,797
Champagne Pool	17.3.83	75°	5.6	8.3	1,102	151	-	-	0.05	35.1	25.4	346	445	53	28	1,898
Waiotapu Geyser	25.3.83	87°	6.4	1.4	351	34	-	-	0.33	14.5	6.2	96	393	123	10.4	511
Sulphur Pool	25.3.83	70°	5.0	2.2	457	81	-	-	0.12	10.8	9.2	157	455	139	3.4	770
SW. Waiotapu Stream	25.3.83	74°	6.5	2.4	350	21	-	-	3.20	11.2	4.4	278	303	52	1.8	444
W. Lake Ngakoro	4.2.84	82°	6.4	3.9	673	20	0.25	0.56	0.08	9.5	10.1	133	251	74	-	979
Lake Ngakoro Pool	25.3.83	99°	6.0	5.3	1,015	33	-	-	0.15	34.4	21.9	21	303	57	4.4	1,659
E. Lake Ngakoro	25.3.83	95°	3.8	<0.05	11	6	-	-	2.70	17.4	1.1	13	141	1,135	1.8	3
SE. Lake Ngakoro	4.2.84	88°	7.0	1.1	341	24	0.14	0.23	3.05	27.6	3.5	406	264	183	<0.5	276
S. Lake Ngakoro	4.2.84	75°	7.8	3.4	609	21	0.28	0.78	0.02	6.4	11.1	140	233	87	-	944

Li = lithium, Na = sodium, K = potassium, Rb = rubidium, Cs = caesium, Mg = magnesium, Ca = calcium, B = boron, HCO_3 = bicarbonate, SiO_2 = silica, SO_4 = sulfate, H_2S = hydrogen sulfide, Cl = chloride. - = below level of detection. Data source Hedenquist 1983 and Hedenquist 1991.

Table 3.6 Chemical composition of geothermal well discharges, Waiotapu Geothermal Field. Discharge enthalpies in kj/kg and chemistry in mg/kg (ppm).

Well	Date	Enthalpy	pH*	Li	Na	K	Rb	Cs	Mg	Ca	B	HCO_3	SiO_2	SO_4	Cl	T_{QA}	T_{NKC}
WT1	6.66		9.3	6.7	625	72	-	-	-	3.3	13.3	-	545	122	836	232°	233°
WT3	9.9.57	770	8.8	4.0	535	38	-	-	-	11.5	10.9	37	254	83	673	183°	211°
WT4	2.62	1,279	7.5	8.3	965	135	-	-	-	22.5	25.3	26	450	48	1,600	218°	235°
WT5	20.9.57	-	7.6	3.2	770	59	-	-	-	-	16.5	-	-	4	949	-	161°
WT6	22.9.58	1,000	8.8	5.9	706	103	-	-	-	9.6	12.8	110	353	89	1,063	208°	240°
	63	-	8.9	6.5	860	155	-	-	0.06	10.0	21.0	65	470	52	1,450	198°	234°
WT7	10.7.59	1,047	8.7	6.1	765	87	-	-	-	10.0	4.2	65	356	-	1,260	-	-
	2.62	877	8.7	5.7	836	106	-	-	-	9.0	20.4	53	356	86	1,285	203°	235°
WT8	17.2.82	-	5.7	3.6	253	21	0.29	0.31	0.01	1.9	3.9	583	240	40	341	184°	200°

Enthalpy = total heat content of a system. Li = lithium, Na = sodium, K = potassium, Rb = rubidium, Cs = caesium, Mg = magnesium, Ca = calcium, B = boron, HCO_3 = bicarbonate, SiO_2 = silica, SO_4 = sulfate, Cl = chloride, T_{QA} = temperature calculated from quartz geothermometer, T_{NKC} = temperature calculated from sodium-potassium-calcium geothermometer.

* pH measured at room temperature (~20°C), - = below level of detection. Data source Hedenquist and Browne (1989; and reference therein).

Table 3.7 Chemical and composition of representative springs at Waikite. Chemistry in mg/kg (ppm).

Spring	Date	Temperature (°C)	pH	Li	Na	K	Rb	Cs	Mg	Ca	B	HCO_3	SiO_2	SO_4	H_2S	Cl
Waikite																
S 5576	1991	99°	7.1	0.6	67	11	<0.05	0.05	1.20	4.4	0.6	122	129	16	-	47
S 5577	1991	74°	7.1	0.8	65	13	<0.05	0.07	1.30	4.9	0.6	161	144	16	-	58
S 5580	1991	96°	7.9	2.4	230	9	0.12	0.35	0.19	8.7	1.5	361	183	39	-	150
S 5585	1991	27°	8.8	2.4	224	9	0.12	0.32	0.13	1.6	1.5	300	174	38	-	146
S 5586	1991	82°	7.8	2.2	215	9	0.11	0.31	0.22	7.8	1.5	338	167	39	-	145
S 5587	1991	48°	7.4	2	199	8	0.08	0.25	0.28	7.5	1.4	302	141	37	-	132
S 5598	1991	98°	7.9	2	202	7	0.08	0.29	0.20	7.1	1.4	278	150	38	-	140
Waikite Scarp and Spring																
S 5651	1991	98°	8.1	3	290	16	0.14	0.26	0.03	0.9	1.8	432	277	46	-	199
S 5670	1991	72°	8.8	2	211	15	0.05	0.08	0.05	0.5	1.3	275	258	34	-	139
S 5671	1991	49°	8.5	2	220	16	0.06	0.08	0.12	0.9	1.3	313	243	34	-	136
Scalding Spring																
S 5644	1991	89°	8.0	2.9	322	20	0.13	0.18	0.09	0.5	2.2	454	304	45	-	237

Li = lithium, Na = sodium, K = potassium, Rb = rubidium, Cs = caesium, Mg = magnesium, Ca = calcium, B = boron, HCO_3 = bicarbonate, SiO_2 = silica, SO_4 = sulfate, H_2S = hydrogen sulfide, Cl = chloride. - = below level of detection. Data source Glover et al. (1992).

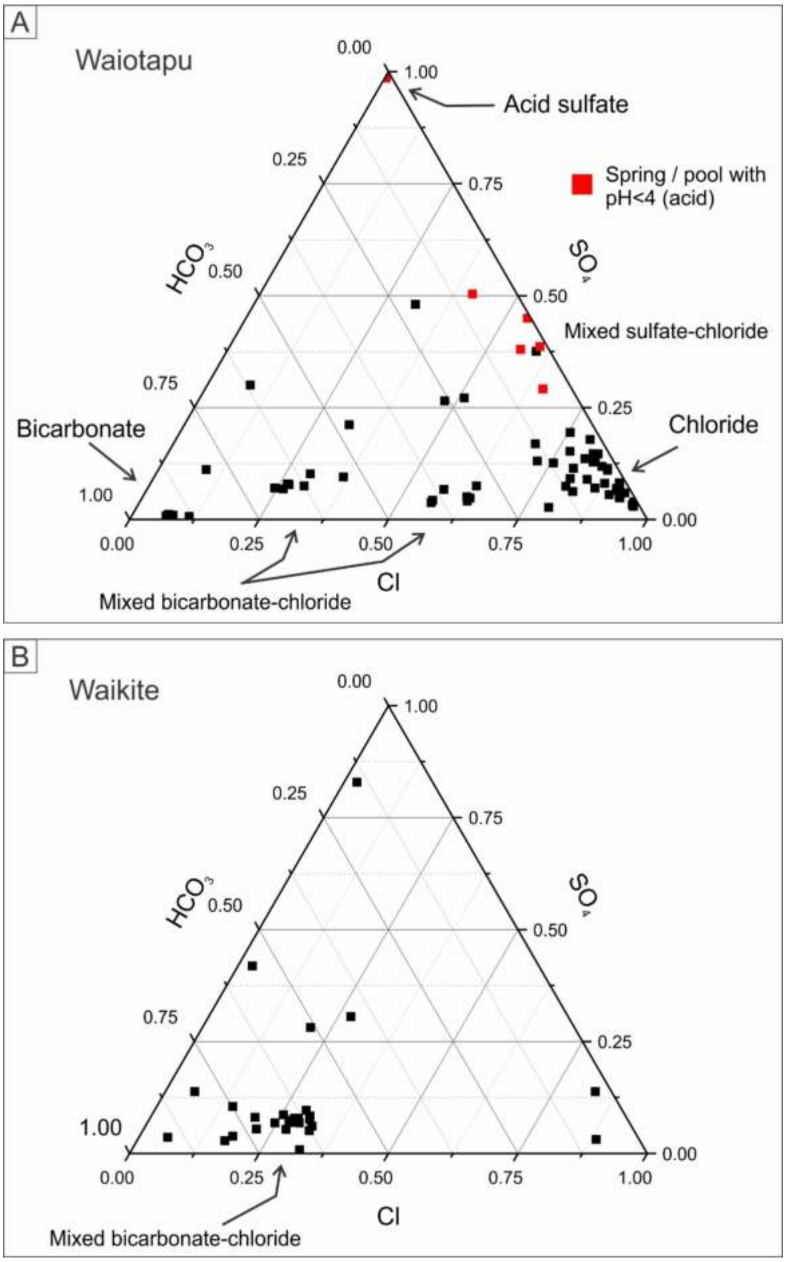

Figure 3.20 Ternary plots showing the relative proportions of Cl, HCO_3 and SO_4 for the springs from A) Waiotapu and B) Waikite. Waiotapu has a diversity of different fluid types that include chloride, acid sulfate, mixed acid sulfate-chlorite and mixed bicarbonate-chloride. Acid features are those with a pH <4 (after Hedenquist 1991). Waikite mainly has mixed bicarbonate-chloride with high amounts of bicarbonate. All data and data source references in Appendix 1.

3.4.2 Chemistry, Temperatures and pH of Individual Thermal Features

Annual monitoring of individual thermal features provides insights into the stability or change of a feature over time and collectively provides insight into possible field wide shallow hydrologic change. At Waiotapu and Waikite, there are a limited number of thermal features for which temperature and pH measurements have been repeatedly measured, with most data collected annually since 2010 by the Waikato Regional Council (Littler 2015; Wilson 2019). Features regularly measured include, Champagne Pool, Waiotapu Geyser, Oyster Pool, Lake Ngakoro, Lady Knox Geyser, Knox hole spring and channel, Venus Pool (Western Pool), The Hidden Pool, and Kerosene Creek (Figure 3.21). Those in the Waikite area include, Te Manaroa, lower Supply Spring, Pool adjacent to Supply Spring, Waikite Scarp and Spring, plus the Scalding Spring and HT Geyser (Figure 3.22). Temperature and pH measurements over time for these features are graphically presented in Figures 3.23, 3.24 and 3.25.

In general, the temperature and pH of fluids for the thermal features at Waiotapu listed above over the period measured have remained consistent (Figures 3.23 and 3.25). There is some scatter likely due to slight differences in sampling point locations, and for cooler features (<50°C) the likely greater influence of groundwater and air temperatures. Temperatures for the Waiotapu Geyser appear to show a slight decrease over time with those between 1996 and 2012 averaging 88°C and those between 2012 and 2019 averaging 80°C (Figure 3.23). Both the Lady Knox Geyser (limited measurements) and Knox hole channel have slightly lower temperature values recorded between 2012 and 2014, but the reason for this episode of decrease is not known. Temperatures for Lake Ngakoro are slightly above ambient and show scatter that is attributed to measurement using a TIR thermometer and likely variable influence of groundwater.

Venus Pool was used traditionally for bathing and soothing of aches (Section 2.5.4.1). The water chemistry (Table 3.5) show the water to be of mixed sulphate -chloride type having an acidic pH (3.7) indicating dissolution of H_2S in the water, but also having relatively high concentrations of Cl and other deep-geothermal water indicators such as lithium, boron, rubidium and caesium (Table 3.5). The measured pool temperatures vary between 37°C and 49°C (Figure 3.23, Appendix 1) and probably depend on climatic conditions such as rainfall. These warm temperatures will provide therapeutic relief to joints and tired muscles.

Most thermal features at Waikite have consistent temperatures with no discernible change over the periods measured (Figures 3.24 and 3.25). The Lower Supply Spring appears to show a slight decrease in temperature of 97° to 94°C from 2016; though there is some scatter in the results and inclusion of several spurious values (Figure 3.24).

For Waiotapu and Waikite areas, there are only four springs / pools for which chemical analyses have been repeatedly determined over time. They are Champagne Pool, Te Manaroa, Scalding Spring and HT Geyser. Figure 3.25 presents temperature, pH, and selected element chemistry (chloride, sodium, silica, and bicarbonate) plots for these four thermal features. Champagne Pool temperature, pH and chemistry (chloride, sodium, silica) have remained consistent between 1915 and 2019. Temperature, pH and the chemistry for Te Manaroa, Scalding Spring and HT Geyser, Waikite, show overall consistency since 2008 (Figure 3.25). Despite the limited number of surface features with repeated chemical analyses, the temperature and chemistry for the four thermal features measured are consistent and show no significant change over the time spans sampled (Figure 3.25).

As an additional note, the chemistry of the Champagne Pool is unique with the pool occupying a vent created by a hydrothermal eruption. It discharges 75°C chloride waters that have the highest chloride content in the area and best represents undiluted, but boiled reservoir fluids (Hedenquist and Browne 1989). Its waters have high concentrations of CO_2 that nucleate and bubble within a couple of meters of the surface creating the distinctive effervescence (bubbling). The high CO_2 also causes the water to be slightly acidic (pH = 5.5) and this stabilises precipitation of bright orange amorphous arsenic and antimony sulfur colloids that spectacularly colour the pool edges. Moreover, these arsenic and antimony sulfur colloids very effectively scavenge very low concentrations of gold and silver. Arsenic-antimony sulfides in sinter surrounding the pool can have very high grades of precious metals, with up to 543 grams per tonne gold and 745 grams per tonne silver (Hedenquist and Henley 1985; Pope et al. 2004 and 2005; Pope and Brown 2014). For comparison, depending on the mining operation, gold as low as 4 grams per tonne can be economically extracted.

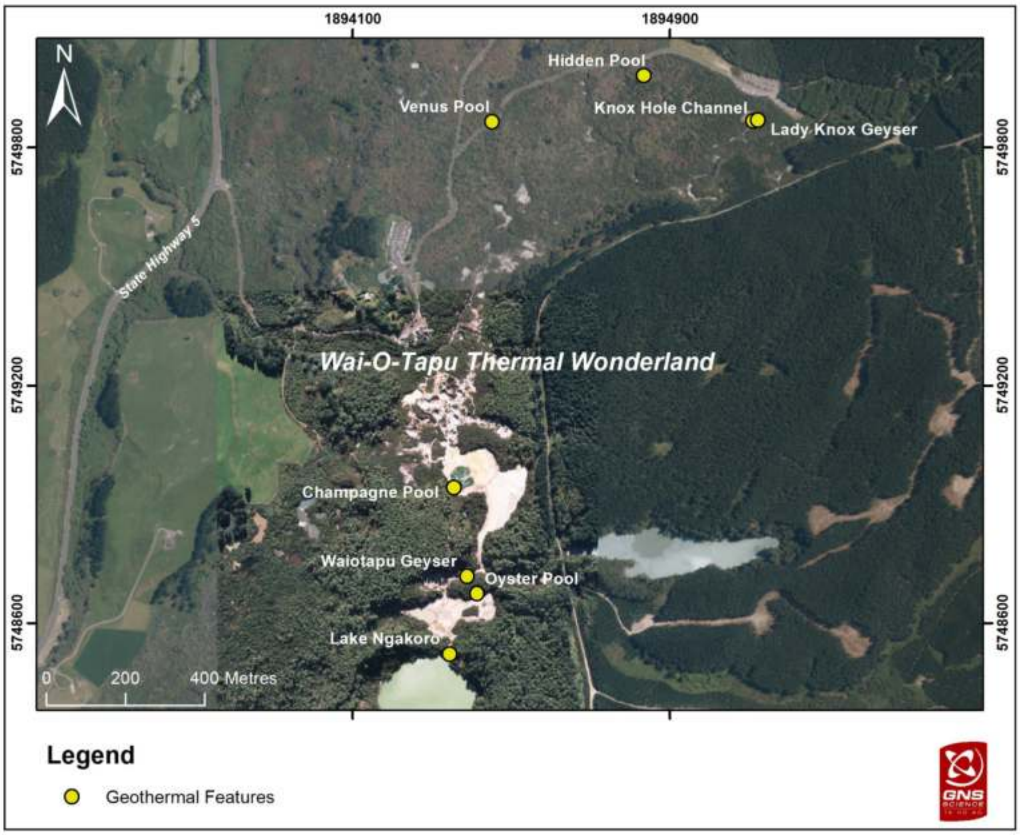

Figure 3.21 Aerial image of Waiotapu showing the locations of selected geochemically monitored, geothermal features (yellow dots). Aerial image sourced from LINZ Data Service (2021) and licensed for re-use under the Creative Commons Attribution 4.0 New Zealand licence.

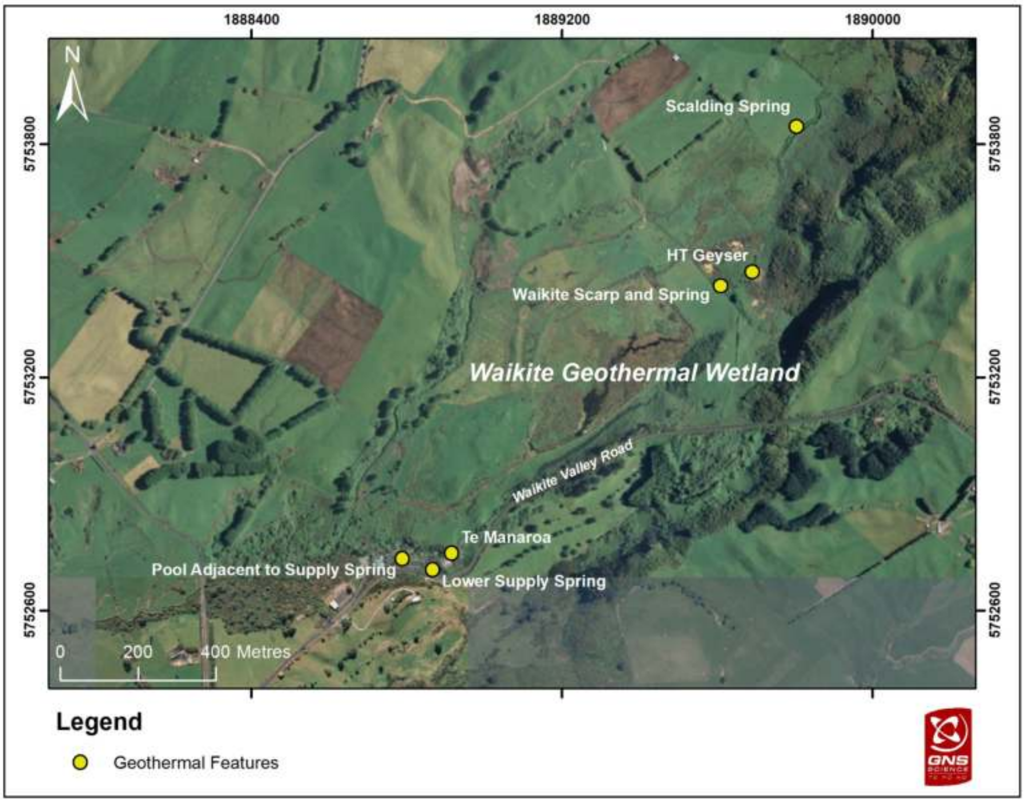

Figure 3.22 Aerial image of Waikite showing the locations of selected geochemically monitored, geothermal features (yellow dots). Aerial image sourced from LINZ Data Service (2021) and licensed for re-use under the Creative Commons Attribution 4.0 New Zealand licence.

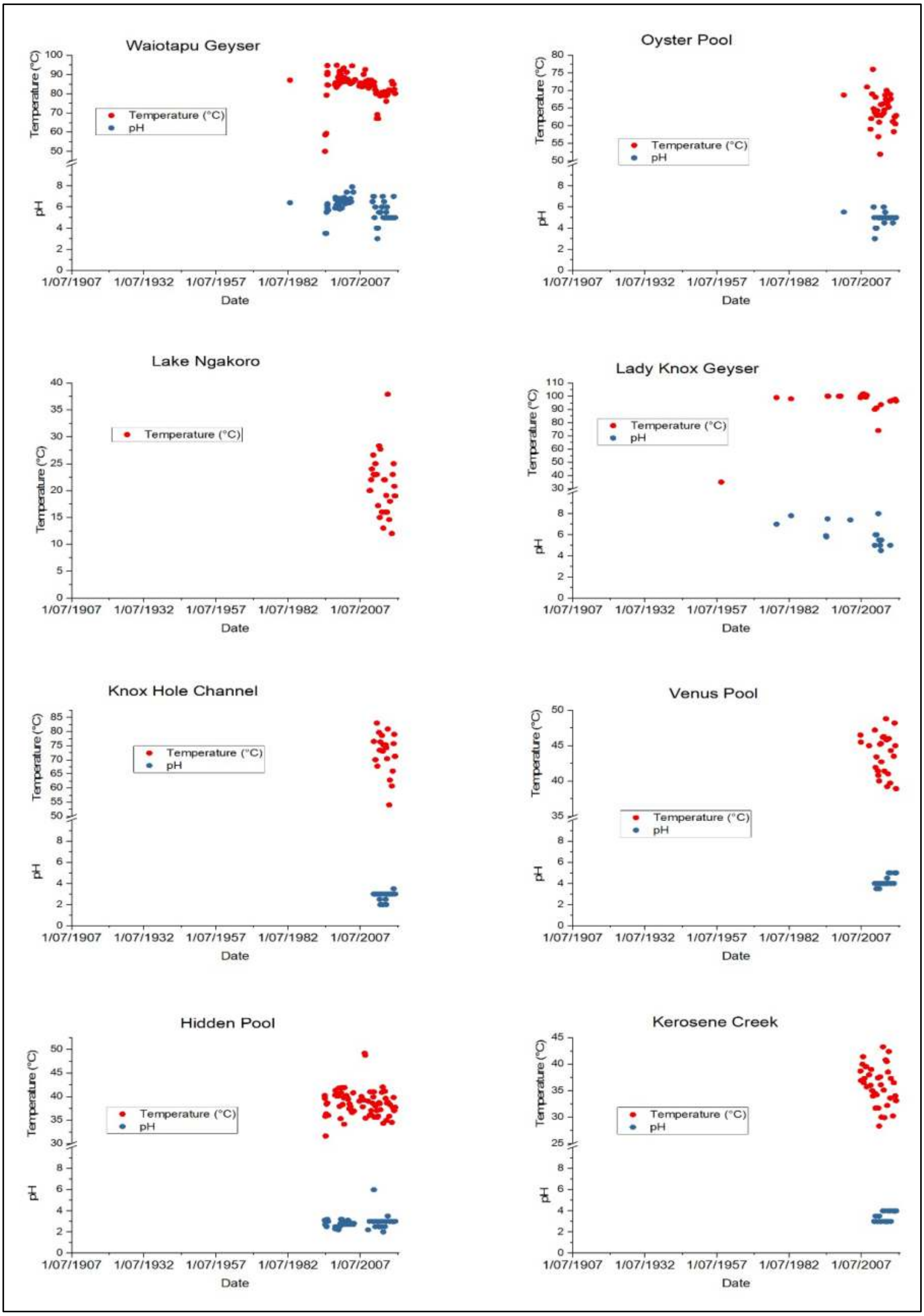

Figure 3.23 Temperature and pH data for Waiotapu Geyser, Oyster Pool, Lake Ngakoro, Lady Knox Geyser, Knox hole channel, Venus Pool and The Hidden Pool, Waiotapu. Their locations are shown in Figure 3.21. Data and reference source detailed in Appendix 1.

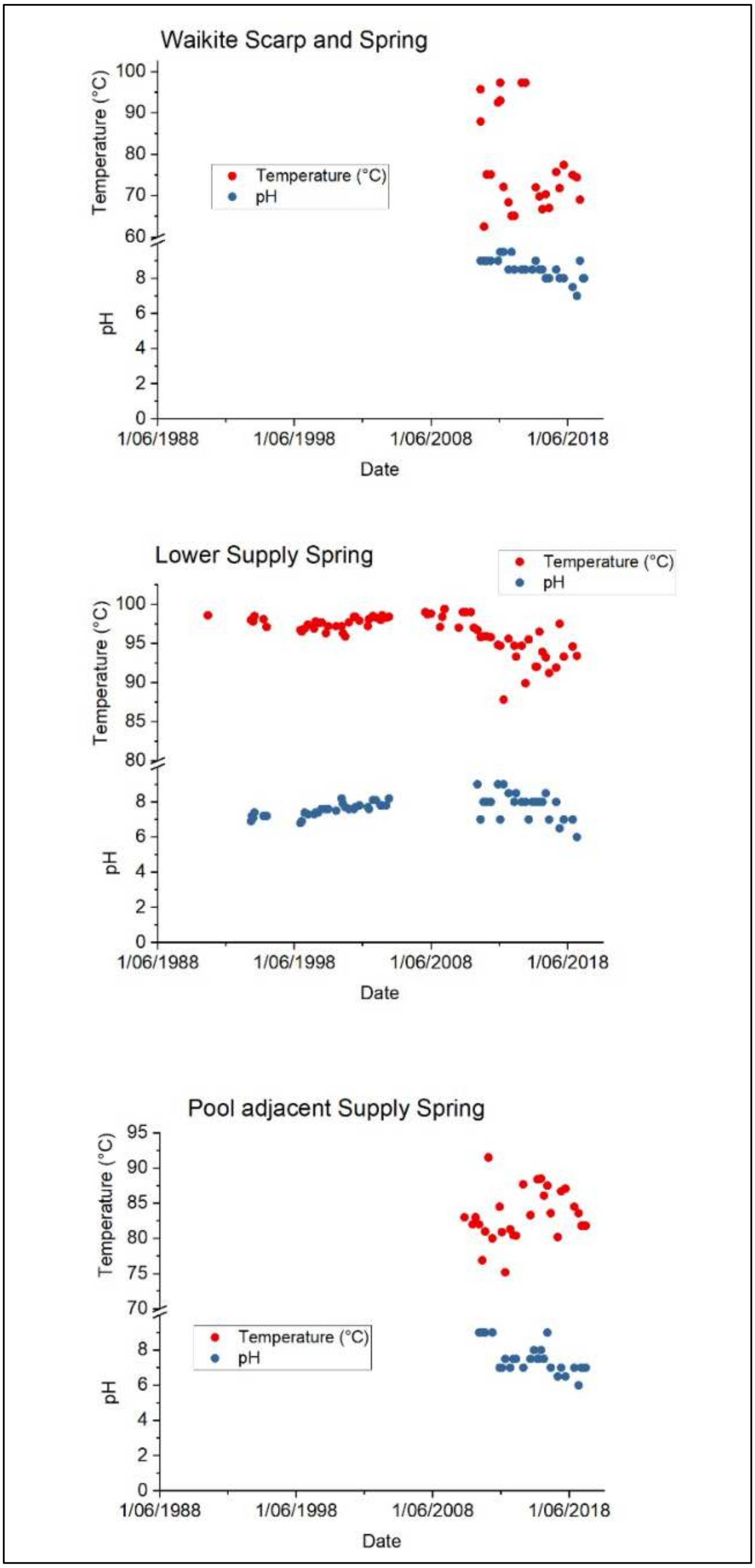

Figure 3.24 Temperature and pH data for Waikite Scarp and Spring, lower Supply Spring and the Pool adjacent to Supply Spring, Waikite. Their locations are shown in Figure 3.22. Data and reference source detailed in Appendix 1.

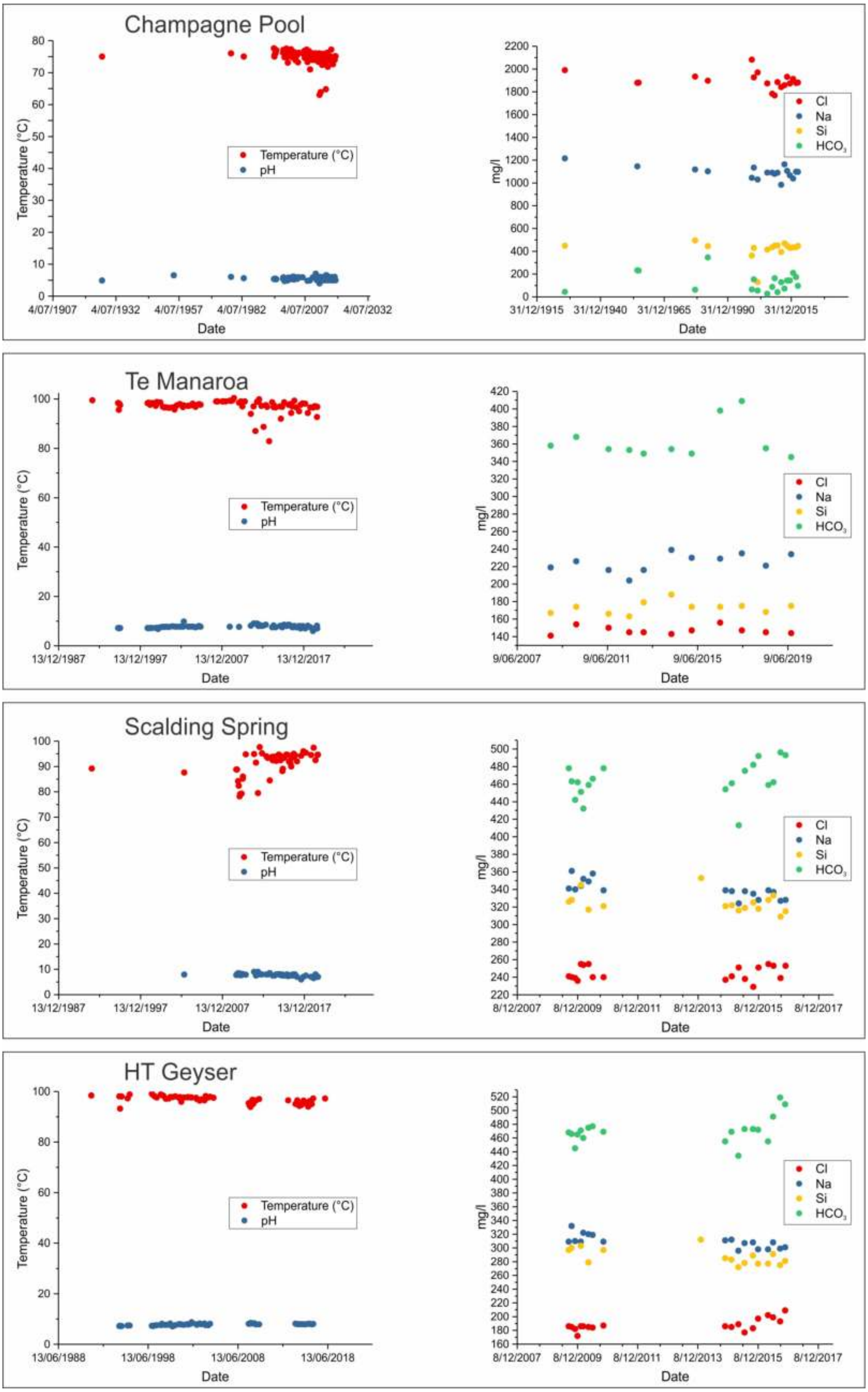

Figure 3.25 Temperature / pH and selected element fluid chemistry (Cl = chloride, Na = sodium, Si = silicon, HCO_3 = bicarbonate) plots versus time for the Champagne Pool, Te Manaroa Spring, Scalding Spring and HT Geyser. The locations of these thermal features are shown in Figures 3.21 and 3.22. Data and reference source detailed in Appendix 1. Note that the date range for the Champagne Pool is different from the other three sites.

3.4.3 Thermal and Hydrologic Change

While most surface features detailed here show no significant temperature, pH or chemical change over the documented time range, there have been some field changes over the last 150 years. Abundant steam used to discharge from the west flank of Maunga Kakaramea in the 1870s but now is reduced to mere wisps of vapour (Lloyd 1959). There is also evidence of much older change. Broken silica sinter deposited from former discharging chloride waters is present about 400 m north of Champagne Pool in an area now characterised by steaming ground. There is also an occurrence of sinter not associated with active springs ~1 km west and southwest of Lake Ngakoro. In both cases these occurrences of sinter indicate areas of former discharging chloride waters that have since ceased. This demise may be due to the lowering of the water table (Lloyd 1959; Hedenquist and Browne 1989).

There is also evidence of thermal change from fluid inclusion temperatures when compared against current measured temperatures. Fluid inclusions are microscopic pockets of fluid trapped in crystals of quartz and calcite that can be heated and frozen to determine the temperature at which they were trapped and their apparent fluid composition. Fluid inclusions measured in quartz from wells WT-4, WT-6 and WT-7 have temperatures of trapping that match the present measured well temperatures, indicating thermal stability of this part of the reservoir (Hedenquist and Browne 1989). However, for the northern wells WT-1, WT-2 and WT-3 (450 and 435 m deep), fluid inclusions in quartz have temperatures of trapping that are 20° to 40°C hotter than present measured well temperatures. These temperature differences imply a cooling of this part of the reservoir that could be due to either a southward shift in the focus of reservoir fluid upflow, or alternatively an incursion of cool steam-heated waters (Hedenquist and Browne 1989). Regardless, though many features and areas appear consistent over ‘short’ time periods, localised changes in surface thermal features and subsurface fluid temperatures attest to the highly dynamic and changeable hydrologic structure of the geothermal system.

3.5 Conceptual Model of the Waiotapu and Waikite Geothermal Systems

A conceptual model of the Waiotapu and Waikite geothermal systems as presented in Giggenbach et al. (1994) is presented below. The conceptual model summarises key geological and hydrological processes that are understood to be occurring within the geothermal system based on the available data. It also provides a simple way of visualising how the geothermal system works and is essential to understand the processes that could be occurring, and therefore provide input into how best to manage the system according to the desired objectives and outcomes.

Figures 3.26 and 3.27 show a north-south and west-east cross-section through the Waiotapu geothermal system. Key aspects of the conceptual model include:

- The source of deep fluids for Waiotapu is beneath the dacite dome of Maunga Kakaramea with the prevailing hydrologic gradient causing lateral flow to the south.
- Vapour separating from the upwelling fluids has generated acid condensates above the upflow (yellow area, Figure 3.26), whereas mixed chloride-sulfate and chloride waters discharge 4 km to the south.
- A tongue of chloride water may extend towards Reporoa where they mix and are replenished with volatiles and heat from another possible source (a separate up flow from the Reporoa geothermal system).
- Waikite fluids are an outflow from the Waiotapu up flow and are likely to be derived from the envelope of lower temperature waters surrounding the main columns of high temperature, high chloride waters.

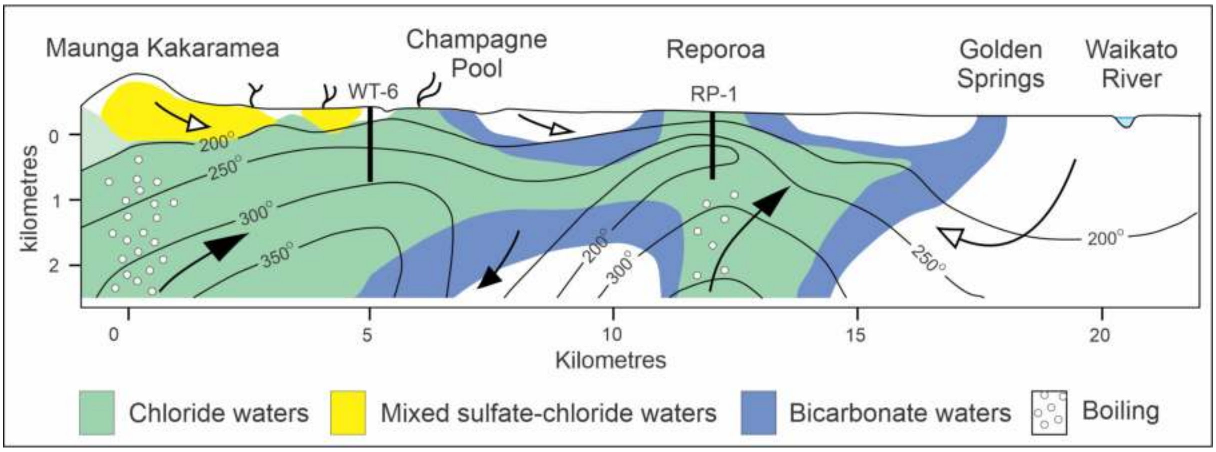

Figure 3.26 Conceptual cross-section model (north-south) for the Waiotapu and Reporoa Geothermal Fields compatible with geochemical evidence (from Giggenbach et al. 1994). Note: different vertical and horizontal scale.

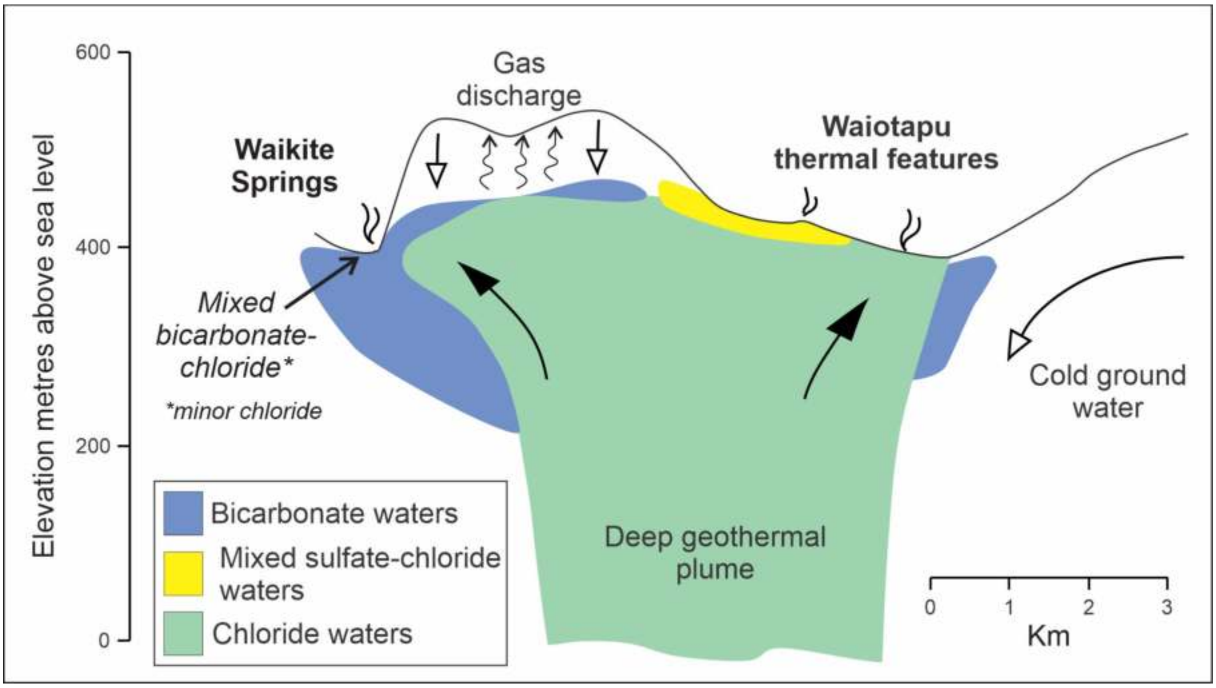

Figure 3.27 Conceptual cross-section model (west-east) for the Waiotapu and Waikite Geothermal Fields (modified from Bibby et al. 1994). Note: different vertical and horizontal scale.

3.6 Vegetation

Geothermal fields present environments for which unique thermotolerant vegetation can grow. Conditions such as heat, hot water, steam, high and low soil/water pH and steam-altered soils present challenging growing conditions. Thus, it is common to see the species that do grow in these areas to be unique to geothermal areas, and therefore ecologically significant both at a national and international scale. Waiotapu and Waikite have 126.8 ha and 84.5 ha of geothermal habitat identified as internationally and nationally significant, respectively (Beadel et al. 2018).

The Waiotapu and Waikite areas have seen much change in vegetation over the last 600 years. Key drivers of change include:

- Early Maori settlement.
- Early European settlement.
- The eruption of Mt Tarawera in 1886.
- Land use intensification and diversification (exotic forestry and pasture).
- Legal protection and management policies for some areas and rehabilitation.

From early times, iwi capitalised on the fertile volcanic soil by harvesting mahinga kai (wild foods) as well as planting crops in and around the Waiotapu and Waikite geothermal areas. Up to the European contact period, fern roots, tuna and koura, ducks and birds provided a staple diet, all of which were plentiful in and around the wetlands and swamps associated with the Waiotapu geothermal area. Fern root was a staple carbohydrate for iwi until the introduction of potatoes and maize. This is supported by the documented accounts of camp sites, houses, earthworks and ochre diggings that were visible prior to forestry and pastoral farming in the early to mid-1900s.The tribe was also known for the proficiency of their weaving skills and flax was abundant in the area and protected to provide ongoing supply when needed. The wetlands of the Otamakokore Stream at Waikite were particularly abundant with flax that was collected and used by iwi long before flax scraping and milling was introduced to the area by Europeans as a means of income.

3.6.1 Current Vegetation Mapping

This section summarises current vegetation and vegetation changes that occurred in the last 20 years. It does not detail earlier vegetation changes.

Figure 3.28 summarises the landcover in the Waiotapu/Waikite areas (Landcare Research 2015). This map is done at a scale of 1:50,000 and so provides a general landcover map. Landcover is dominated (based on area) by high producing exotic grass land, exotic forest and indigenous forest. Areas where surface geothermal activity occurs are punctuated with areas of Manuka and/or Kanaka, and broadleaved indigenous hardwoods. Gorse and broom is mapped on the southern side of Maunga Kakaramea, and mixed exotic shrubland is mapped on the southern end of the Waikite geothermal area. Landcare Research (2015) shows that the landcover classification over the geothermal areas has changed little since 1996, except for the area of gorse and broom on the southern side of Maunga Kakaramea which was mapped as exotic forest in 1996 and 2001. This suggests that the gorse and broom may have grown since the forest was harvested.

Wildland Consultants Ltd. (2014) summarises geothermal vegetation of the Waikato Region in detail. We summarise key elements of this report below.

Approximately 20.2 ha of geothermal vegetation was mapped in the Waikite Geothermal Field (which also encompasses an area defined as the Northern Paeroa Range) (Figures 3.29 and 3.30). It is comprised of c.8.7 ha of geothermal wetland, c.0.9 ha of nonvegetated raw-soilfield, and c.10.6 ha of terrestrial geothermal vegetation. This is mapped over several disjointed areas. Plant species that have been mapped at Waikite include the second largest population in New Zealand of *Christella* aff. *dentata* ("thermal"), *Kunzea ericoides* var. *microflora* (prostrate kanuka), *Cyclosorus interruptus*, *Thelypteris confluens*, *Nephrolepis flexuosa*, *Dicranopteris linearis*, *Hypolepis dicksonioides, Lycopodiella cernua* and *Psilotum nudum.* Reeves et al. (2018b) document remediation works on the wetland that include damming, stream diversion, planting, fencing and pest control to enhance the geothermal environment for thermotolerant vegetation.

Geothermal fern monitoring has been carried out by DOC in the wetland at Waikite since 2010, focused on most of the species listed above. DOC (2019) documents the following:

> "Results from the 2019 monitoring show that overall abundance of live *Christella* fronds has increased yearly from 2010 to 2014. Although numbers decreased between 2014 and 2019, numbers remain high. Overall *Christella* is found in 11 of the 12 sections monitored. The 2019 total displays gradual slight increase since 2017."

The decrease in numbers was reported as likely related to increased shading as the indigenous plantings mature and by changes in water levels since a weir was introduced in 2014 to increase water levels in the wetland.

The Northern Paeroa Range site is relatively small (approximately 0.3 ha) and consists of seven areas with a few prostrate kanuka plants. Monitoring data suggests that there was a large increase in vegetated area (c. 7 ha) between 2004 and 2007 at Waikite (due to the restoration work) (Beadel et al. 2012) but has been no overall change in the amount of area of geothermal vegetation between 2011 and 2014 (Wildland Consultants Ltd. 2014).

Approximately 221.1 ha of geothermal vegetation is mapped at Waiotapu (Figures 3.31 to 3.35) and includes c.181.5 ha of terrestrial vegetation, c.13.2 ha of nonvegetated raw-soilfield, and c.26.4 ha of geothermal wetland (Orutu Wetland). Plant species include prostrate kanuka, *Cyclosorus interruptus*, *Schizaea dichotoma*, *Nephrolepis flexuosa*, *Dicranopteris linearis*, *Calochilus paludosus*, *Calochilus robertsonii*, *Petalochilus alatus, Stegostyla atradenia*, and *Korthalsella salicornioides.* The population of *Cyclosorus interruptus* in Orutu Wetland is the largest population of this species at any geothermal site in New Zealand. Wildland Consultants Ltd. (2014) recognises that pest plants (such as wilding pines) and pigs in the Orutu Wetland are major threats to the geothermal vegetation at Waiotapu. An analysis of aerial photographs between the 1940s and 2007 suggest a decrease in the extent of geothermal vegetation at Ngapouri, Waiotapu North, Maunga Kakaramea, and Waiotapu South, with no change at Maunga Ongaonga (Beadle et al. 2012). Monitoring data suggests that there has been no overall change in the amount of area of geothermal vegetation between 2011 and 2014 (Wildland Consultants Ltd. 2014).

Figure 3.36 provides an example of change in landcover between 1920 and 1999 at the entry of Wai-o-tapu Thermal Wonderland.

A key limitation of the mapping discussed above is that it will only map large areas of vegetation types because mapping is done at regional to local scales, and not to site-specific scales.

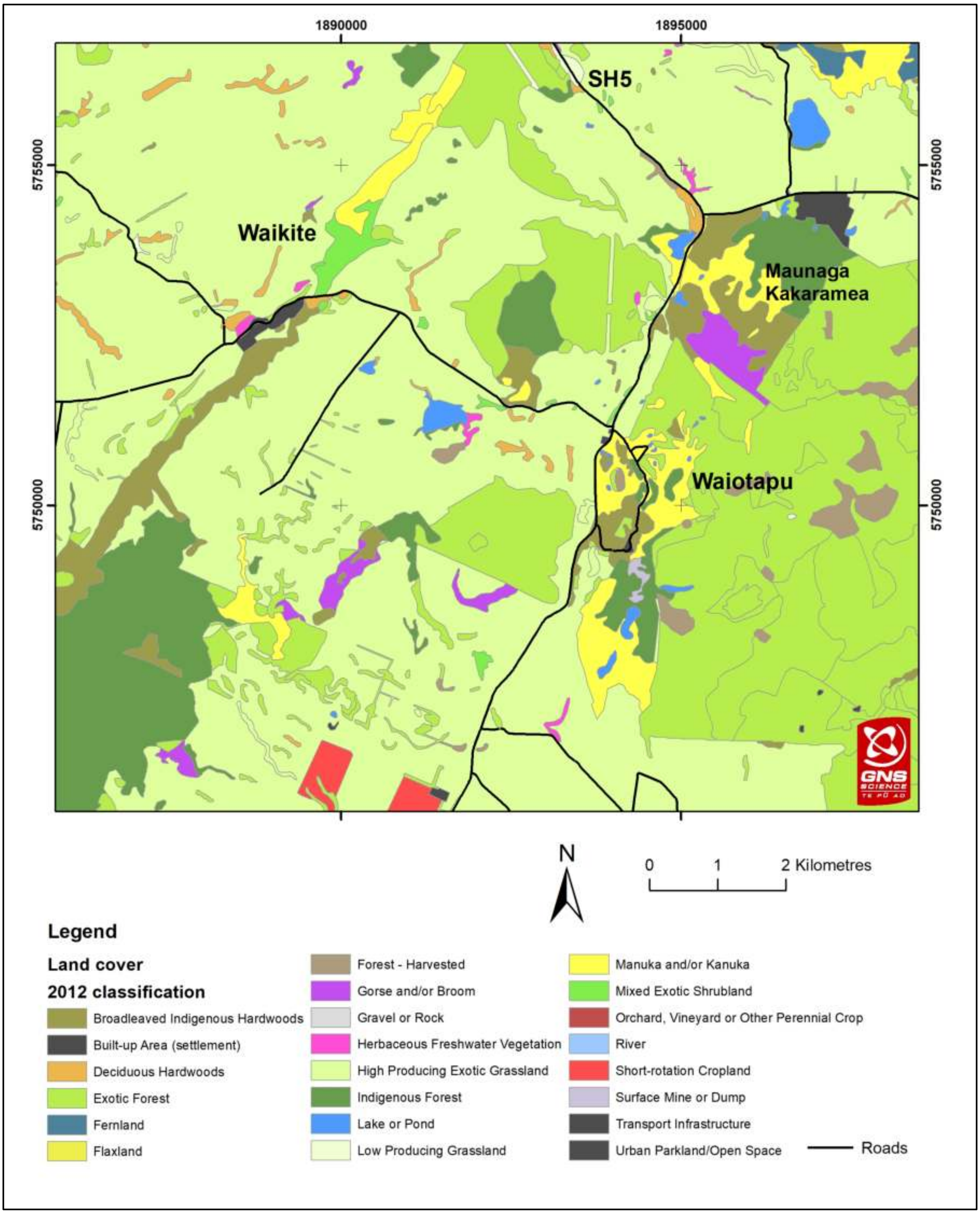

Figure 3.28 Landcover in the Waiotapu/Waikite areas (from Landcare Research (2015).

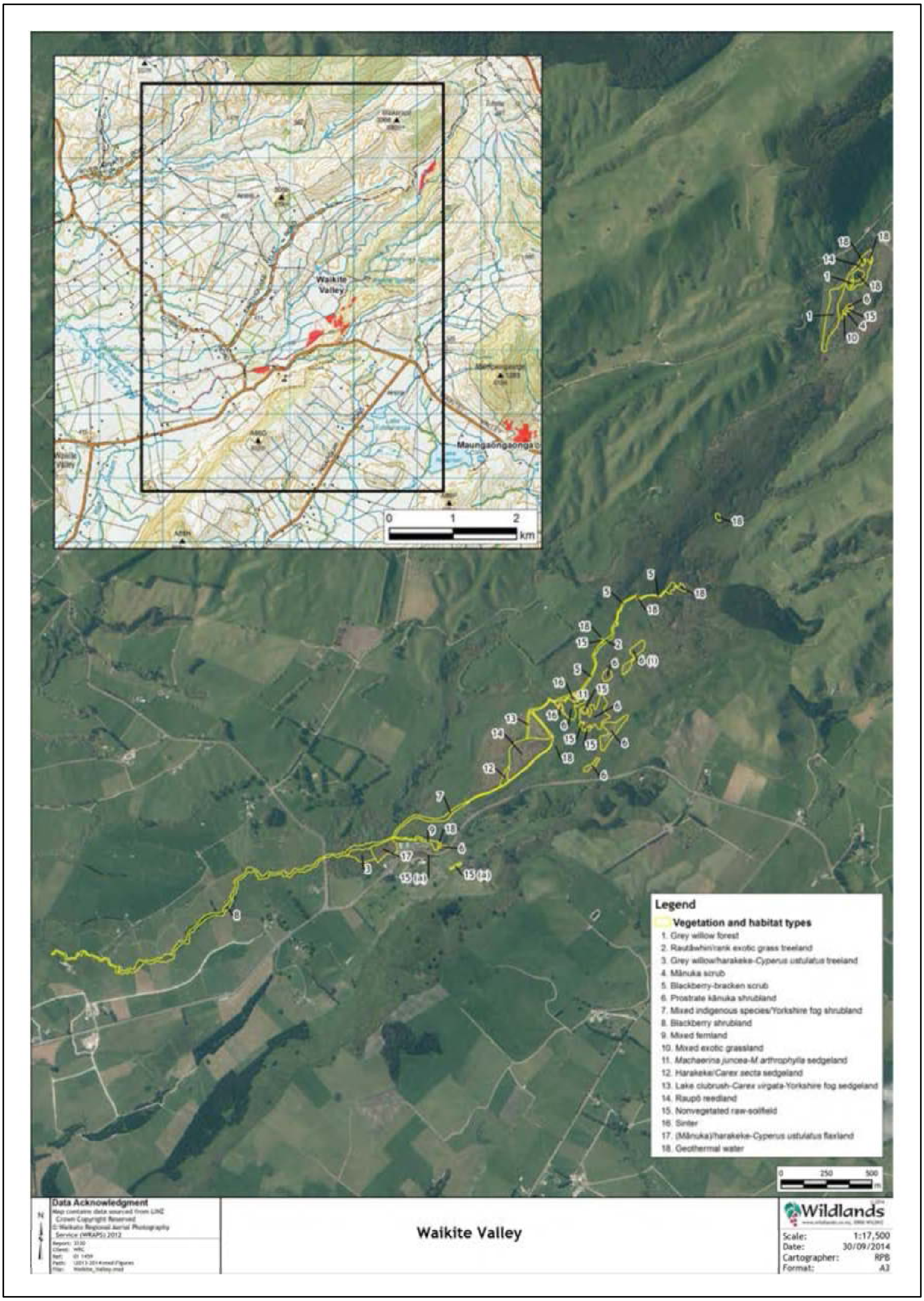

Figure 3.29 Detailed map of geothermal vegetation in the geothermal areas of Waikite (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

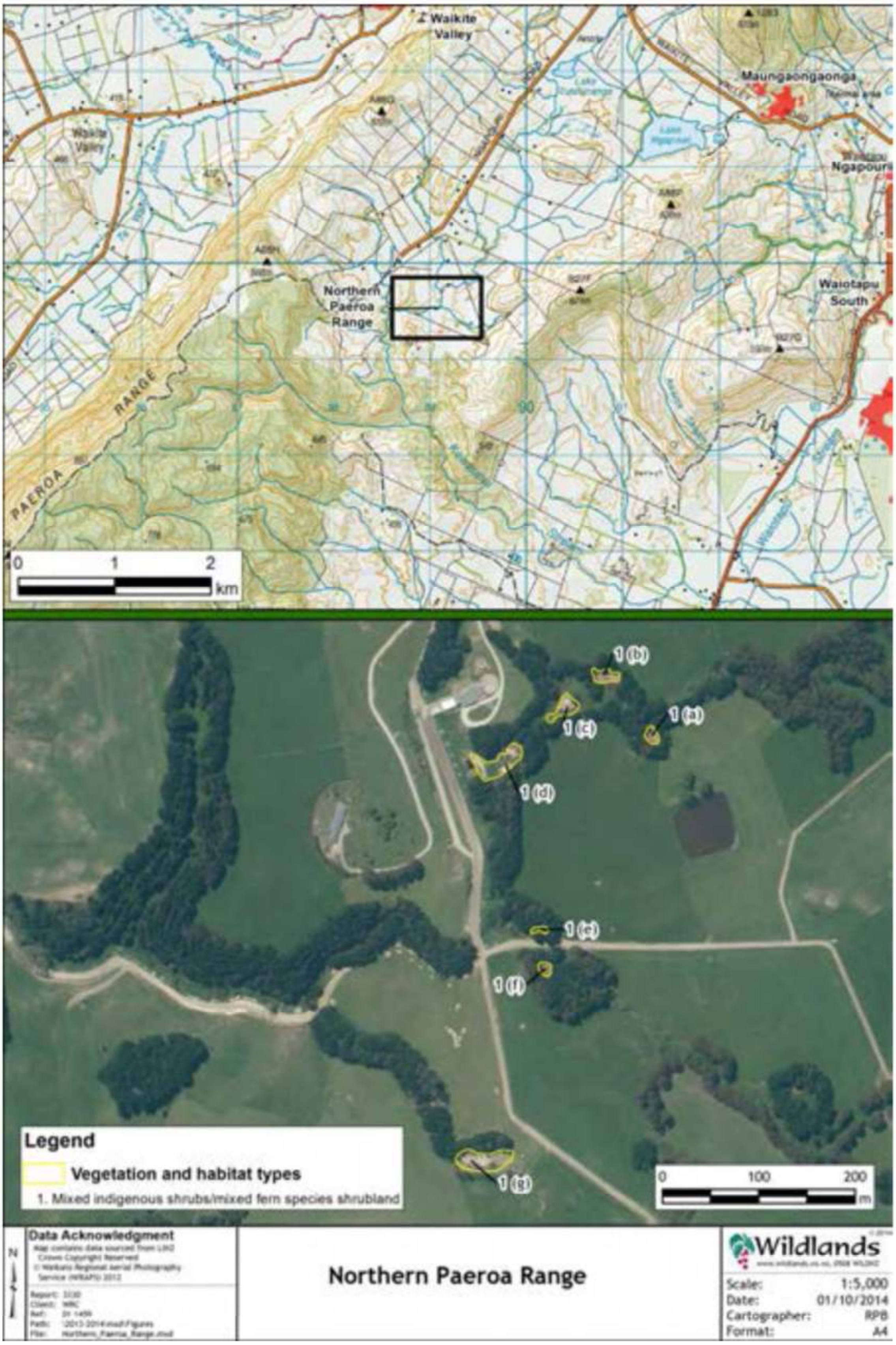

Figure 3.30 Detailed map of geothermal vegetation in the Northern Paeroa Range area (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

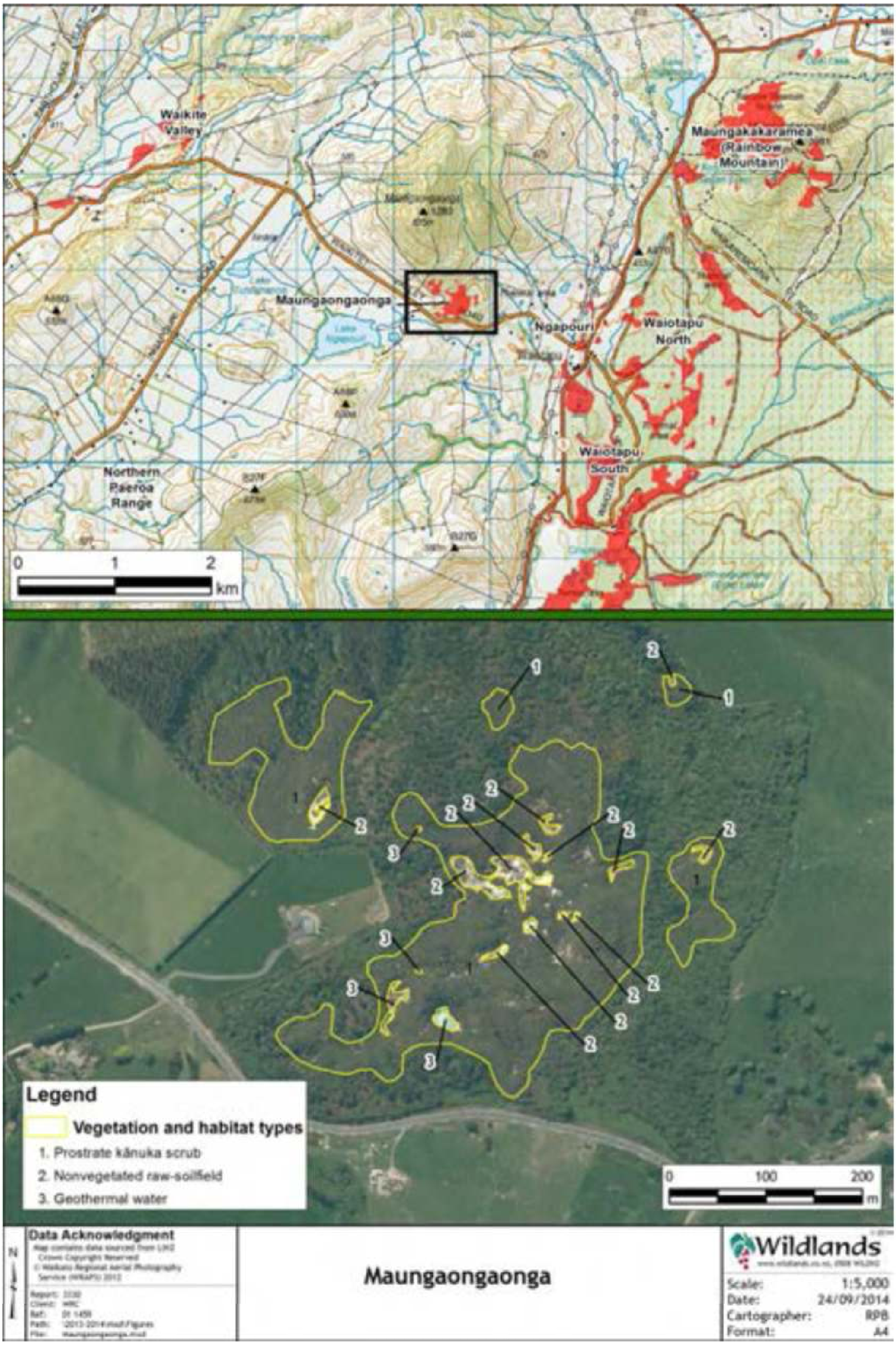

Figure 3.31 Detailed map of geothermal vegetation in the geothermal areas of Maunga Ongaonga (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

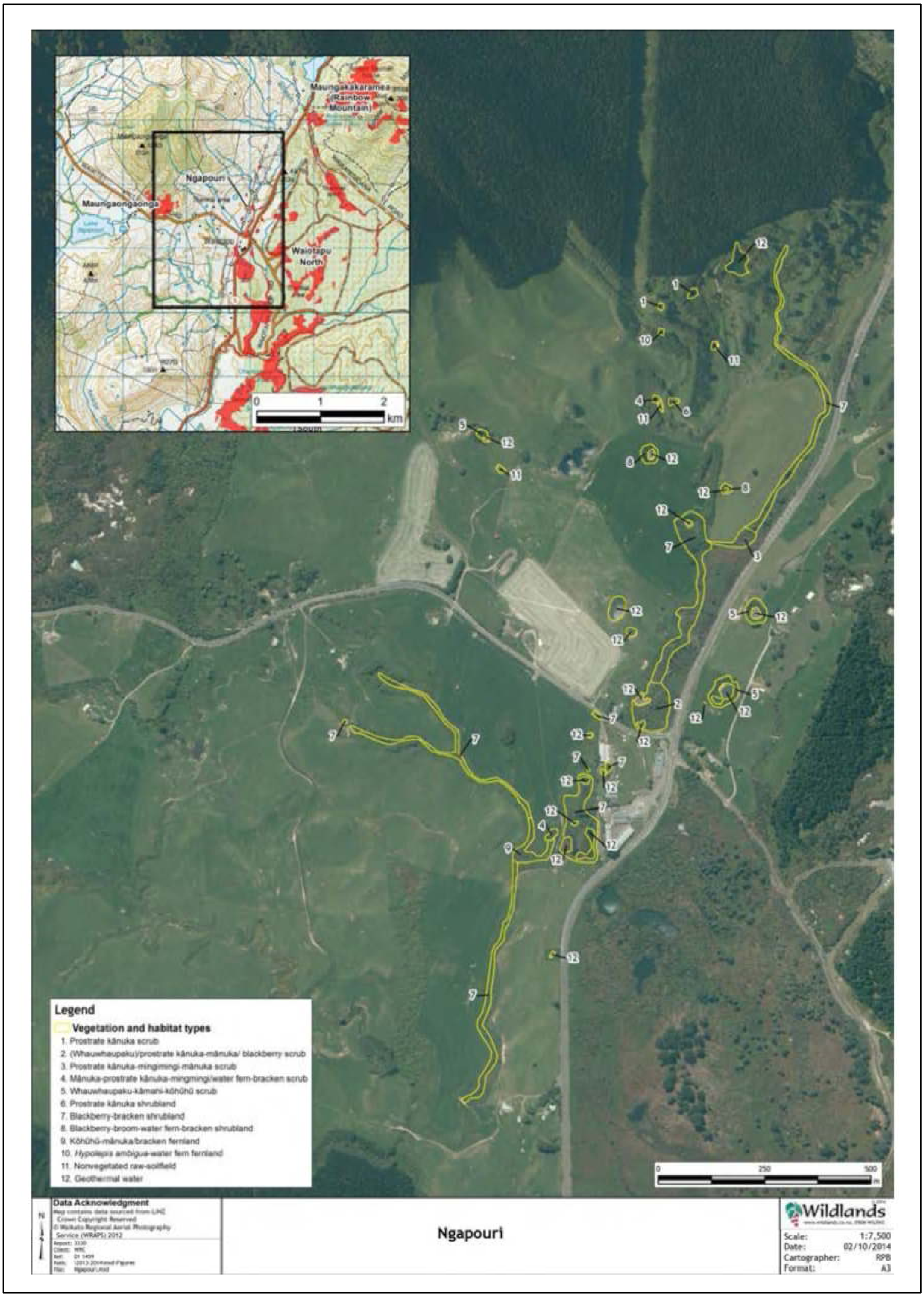

Figure 3.32 Detailed map of geothermal vegetation in the geothermal areas of Ngapouri (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

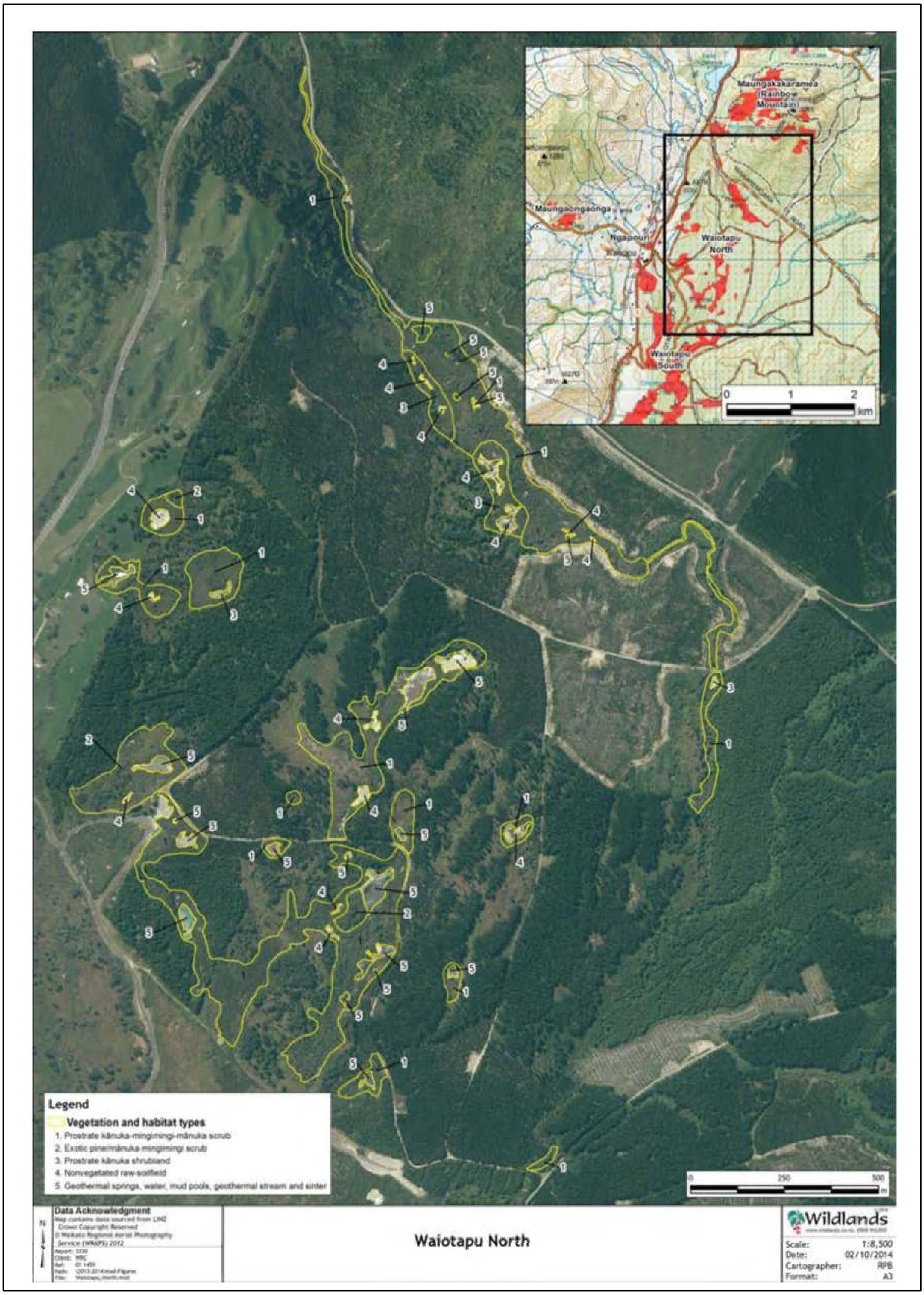

Figure 3.33 Detailed map of geothermal vegetation in the geothermal areas of North Waiotapu (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

Figure 3.34 Detailed map of geothermal vegetation in the geothermal areas of Maunga Kakaramea (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

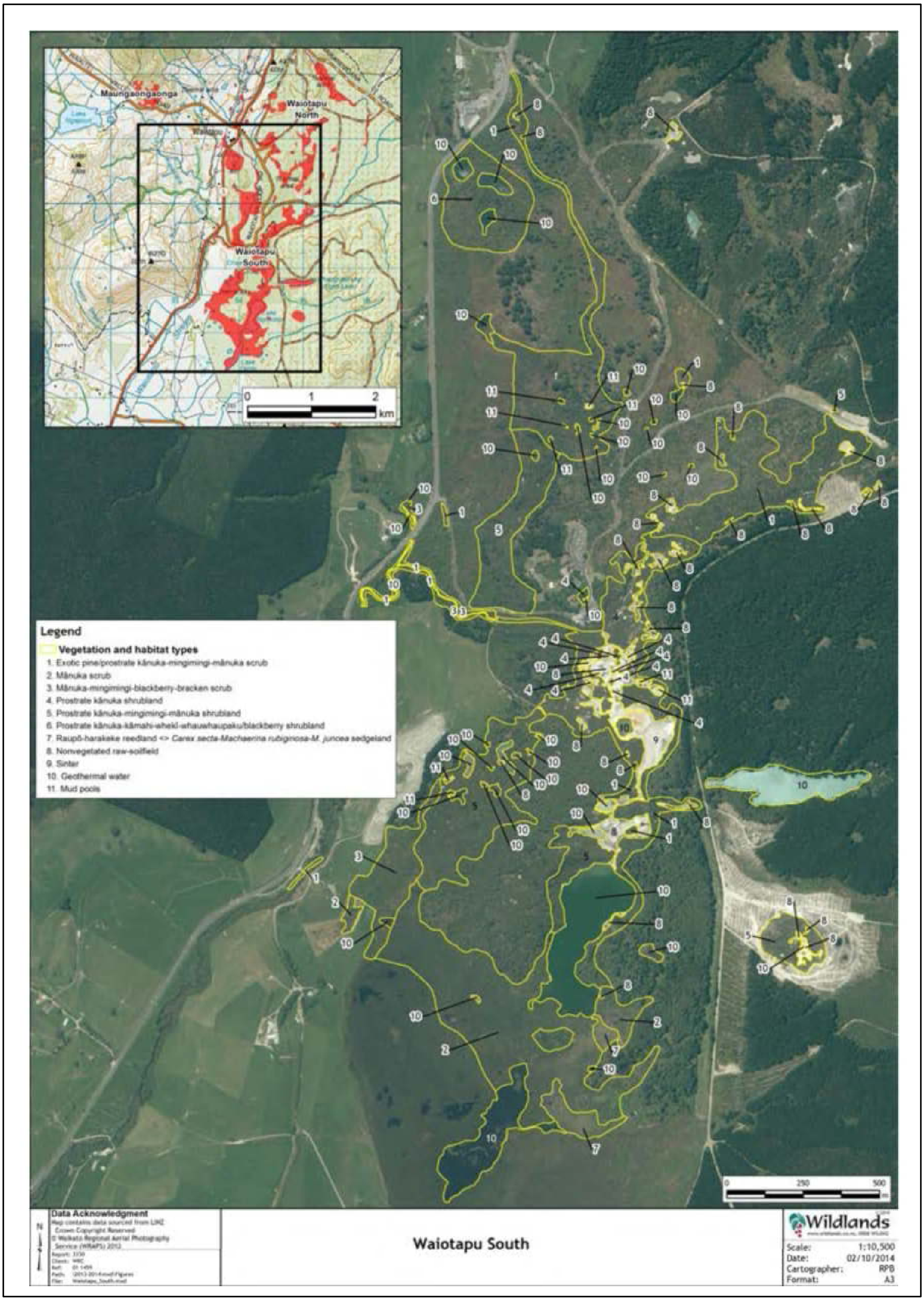

Figure 3.35 Detailed map of geothermal vegetation in the geothermal areas of Waiotapu South area (from Wildland Consultants Ltd. 2014). The insert map shows the area covered in the aerial photograph with red areas showing the locations of geothermal surface activity.

Plate 5A
Overview of Main Crater, Waiotapu, pre 1920 (Source: Rotorua Museum)
Taken from site of original accommodation house

Plate 5B
Overview of Main Crater, Waiotapu, 1999 (Source: Bruce Burns)

Note increase in both geothermal and non-geothermal vegetation

Figure 3.36 Example of change in landcover between 1920 and 1999 in central Waiotapu (from Ward et al. 2000).

3.6.2 Waiotapu Lake Ecosystems

The Ngati Tahu-Ngati Whaoa Iwi Environmental Management Plan (NTNWRT 2019) notes that four lakes in the rohe (Ngakoro, Orotu, Whangioterangi and Rotowhero) are part of the internationally significant geothermal wetland complex at Waiotapu. As the water is geothermal, they do not support the same freshwater life as other lakes, but they are valued as a rare ecosystem.

It goes on to describe the reasons for the high international significance of these lake ecosystems as follows:

- Lake Ngakoro has a rare terrestrial ecosystem on its margins (scrub or shrubland on heated ground), its natural connectivity between the land, lake and geothermal activity is intact. It has a good proportion of native vegetation in the catchment (36%), with some pine present but a wide buffer around the wetland.
- Nearby Lake Orotu has 30% native vegetation in its catchment and its margins are home to the largest known population in the region of the rare geothermal fern *Cyclosorus Interruptus*. The area is smaller than Ngakoro and has nutrient inputs from the farmland to the south.
- Lake Whangioterangi has less indigenous vegetation in the catchment (6%) and a relatively narrow riparian buffer. The lake is approximately 3 ha in size and 25 m deep.
- Lake Rotowhero is a small (2.6 ha) geothermal lake with 7% indigenous vegetation in its catchment and a small but intact riparian buffer. It supports geothermal vegetation on its margins. It is fed by acid sulfate-chloride springs. Algae are the only plants recorded from this lake and the acid conditions are not conducive to fish life.

The geothermal lakes (above) are naturally acidic and unlikely to have ever supported a diversity of fish life. However, they provide habitat for native waterbirds and wetland birds like matata (fernbird), pueto (spotless crack), kawau tui (little shag), kawau tuawhenua (black shag) and weweia (dabchick).

General threats to geothermal vegetation include geothermal fluid extraction (which can alter the surface heat flow) (limited geothermal takes do exist on the geothermal field), tourism and recreation, rubbish, pest plants, livestock, pest animals, fire, development and herbicide/fertilisers (Beadel et al. 2018). Ward et al. (2000) discuss that geothermal vegetation is highly susceptible to trampling and that the public walking tracks at Waiotapu Thermal Wonderland provide adequate protection to prevent more than minimal damage to the surrounding vegetation.

3.6.3 Vegetation Summary

The geothermal system at Waiotapu and Waikite supports a range of unique vegetation that is ecologically significant at national and international scales. The total area consists of approximately 30% of geothermal vegetation/habitats in the Waikato Region. Outside of the geothermal areas, landcover has largely been developed into exotic grass land, exotic forest and indigenous forest.

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APPENDICES

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APPENDIX 1 COMPILATION OF SURFACE GEOTHERMAL FEATURE DATA IN THE WAIOTAPU AND WAIKITE GEOTHERMAL SYSTEMS

Appendix 1 is provided as a file attachment in the PDF file.

APPENDIX 2 GEOTHERMAL SURFACE FEATURES CURRENTLY MONITORED BY WAIKATO REGIONAL COUNCIL

Waikato Regional Council Site Number	Geothermal Field	Name	NZTM Easting	NZTM Northing
3073_107	Waikite	Hot Pools Supply Spring	1888867	5752705
3073_108	Waikite	Pool adjacent to Supply Spring	1888789	5752733
3073_109	Waikite	Scalding Spring	1889804	5753845
3073_110	Waikite	Waikite Scarp and Spring	1889608	5753435
3073_111	Waikite	Waikite Scarp and Spring: Spring 2	1889615	5753438
3073_32	Waikite	WAF5586/Te Manaroa Pool	1888908	5752737
3073_85	Waikite	WAF5651/HT Geyser	1889690	5753471
3074_124	Waiotapu	Kerosene Creek	1896006	5751573
3074_174	Waiotapu	WTF1049 The Hidden Pool	1894834	5749981
3074_177	Waiotapu	WTF1052 Lady Knox Geyser	1895110	5749868
3074_178	Waiotapu	WTF1053 Knox hole spring and channel	1895110	5749868
3074_184	Waiotapu	WTF1059 Weather Pool	1894317	5749245
3074_185	Waiotapu	WTF1060 Devil's Bath	1894246	5749164
3074_192	Waiotapu	WTF1067 Sinter Terraces-Foreground Pool	1894424	5749032
3074_195	Waiotapu	Waiotapu Geyser	1894389	5748719
3074_199	Waiotapu	WTF1075 Oyster Pool	1894414	5748676
3074_212	Waiotapu	WTF1088 Lake Ngakoro	1894344	5748522
3074_280	Waiotapu	Venus Pool in creek on Lady Knox Rd	1894452	5749865
3074_281	Waiotapu	Waiotapu Loop Rd Pools	1893976	5749319
3074_282	Waiotapu	WTF2069 Pool N of Jean Batten Geyser	1894450	5748950
3074_286	Waiotapu	WTF3064 Champagne Pool Sampling Site 3	1894415	5748948
3074_291	Waiotapu	Champagne Pool Sampling Pt 4	1894355	5748943
3074_292	Waiotapu	Kerosene Creek Large Pool	1895989	5751522
3074_293	Waiotapu	Knox hole channel	1895122	5749870
3074_294	Waiotapu	Waiotapu Geyser outlet 1	1894386	5748722
3074_295	Waiotapu	Waiotapu Geyser outlet 2	1894381	5748718
3074_296	Waiotapu	Lake Ngakoro inflow	1894343	5748534

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