Ngā pūnaha ngāwhā o Te Moana-ā-Toitehuatahi

Bay of Plenty Geothermal Systems

The Science Story

GNS Science | Bay of Plenty Regional Council

Environmental Summary Report – September 2021

Prepared by:
Brad Scott – GNS Science,
Paul Scholes – Bay of Plenty Regional Council

This report has been jointly written GNS Science and the Bay of Plenty Regional Council. We acknowledge the mahi of the practitioners and scientists whose work we rely upon, and thank GNS Science, BOPRC Geothermal and Graphics teams for their contributions.

Rārangi upoko
Contents

He kupu whakataki me te take
Introduction and purpose

Kei Toi Moana ngā āhuatanga i raro i te Wāhanga 30 me te Wāhanga 14 o te Ture Whakahaere Rauemi (Resource Management Act – RMA) mō te whakahaeretanga o ngā rauemi ngāwhā. Ka whakahaerehia ngā pūnaha i raro i te Taukī Kaupapa ā-Rohe me ngā whakaritenga ā-rohe, ki te whakamana i te Taukī Kaupapa ā-Rohe o Te Moana-a-Toitehuatahi.

Kei te whakarāpopoto tēnei pūrongorongo i ngā mōhiohio mō Ngā Pūnaha Ngāwhā i Te Moana-a-Toitehuatahi, i ngā mātauranga pūtaiao onāianei o te mātai aronuku, te mātai ahupūngao ā-nuku me te mātai matū. Ka whakaaturia hoki te mōhiohio mō ngā āhuatanga ngāwhā o runga, te wainuku, te whakamahinga hou o ngā pūnaha me ngā aroturukinga anō e whakahaere ana. Ka taea ngā taipitopito mōhiohio o tēnei whakarāpopototanga te kite i ngā pūrongorongo me ngā tuhinga pūtaiao i te rārangi tohutoro me te rārangi pānui.

Kāore he taipitopito kōrero o te whakamihanga Māori me te noho, ko Te Ao/tirohanga mātauranga rānei kei roto.

The Bay of Plenty Regional Council has functions under Section 30 and Section 14 of the Resource Management Act (RMA) including obligations to mange geothermal resources. It manages systems under the Regional Policy Statement and regional plans, to give effect to the Bay of Plenty Regional Policy Statement.

This report summarises information about Geothermal Systems in the Bay of Plenty, the current scientific knowledge of the geology, geophysics and chemistry. Also presented where possible is information for surface geothermal features, aquifer, current use of the systems and other monitoring where conducted. Detailed information on which this summary is based can be found in the reports and scientific papers in the reference and reading list.

A detailed history of Māori use and occupation, or the Te Ao/Mātauranga perspectives of geothermal are not included.

Mātai aronuku ā-rohe

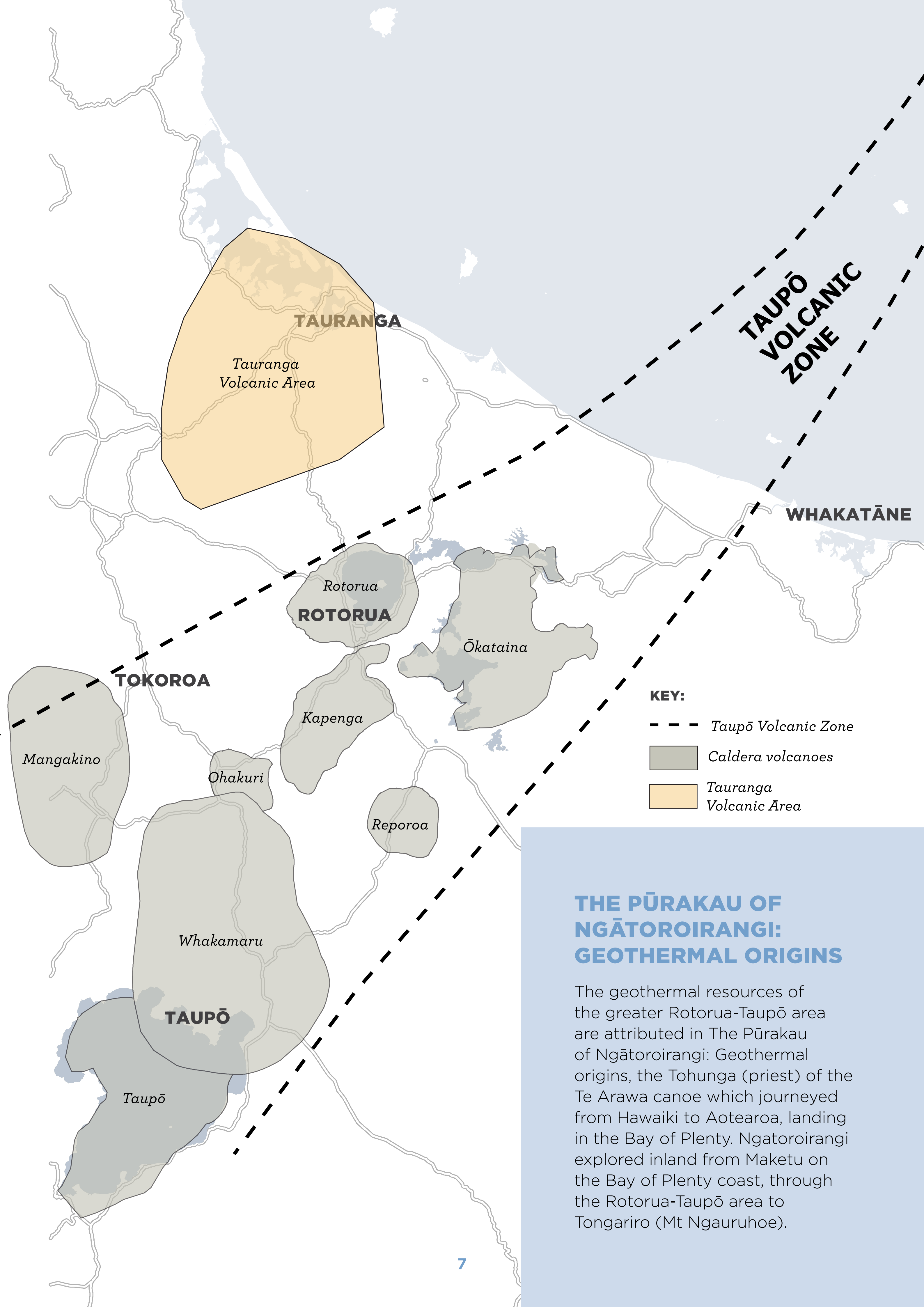
Regional geology setting

The Taupō Volcanic Zone (TVZ) started forming about 2 million years ago as volcanic activity moved east abandoning the Coromandel Volcanic Zone and the associated Tauranga Volcanic Centre. The volcanic activity in these zones is dominated by stratovolcanoes, and large-scale caldera volcanism.

A major feature of the TVZ is the active Ōkataina and Taupō Volcanic Centres. These centres have erupted large volumes of magma (around 160 km^3) in the last 27,000 years from shallow magma storage areas. Three caldera volcanoes have been active in the Bay of Plenty region; Ōkataina, Rotorua and Kapenga. The youngest caldera forming eruption is from the northern portion of Ōkataina about 60,000 years ago. Rotorua caldera formed about 230,000 years ago.

The TVZ is also the focus of substantial heat flow and tectonic activity with a very high density of faulting present.

The TVZ hosts many large-scale geothermal systems, 12 within the Bay of Plenty region.



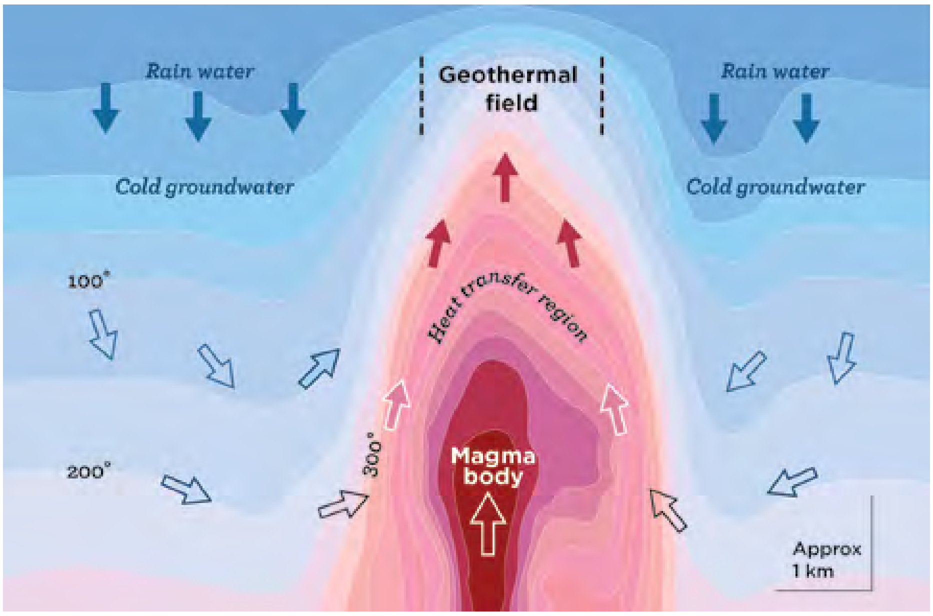
THE PŪRAKAU OF NGĀTOROIRANGI: GEOTHERMAL ORIGINS

The geothermal resources of the greater Rotorua-Taupō area are attributed in The Pūrakau of Ngātoroirangi: Geothermal origins, the Tohunga (priest) of the Te Arawa canoe which journeyed from Hawaiki to Aotearoa, landing in the Bay of Plenty. Ngatoroirangi explored inland from Maketu on the Bay of Plenty coast, through the Rotorua-Taupō area to Tongariro (Mt Ngauruhoe).

Ngāwhāriki / ngā pūnaha ngāwhā
Geothermal systems

He aha te pūnaha ngāwhā
What is a geothermal system

To form a large-scale geothermal system, you need three items to come together. They are a heat source (comes from the caldera volcanoes), water (thanks to the climate we have this) and thirdly fractures for the water to flow through from depth (sometimes many kilometres below the surface) to the surface (regional faulting).



Schematic of a geothermal system

Ka pēhea a Toi Moana e whakamomo ana i ngā ngāwhā

How Bay of Plenty Regional Council classes geothermal systems

New Zealand's geothermal systems are now managed under the Resource Management Act 1991.

Under the Act the Regional Council has responsibility for:

1. **Allocation of geothermal energy and geothermal fluid and discharges to land, air and water**
2. **Protection of the surface features**
3. **Protection of people from geothermal hazards.**

There are several relevant regional planning documents that guide management of the geothermal resource, including the Bay of Plenty Regional Policy Statement and regional plans.

In the Bay of Plenty region the geothermal systems have been classified into management groups which reflect their unique values and current uses. The classification process is set out in the Bay of Plenty Regional Policy Statement (RPS) Part 3. The purpose of the classification is to manage our geothermal resource sustainably by establishing different management purposes for different systems, for example the extractive use of the resource is confined to some geothermal systems, while other systems are protected for their intrinsic values (see Table, page 11).

The management groups and systems are:

Group 1	**Protected systems:** Waimangu-Rotomahana-Tarawera, Moutohorā Island (Whale Island), Whakaari/White Island.
Group 2	**Rotorua system** (mix of preservation and use)
Group 3	**Conditional development systems:** Rotomā-Tikorangi, Tikitere-Ruahine, Taheke and Lake Rotokawa-Mokoia Island.
Group 4	**Development systems:** Kawerau, Lake Rotoiti and Rotomā-Puhipuhi.
Group 5	**Low temperature systems:** Mayor Island (Tuhua), Tauranga-Mount Maunganui (Mauao), Pāpāmoa-Maketu, Awakeri, Pukehinau (Rangitāiki) and Manaohau (Galatea).

Rotorua geothermal systems can be seen in a video here:
https://youtu.be/i8_ZPHV8reg

LOCATION MAP OF BAY OF PLENTY GEOTHERMAL SYSTEMS AND CLASSIFICATIONS

BAY OF PLENTY REGIONAL MANAGEMENT GROUPS RELATED USE AND POTENTIAL USE

Geothermal management group	Geothermal systems	Existing use	Significant geothermal features (SGFs)	Potential for extractive use
Group 1: Protected systems	Waimangu-Rotomāhana Tarawera, Whakaari/ White Island, Moutohorā Island (Whale Island)	No existing extractive use. High tourism value.	Numerous with some outstanding characteristics	No potential for extractive use
Group 2: Rotorua system	Rotorua	High levels of existing use. Extractive and non-extractive including tourism, domestic and municipal.	Numerous with some outstanding characteristics	Limited potential for further extractive use
Group 3: Conditional development systems	Tikitere, Taheke, Ruahine, Lake Rotokawa-Mokoia Island, Rotomā-Tikorangi	Non-extractive use through tourism at Tikitere, well and spring use in other systems. Exploration.	Numerous with some outstanding characteristics	Potential for development of extractive use (heat or fluid).
Group 4: Development systems	Kawerau	High levels of existing use predominantly power generation.	Limited number of SGFs	Potential for development of extractive use (heat or fluid)
	Lake Rotoiti (outflow is in the bed of the lake) Rotomā–Puhipuhi	No existing extractive use.	Few or no SGFs	
Group 5: Low temperature systems	Tauranga–Mount Maunganui (Mauao) Pāpāmoa–Maketu, Awakeri	Varying levels of existing extractive use: domestic, commercial and municipal.	Few or no SGFs	Potential for development of extractive use (heat or fluid)
	Mayor Island (Tuhua), Pukehinau (Rangitāiki), Manaōhau (Galatea)	No existing extractive use.	Few or no SGFs	

Ngā hapori
Communities

The geothermal resources within the Bay of Plenty region are multi-faceted and valued highly. Geothermal resources have significant Māori cultural and ecosystem values and these intrinsic values associated with geothermal ecosystems and Māori cultural use are significant to the region, although are not easily quantified.

Geothermal resources are used extensively within the Bay of Plenty and are valued for a range of reasons. Uses include, for electricity generation, direct use for space and water heating, home heating, public pool heating, industrial use, horticultural purposes and tourism.

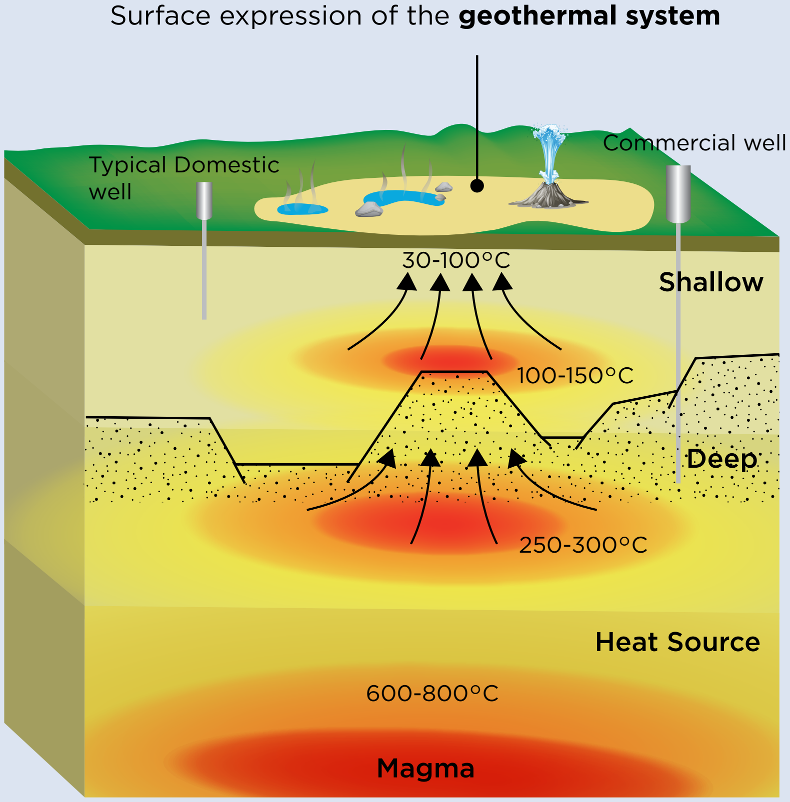
How do you define or map the boundaries of a geothermal system?

For most people a geothermal system is perceived to be the surface features, springs, ponds, lakes and steaming ground. This is the normal perspective and often has emotional or cultural attachment too. However, the subsurface processes and pathways that result in geothermal fluids and gases reaching the surface can have a very different footprint to the surface expression.

One way to think of a geothermal system is a boundary around where the surface features are located. This can work well for managing some aspects of geothermal systems. However, surface features only exist if there are fractures to the surface. So sometimes a geothermal system can extend well beyond the area of surface expression at depth.

Studies of geothermal systems by shallow drilling and geophysical prospecting methods have shown that they are variable under the ground. The most common prospecting method is electrical resistivity. This often looks at 500 m and 1000 m depth. So, using drill hole and resistivity data another boundary can be drawn for a geothermal system. This defines the shallow portion of the system, say the top kilometre.

Exploitation and exploration have shown that geothermal systems extend to several kilometres depth. The very deep portions are explored by drilling and a geophysical method called magnetotellurics (MT). The MT method uses measurements of natural geomagnetic and geoelectric field variation at the Earth's surface. From



Showing extent of surface features, shallow and deep geophysics

these data one can infer much deeper the subsurface electrical conductivity. MT measurements allow detection of resistivity anomalies associated with geothermal down to depths around 8-10 km. While drilling reaches to around 3 km.

In summary geothermal systems can be defined in three depth slices, the surface usually defined by the presence of geothermal features, the shallow or top kilometre defined by DC resistivity and drilling. Then the deep portion by drilling to around 3 km and MT surveys to as much as 10 km depth. Each one of these can produce a different boundary for defining the geothermal system. This variability can create issues in defining and managing the resources. For example, Tikitere-Ruahine system maybe linked to Taheke system, or a possible link between Waimangu-Rotomahana-Tarawera and the Waiotapu system to the south could exist.

Historically, collected datasets can play a vital role not only in producing and understanding conceptual models of the geothermal system, but also provide data to help understand impacts from utilisation of exploitation. Mātauranga Māori knowledge may supplement published research and add to accounts of historical changes of the resource over time. Te Ao Māori perspectives also recognise the interconnectivity of resources and systems and sometimes the ‘boundaries’ defined for planning purposes may not always reflect that.

Ngā āhuatanga ngāwhā o runga
Surface geothermal features

About 3000 surface geothermal features are recognised in the Bay of Plenty. There are a wide variety of types including some of New Zealand's last remaining geysers.

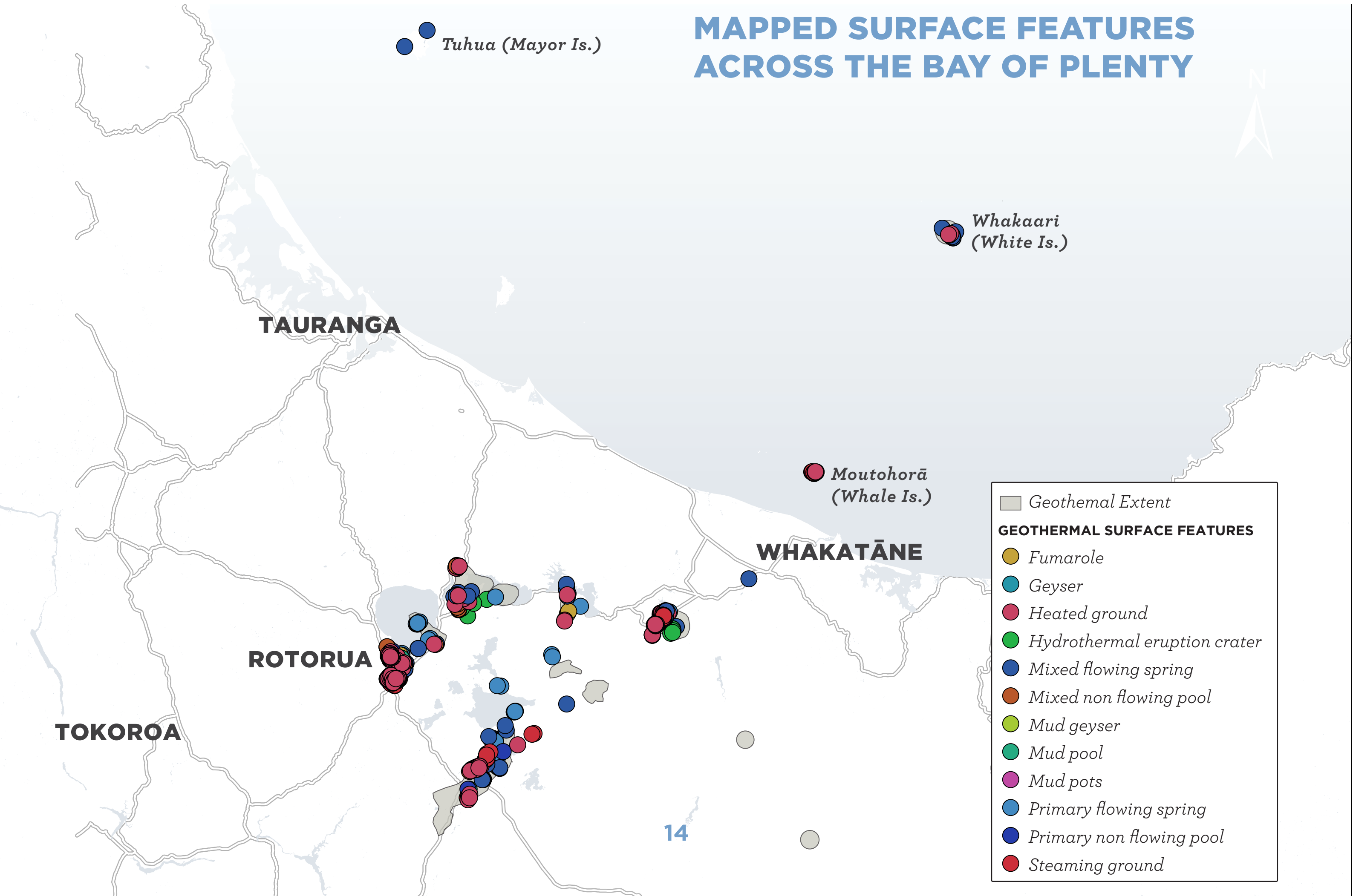
The subsurface processes and pathways result in geothermal fluids and gases reaching the surface to form the wide variety of features seen in the Bay of Plenty.

There are also three habitats associated with surface geothermal features; an aquatic one (springs and streams), the terrestrial one (warm and heated ground) and the micro-climate atmosphere.

This variety can be broken down into four types:

1. Those fed by primary hot geothermal fluids that rise from depth via fractures and come directly to the surface.
2. Those created by the primary hot geothermal fluids mixing with cold shallow groundwater on the way to the surface.
3. Those created by steam mixing with cold shallow groundwater and soils.
4. Those where steam rises to the surface heating the ground.

MAPPED SURFACE FEATURES ACROSS THE BAY OF PLENTY

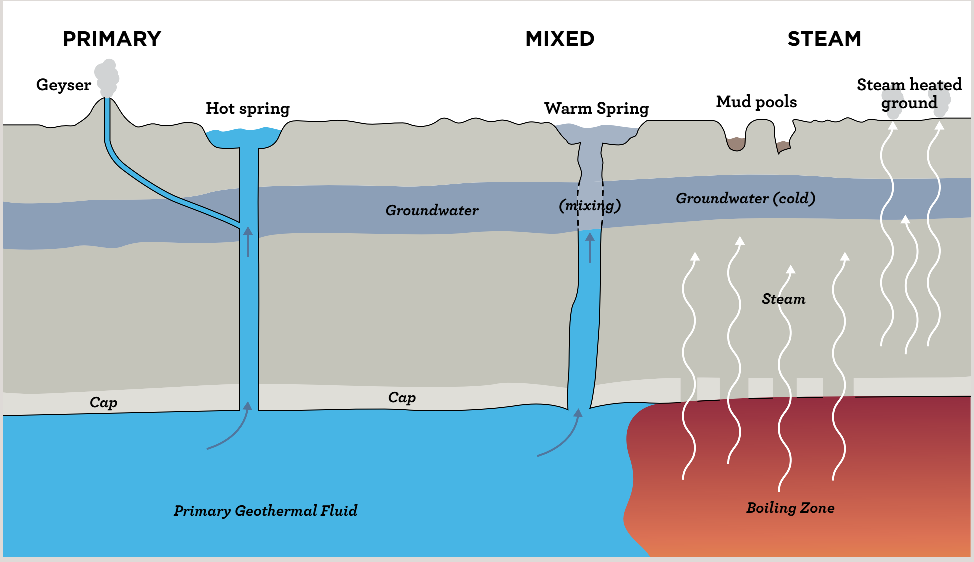


Primary fluid type: A geothermal spring which maintains a continuous (or regular intermittent) overflow of chloride-enriched primary geothermal water or a depression, that naturally receives primary geothermal waters from depth. These are very likely to be sinter-lined and deposit sinter in the overflow channel. The waters in the pools will be clear and hot. Geysers are a special subset.

Mixed fluid type: A geothermal spring which has an overflow of mixed geothermal fluid (geothermal water and ground water) or a depression, that naturally contains mixed geothermal waters. The waters will be acidic, with coloured-milky tones.

Steam heated type: Steam rising from depth mixes with ground water to make acid waters. This makes the grey pools and when soils and clay are included the mud pools form.

Heated Ground: A ground area that radiates heat from underground geothermal sources, discharging steam, diffusively through surface soils. If the steam flow is strong enough a fumarole may form.



SCHEMATIC REPRESENTATION OF SURFACE GEOTHERMAL FEATURES

Aspects of the geothermal feature types can also be seen in a video here: https://youtu.be/CdNi43qQa7o

Te māramatanga o te hua o ngā āhuatanga ngāwhā o runga
Understanding the value of surface geothermal features

The BOP Regional Policy Statement uses criteria to identify the values of surface features, under three groups of values; Natural Science, Aesthetic and Associative.

The natural science factors cover how representative or distinctive a feature may be, along with its diversity or rareness. Also included are the resilience or vulnerability of the feature to change.

The aesthetic values are related to the perception and/or appreciation of the values or principles the community would associate with a surface feature, via how memorable or natural the feature appears.

The associative values examine the extent to which a geothermal feature is valued for its historical, recreational, educational or scientific values and the extent to which a geothermal feature is clearly special or widely valued by Tangata Whenua by reason of traditional values.

It is recognised that there are multiple values associated with the surface features, however, different people can value surface features in different ways.

Based on the criteria defined in the BOPRC RPS it is possible using a numerical ranking scheme (1-5) with descriptors and weightings to establish the relative significance of surface geothermal features. Ideally, all the factors contributing to the values would have equal weighting, but some are arguably more important contributors to overall significance than other criteria. The key ones are rarity, vulnerability and naturalness.

Using only the criteria for natural science and aesthetic values the ranking system ranks the surface geothermal features in this order for significance:

1. **Geyser**
2. **Flowing spring (primary fluid)**
3. **Mud geyser**
4. **Fumarole (steam vents)**
5. **Active mud pots**
6. **Non-flowing spring (primary fluid)**
7. **Mixed flowing spring (mixed chemistry)**
8. **Mud pool**
9. **Intermittent or active hydrothermal crater**
10. **Steaming ground**
11. **Mixed pool (mixed chemistry)**
13. **Heated ground**

The utilisation of fluids from a geothermal system may result in changes in water temperature, chemical composition, groundwater level, and flow rate of surface springs. This may, in part, be caused by changes in the mix between geothermal fluids and groundwater as a consequence of use. How the geothermal system and groundwater system interact (water temperature, chemistry, flows) is key to assessing potential effects on the geothermal resource with increased use in the area.

Te māheuheu ngāwhā me ngā kāinga Geothermal vegetation and habitats

Vegetation growth at Whakarewarewa

Geothermally-influenced landscapes are dynamic ecosystems. The heat and soil chemistry of geothermally-active soils influence vegetation composition and structure. The dominance of geothermal kānuka, mānuka, and mingimingi within areas of heated soils are examples of species that have adapted to geothermal environments. Geothermal habitats are rare ecosystem types in New Zealand.

Geothermal ecosystems also provide habitats for threatened species and represent areas of high biodiversity value. Stream sides, heated ground, and hydrothermally altered ground, which are all found within the Rotorua system, are classified as 'Critically Endangered' ecosystem types. The total of geothermal habitat in the Bay of Plenty Region is approximately 632.4 hectares over 50 sites (based on mapping to 2019).

LAND USE EFFECTS ON SURFACE GEOTHERMAL FEATURES AND ECOSYSTEMS

Geothermal surface features and ecosystems can be threatened by urban development, tracking and earthworks, vegetation clearance, structures, grazing and rubbish disposal. In some cases, surface features are infilled to create useable ground.

The process of urbanisation and land utilisation can also influence natural processes through redirection of heat flow (steam and gas) due to asphalting of road surfaces, building over warm ground and the redirection of runoff into geothermal features or collapse holes.

Human settlement, has reduced the area and function of geothermal ecosystems and they are now recognised as being a high priority for protection.

Explosive mud eruptions from a reactivating geothermal surface feature near Whakarewarewa, Rotorua

Ngā matepā
Hazards

There are several hazards associated with geothermal areas, these include high temperature fluids and steam, gas, subsidence and ground collapse and hydrothermal (steam) eruptions. Mitigation and protection can be achieved by using setbacks and controlling the allowable development activities. Restricting access in areas of known risk.

Ngā rua turakitanga
Collapse holes

A significant problem can be collapsing ground. The formation of collapse holes is a hazard in all geothermal areas. However, this is usually restricted to areas of higher heat flow where steam is present with shallow ground water levels and usually little infrastructure is present.

Weakening of the ground occurs by steam and/or acid condensate altering the ground (hydrothermal alteration), resulting in the formation of a cavity as ground water flows carry clays formed by the hydrothermal alteration away in solution. Such cavities with time can work their way to near the surface and then collapse. Excavation and filling of geothermal areas and surface features will mask the surface activity until it re-establishes itself. This may not always be passive.

Te mimititanga
Subsidence

Subsidence can be induced by production (fluid and heat use) of the large-scale geothermal systems. The rock formations at depth are dewatered and the pores collapse. This was a significant issue in the early production days. Lessons from the early days and reinjection regimes have decreased the occurrence of wide spread subsidence today.

Ngā pupuhatanga ngāwhā
Hydrothermal eruptions

Hydrothermal eruptions can occur in any part of a high-temperature geothermal system, when there is an abundance of steam present. They are difficult to predict and vary greatly in size. However, the more common ones are usually small, only affecting up to 10-15 m of the surrounding area from the vent. Small hydrothermal eruptions are most likely to occur in places where the geothermal heat flow is very high, where there are boiling springs and high steam flows. Geysers are a form of repeated hydrothermal eruption.

Minor events originate at depths of a metre or so below ground and discharge mostly water, mud and blocks to few metres from the vent.

In many of the high temperature geothermal systems, major-very large explosions are preserved in the geological record. The origins are unclear, most likely caused by nearby volcanic activity, related to events like large lake level changes or triggered by major local earthquakes or large distant-regional earthquakes.

The geological record suggests these are very infrequent, occurring a few times in the lifetime of a geothermal system. The related geological event (eruption, earthquake) is likely to have an equally major impact.

Small scale steam and hot water eruption (geysering), Whakarewarewa Village.

HOW DO STEAM ERUPTIONS OCCUR?

Imagine an electric jug on the bench at home. There will be water and steam present as it boils. The lower the water level, the larger the proportion of steam present. As the jug is filled the proportion of steam decreases. The same happens in the geothermal system. As the discharge via bores draws down the water level, more steam is produced in the shallow geothermal aquifer and the likelihood of eruptions increases.

Haurehu
Gas

All geothermal systems produce gas. The Rotorua system is the most famous for its distinctive rotten egg odour, from the hydrogen sulphide (H_2S) gas. Geothermal systems also produce carbon dioxide (CO_2) and methane (CH_4) gas. As the hot fluids rise to the surface they carry the dissolved gases in them. They are released in solution via the surface features or as gas through the soil after separation of the fluid and gas phases. Areas of high gas flux are expected over the up-flow zones and near the strongest surface activity.

Gas can be found in concentrations above lethal thresholds in contained or enclosed locations, however it dilutes quickly in open spaces. If care is taken in enclosed locations the gas hazard is minimal. Health studies do not demonstrate there are any known health issues from geothermal gas.

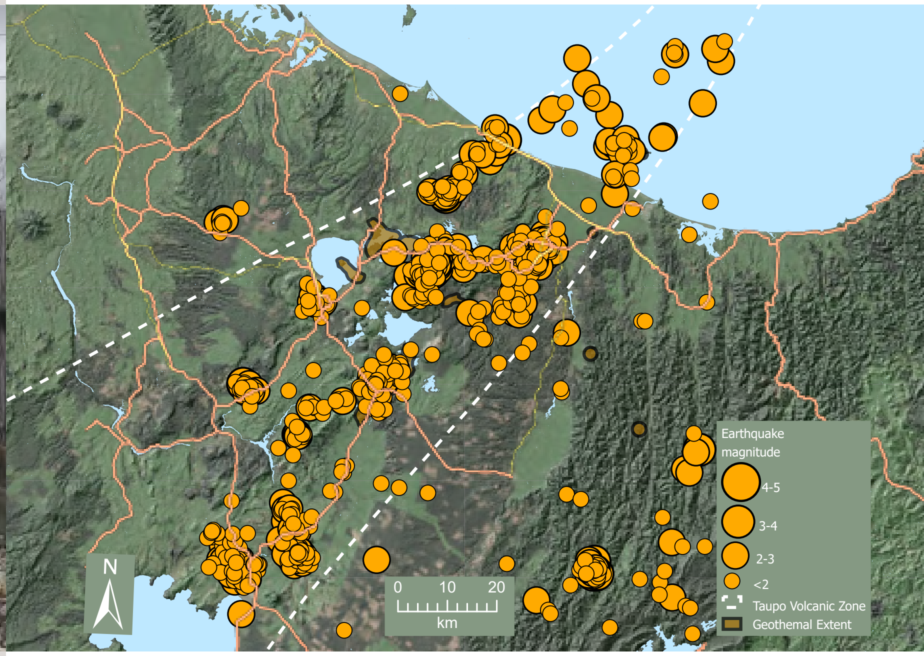
Measuring CO2 at Whakarewarewa, Rotorua

Te mahinga o te rū whenua
Earthquake activity

The Taupō Volcanic Zone is a zone of thinner crust in the greater Rotorua-Taupō area, where due to plate tectonic processes a rift has formed. The rift is characterised by faulting (Taupō Fault Belt) and large-scale caldera volcanoes. These tectonic and volcano process have led to the area being characterised by numerous shallow (less than 30 km deep) earthquakes. Each year around 800-1000 shallow earthquakes are located in the Bay of Plenty area.

Some earthquakes are clustered around the faults, while others focus on the larger volcano-geothermal areas. However not all geothermal or volcanic areas have regular earthquakes. Geothermal production can create small-moderate local earthquakes.

Earthquakes located by the GeoNet project in the last 12 months, 737 events (Jan 2020–Jan 2021), shallower than 30 km depth.



Ngā wāhi ngāwhā i Te Moana-a-Toitehuatahi

Geothermal fields in the Bay of Plenty Region

Following are summaries of the knowledge and understanding of the geothermal systems in the Bay of Plenty region. They are presented in order of the classifications in the Regional Policy Statement (RPS) outlining a description of the resource, management use and development if applicable, current state and trends, models if available and the future outlook.

Some systems have been the focus of research and or development for 50-70 years producing a wealth of information. However, some system information is commercially sensitive and not publicly available. While others have been paid little interest due to size or poor results from early exploration. This is representative of the size of the following summaries.

Group 1 – protected systems

WAIMANGU-ROTOMAHANA-TARAWERA, WHAKAARI/WHITE ISLAND, MOUTOHORĀ ISLAND (WHALE ISLAND)

These contain numerous significant surface features where the vulnerability to extractive use is moderate to high. Surface feature values override extractive values. Protection of the Significant Geothermal Features (SGF), which have outstanding natural, intrinsic, scenic, cultural, heritage and ecological values is a priority. No potential for extractive use.

Waimangu-Rotomahana-Tarawera

A protected system with numerous outstanding surface features of national and international importance. Waimangu Valley-Lake Rotomahana is developed as a tourist attraction (www.waimangu.co.nz). There are various crater lakes and hot springs that are accessible to the public.

MĀTAI ARONUKU ME TE MĀTAI AHUPŪNGAO Ā-NUKU **GEOLOGY AND GEOPHYSICS**

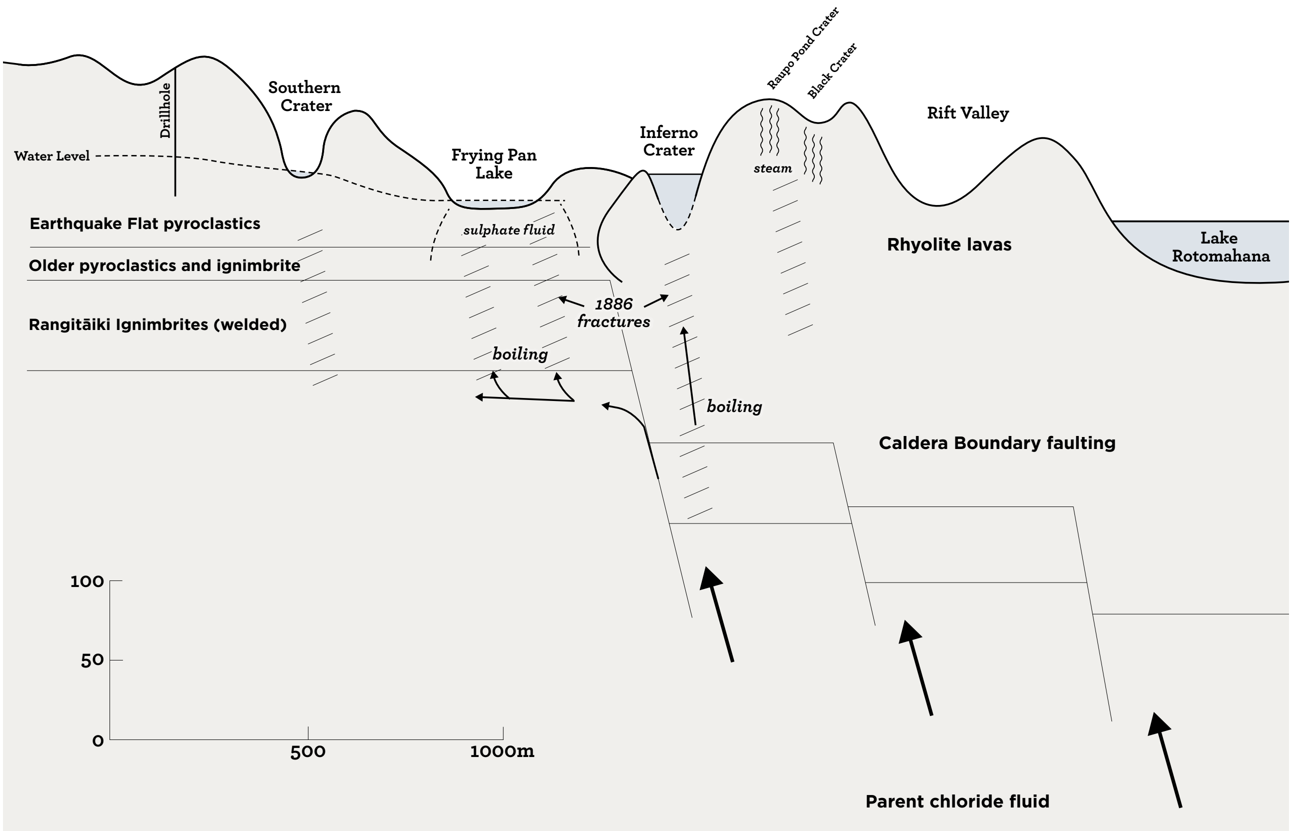
The Waimangu-Rotomahana-Tarawera geothermal field is located across the south-western margin of the Ōkataina Volcanic Centre

(OVC). The 18 km long Tarawera Rift eruption of June 10th 1886 has modified and created the surface expression of geothermal activity in this area. Today the activity is focused in Waimangu Valley and around the south-western shores of and under Lake Rotomahana. This area is unique representing the only geothermal system globally to have had a volcanic eruption through it in recent recorded history.

Prior to the 1886 eruption thermal activity was concentrated around the small, shallow ancestral Lake Rotomahana ('warm lake') home to the famous Pink and White Terraces associated with Otukapuarangi and Te Terata geysers. Following the 1886 eruption, surface activity was focused in the deep 1886 Rotomahana Crater, which soon started to fill drowning features, forming the modern Lake Rotomahana. The Steaming Cliffs on the western edge are now the major surface features including fumaroles, boiling springs and geysers. The geothermal features in the Waimangu Valley did not appear until about 5 years after the eruption. They continue to evolve.

The geology outside of the OVC in the Waimangu area is a flat lying sequence of ignimbrites several 100 m thick, overlain by lava domes. This geology is down faulted into the OVC by the SW boundary collapse faults and structures, in the Lake Rotomahana area.

Like all geothermal systems the Waimangu system can be defined by the surface expression or based on



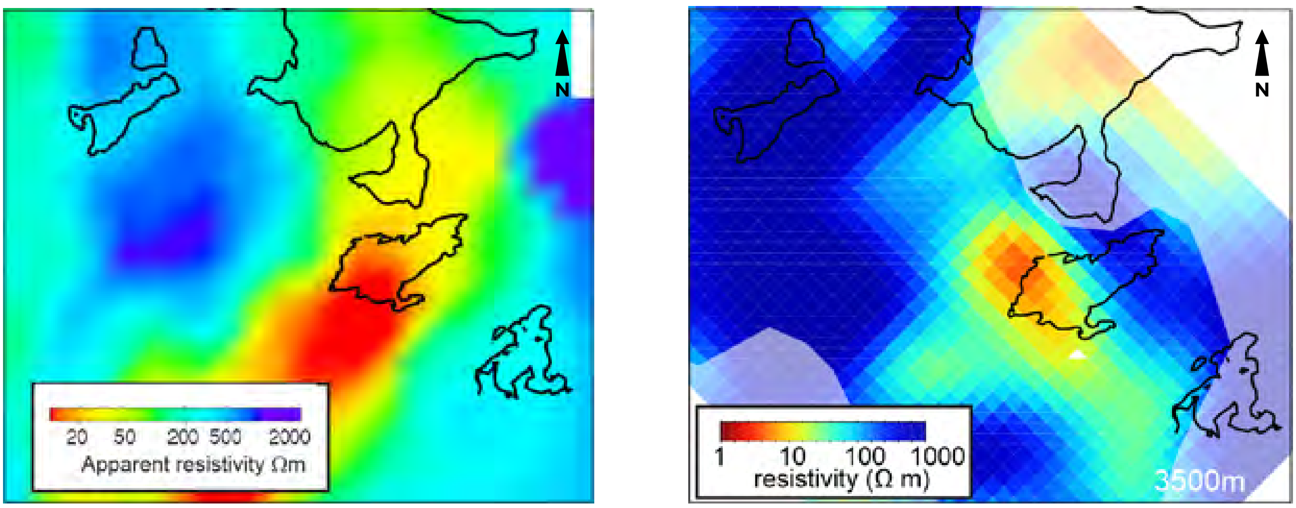
Geological cross section SW to NW showing the geology under Waimangu Valley and in Lake Rotomahana area. After Scott 1991 geophysical data. The geophysical extent of the Waimangu-Rotomahana-Tarawera geothermal field at about 1km depth is broadly defined by the 10 ohm-m resistivity signature. However, it also lies with in a much larger resistivity low defined by the ≤30 ohm-m contour. This larger signature is over 100 km^2 and encloses the geothermal areas of Waiotapu, Waikite and Reporoa. The shallow electrical resistivity data shows a 'separation' from Mount Tarawera and is inconclusive about the separation of Waimangu from Waiotapu.

Deeper looking magnetotelluric data indicates a signal from about 3.5 to 8 km depth associated with the Waimangu-Rotomahana area. In contrast to the shallow resistivity data which trends NE–SW the deeper electrically conductive zone trends NW-SE and lies under the Waimangu-southwestern portion of Lake Rotomahana. Coincident with the OVC boundary and caldera collapse structures. Neither signature indicates a linkage with Mount Tarawera.

MĀTAI AROWAI ME TE MĀTAI MATŪ
HYDROLOGY AND CHEMISTRY

There are no exploration geothermal wells at Waimangu, interpretation of the subsurface hydrology is based on the surface geology, accessory eruption ejecta, shallow groundwater wells and extrapolation from deeper wells nearby at Rainbow Mountain-Waiotapu. This information is combined with the water compositions of the springs to develop an understanding of the subsurface hydrology.

The Waimangu-Rotomahana area is of special interest as the hydrologic changes to the geothermal system are in response to the 1886 Tarawera Rift eruption. Before 1886 the fluid upflow was focused in the terraces area at Lake Rotomahana. The 1886 eruption excavated the shallow part of the upflow zone, fractured pre-existing conduits and created new ones from Rotomahana to the Waimangu Valley area. While the shallow hydrology was greatly transformed the shallow and deep resistivity data and magnetic surveys show sharp boundaries that indicate the deep convective system was probably not perturbed overly by the 1886 eruption.



Maps showing shallow and deep resistivity signatures; a) shallow resistivity, b) deep signal (after Heise et al 2016). Black outlines show southern Rotorua Te Arawa lakes (Lake Rerewhakaaitu to the south-east).

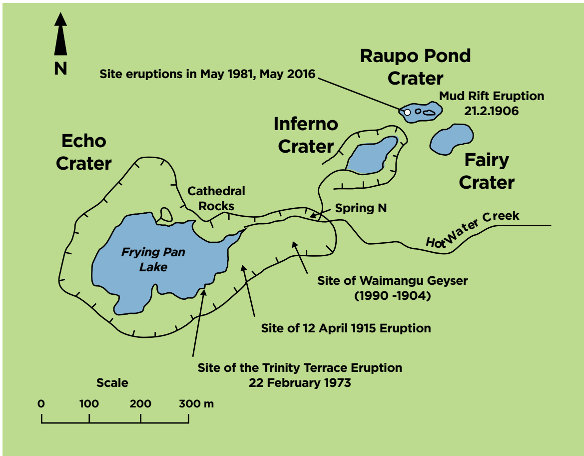
The chemical and isotopic composition of the parent geothermal fluid at Waimangu is distinct from the Waiotapu fluid indicating they are unrelated at depth. Geothermometry of the surface fluids indicate springs in the Waimangu Valley are fed from water at a temperature of around 260-270°C and about 200°C for the Rotomahana Steaming Cliffs area. Enthalpy calculations from the crater lakes at Waimangu also suggest aquifer temperatures around 270-280°C. This is in broad agreement with the resistivity data suggesting a source to the southwest.

However, some isotope geothermometry indicates equilibration temperatures of about 280°C for the Steaming Cliffs area at Rotomahana. This suggests the deep geothermal fluids beneath Waimangu and the Steaming Cliffs have similar temperatures, but near surface conditions cause them to re-equilibrate differently, with cooler temperatures apparent at Rotomahana.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Today the surface features in the Waimangu-Rotomahana area are dominated by large crater lakes, boiling springs discharging near-neutral pH chloride waters of 85-100°C, geysers, fumaroles and hot ground. The surface features in the Waimangu Valley did not appear until about 5 years after the 1886 eruption, while those at Rotomahana evolved as the new lake filled. The largest features are focused in Echo Crater (Waimangu Geyser and Frying Pan Lake) and Inferno Crater. These and the adjacent Raupo Pond Crater have been the focus of several hydrothermal eruptions or disturbances since the early 1900's. The latest was in 2016. The vegetation in the area has all established naturally post the 1886 eruption.

The historic surface activity in or near Echo and Inferno craters is dominated by spectacular geysering associated with the Waimangu Geyser ('black or inky water') that played between 1900 and 1904 ejecting hot water and rock up to 400 m high. A hydrothermal eruption lasting three days within Echo crater in April 1917 created Frying Pan Lake. Since 1971 aspects of the hydrology of two large surface geothermal features at Waimangu have been monitored. Today a complex hydrologic regime dominates between Inferno Crater and Frying Pan Lake with a regular cyclic oscillation in mass discharge and temperature between the two crater lakes.



Map showing primary craters with crater lakes and explosion sites

In 2011 the monitoring of Frying Pan Lake discharge was upgraded in a project jointly funded by Bay of Plenty and Waikato Regional Councils. GNS Science via the GeoNet project also upgraded monitoring of the lake in Inferno Crater in 2012. As the Waimangu system is protected and has no external influences (e.g. drill holes) it makes a good target to record natural variations of a geothermal system. Hence, the data from Waimangu can be used to inform changes observed at other systems. Several perturbations have occurred, including hydrothermal eruptions.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

Although a protected system, Waimangu Valley-Lake Rotomahana has developed as a tourist attraction (waimangu.co.nz). There are numerous outstanding surface features of national and international importance. These range from large crater lakes and hot springs to steaming cliffs and are accessible to the public.

There are no deep bores in the area. One was drilled nearby at Rainbow Mountain; however, its existence was challenged and the threat to Waimangu saw the license revoked. Traditionally the Waimangu-Rotomahana area is considered in context with Mt Tarawera hence the name Waimangu-Rotomahana-Tarawera. The recent deep resistivity data, hot spring chemistry and Lake Rotomahana geophysical surveys and gas flux data challenge this assumption.

Moutohorā (Whale Island)

Moutohorā (Whale) Island is a protected geothermal system and lies about 8 km (11 kilometres from Whakatāne) off the Bay of Plenty coast rising to 353 m above sea level. The island is a Wildlife Management Reserve for endangered birds and plants covering 143 hectare. The name Moutohorā, is a contracted form of Motutohorā, meaning "Whale Island" or "Captured Whale".

Aerial photographs to illustrate western end of the island and surface geothermal expression

MĀTAI ARONUKU ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY AND GEOPHYSICS

The island is the eroded emergent portion of a Quaternary volcanic cone-dome complex. The volcano started its life in a shallow marine-estuary environment. The island is 15 x 5 km wide and elongated east-west. The 353 m high central cone-dome complex is flanked by East Dome, which forms the eastern tip of the island and is the oldest portion (over 60,000 years). The Pa Hill lava dome, which forms the north-west part of the island is over 9000 years old. These three topographic units are separated by two NNE trending faults which have preferentially developed to form valleys that trend inland respectively from Sulphur and McEwans Bays.

Except for reports on the shallow ground surface temperatures about 70 years ago no geophysical investigations have been made to establish the size of the geothermal system. The occurrence of high temperature fumaroles, hot springs and ground temperatures above ambient indicate there is an established geothermal system present. In the absence of data on natural heat output and geophysics to define the extent of the geothermal system, little can be concluded about the resource.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Surface geothermal features are present on the island located primarily between the central cone and Pa Hill lava Dome. Mostly restricted to Sulphur Valley or nearby on the western side of the island. Features include acid hot springs, steaming ground, and fumaroles. Submarine features are also known in the shallow water off the south coast.

Water and gas samples are collected annually by GNS Science as part of the GeoNet volcano monitoring project.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

Numerous archaeological sites of both Māori and European origin have been recorded, including an extensive pa site (Pa Hill) and several house terraces and garden sites, middens, stone tool manufacture areas and stone walls. After permanent Māori occupation ceased in the early nineteenth century, the first European occupation came in the 1830s with an unsuccessful attempt to establish a shore-based whaling station. The venture failed without a single whale being captured. Forty years later came attempts to make money from sulphur. It was extracted and sold to a refinery in Auckland but was of poor quality, and the venture was abandoned in 1895. The next phase of industrial activity came in 1915, when quarrying provided rock for the construction of the Whakatāne River wall. A total of 26,000 tonnes of rock was removed over five years.

The island is a Wildlife Management Reserve and this has led to the island being developed as a tourism attraction. It is one of New Zealand's most restricted pest-free sanctuaries.

Whakaari/White Island

Whakaari/White Island lies 50 kilometres from Whakatāne off the Bay of Plenty coastline. It is an active cone volcano with a Group 1 protected geothermal system. The official gazetted name Whakaari/White Island is a combination of the full Māori name of Te Puia o Whakaari ("The Dramatic Volcano") and White Island given by Captain James Cook in 1769.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

The uninhabited Whakaari/White Island is the 2 x 2.4 kilometre emergent summit of a 16 x 18 kilometre submarine volcano rising from 300-400 metres depth. The island consists of two overlapping volcanic cones, the eastern been younger and the focus of historic volcanic activity and geothermal features. The large amphitheatre like Main Crater is open to the sea with the recent volcanic activity centred about 800 metres from the shore at the western end. A variety of volcanic activity ranging from passive steam and gas emissions, to intermittent small-moderate phreatic (steam), phreatomagmatic (lava and steam), and explosive strombolian (lava) eruptions have occurred historically. The crater floor topography has changed dramatically with time due to landslides and the formation of many new vents and craters. Collapse of the Main Crater wall in 1914 produced a debris avalanche that buried buildings and workers at a sulphur-mining project.

Geophysical and chemical studies show there is a complex and dynamic geothermal system developed around and interacting with the volcanic system. The geothermal system varies in response to the intrusion or eruption of molten rock. Whakaari/White Island has a long and varied history of acid spring discharge, high temperature fumaroles and shallow ephemeral lakes. Between 1976 and 1990, the formation of numerous deep eruption vents resulted in the flow of groundwater flow towards the newly-formed crater(s). This led to the demise of the spring system.

After 2003 ephemeral lakes started to form in the eruption crater complex. Between 2003 and 2015 there were three complete lake filling and evaporative cycles, reflecting varying heat flow through the volcanic system. Lake waters were high in concentrations of chloride (Cl) and sulphate (SO_4) with pH values temporally ranging from + 1.5 to – 1 (acidic). Springs reappeared on the Main Crater floor in 2004, and their discharges varied with lake level.

Source components for the hot springs include magmatic vapour, dissolved andesitic host rocks, seawater and meteoric water. Lake waters consist predominantly of magmatic vapour, meteoric water and solutes derived from the volcanic rocks and their altered derivatives.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

There is no evidence of long-term occupation by Māori due to its rugged terrain, lack of fresh water and continuing volcanic activity.

Attempts were made in the mid-1880s, again from 1898 to 1901, and then from 1913 to 1914, to mine sulphur from the island. Mining came to a halt in September 1914, when part of the western crater rim collapsed, creating a debris avalanche that killed all 10 workers. In 1923, mining was again attempted, however, there was not enough sulphur in the material mined at the island and exploitation ended in the 1930s. Shallow exploration drill holes for sulphur were drilled but no detailed records survive.

Whakaari/White Island is privately owned. It was declared a private scenic reserve in 1953 and is subject to the provisions of the Reserves Act 1977. Visitors cannot land without permission. The main activities on the island have included guided tours and scientific research (marine, biological, geological and chemical). Tourism has been developed on the island and by the early 2000's about 10,000 people visited the island each year with tourism operators. Touristic activities ceased following a fatal volcanic eruption on 9 December 2019.

Group 2 – Rotorua system (mix of preservation and use)

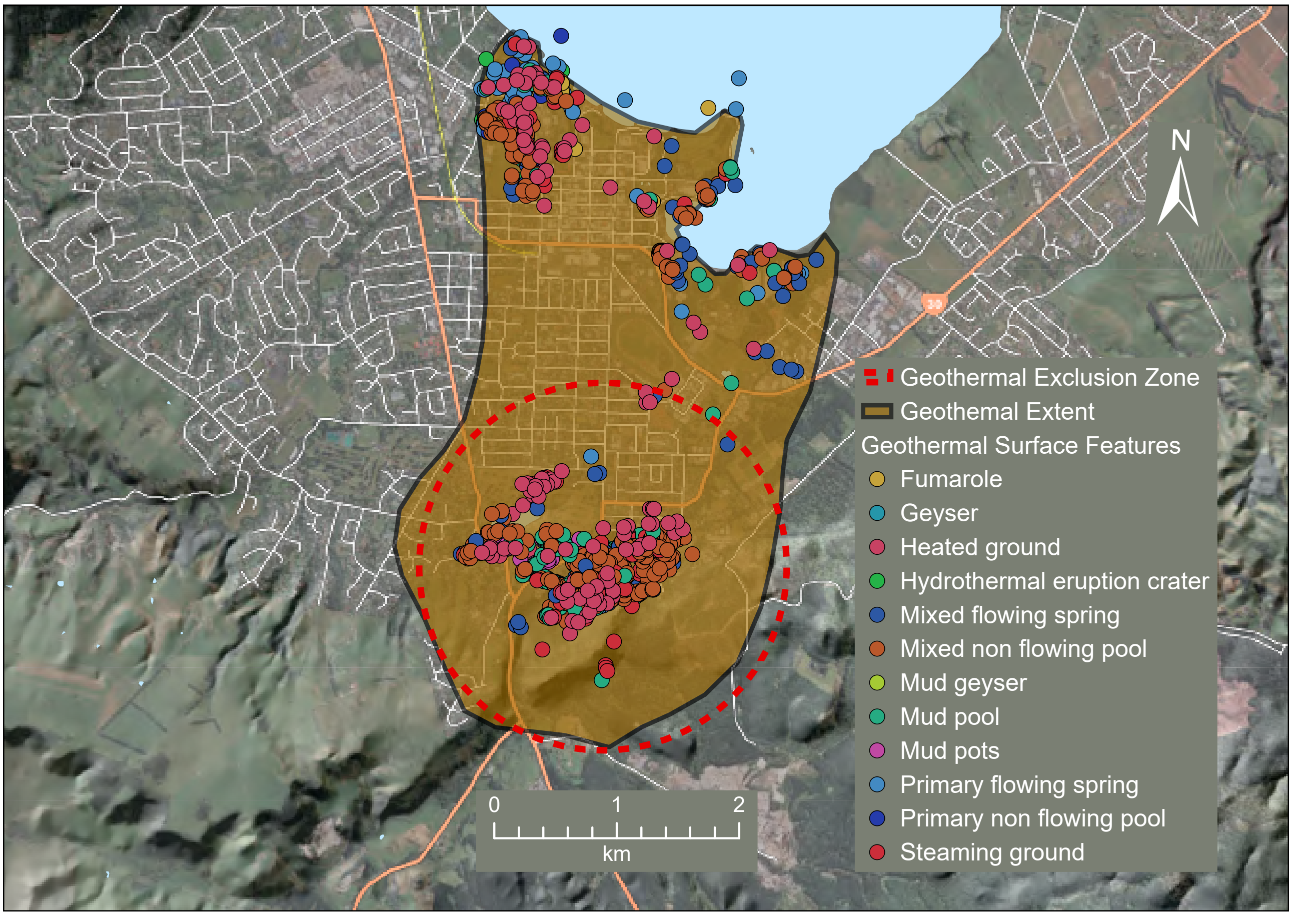
In this system there are high levels of existing use, both extractive and non-extractive. Numerous SGFs, some with outstanding characteristics where the vulnerability to extractive use is high. The Surface feature values rely on reservoir pressure and temperature maintenance and override extractive values. System management that limits extractive uses to avoid, remedy or mitigate adverse effects on the outstanding natural, intrinsic, scenic, cultural, heritage and ecological values. Limited potential for further extractive use.

Rotorua

Initially developed as a spa town using the natural surface features, the Rotorua Geothermal System underlies Rotorua city and has been the focus of significant attention. A growing awareness of the implications of exploitation has led to the need for a stringent management regime so utilisation can be balanced with preservation of the surface features and associated values.

Unique in the world, management regimes introduced in the 1980-90 period and carried over into the Regional Plan have resulted in substantial recovery of the Rotorua Geothermal System.

Further information of the Rotorua geothermal systems can be found on Bay of Plenty Regional Council's website.



Map showing the extent of the Rotorua Geothermal System and location of surface features.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

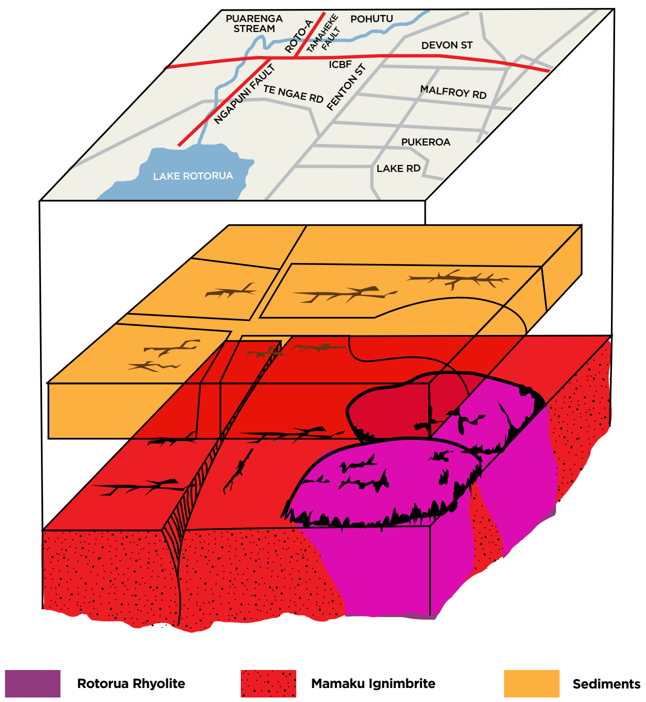
The Rotorua Geothermal System like others in the region is a by-product of the large-scale volcanism in the Rotorua-Taupō area. The very large Rotorua Caldera forming eruption about 230,000 years ago, produced about 200 cubic kilometers of volcanic ignimbrite. Following this eruption, the caldera collapsed to form the modern Rotorua basin. Lava dome building eruptions followed for about 100,000 years leading to features such as Mt Ngongotahā, Mokoia Island, Owhatiura and Pukeroa hill. Erosion has also deposited thick layers of sediment into the basin.

Surface geology, shallow bore hole data and geophysical data give us an understanding of the structures that control the Rotorua geothermal aquifer. There are three key rock types in Rotorua: the ignimbrite; lava of the lava domes; and sediments deposited on the floor of the Rotorua caldera. When the Rotorua caldera collapsed several large fractures (faults) formed in the thick ignimbrite rocks controlling the upward flow of primary geothermal fluid from depth.

Chemistry of the fluids show there is a major up flow of primary geothermal fluids on the eastern side (the Ngāpuna Fault that runs northward from Whakarewarewa to Sulphur Bay). This is also apparent in the deep magnetotallotelluric (MT) geophysics surveys of the region which better define the feed zones. However, there is currently no deep drill hole to quantify these areas. These ascending fluids migrate to the north-west (Kuirau-Ōhinemutu) and south (Arikikapakapa-Whakarewarewa).

Two lava domes that lie over the ignimbrite dominate the geology in the north and west. Pukeroa in the north reaches the surface at Hospital Hill and influences the formation of the surface features at Kuirau and Ōhinemutu. South of Pukeroa is a buried lava dome, Railway Dome. Both lava domes are cracked and broken allowing the flow of primary fluids towards the surface. Across the southern area the structure is complex, dominated by the Inner Caldera Boundary Fault and the Roto-a-Tamaheke Fault. These and other recognised faults feed fluids to the surface features at Whakarewarewa.

Geophysical data indicate at shallow depth the subsurface system covers about 12 km^2; similar in extent to the surface expressions of springs and hot ground. The system also extends about



Block diagram showing the major geological and structural features of the Rotorua Geothermal System

2 km north under the lake and south of Whakarewarewa. Deep survey work indicates near vertical boundaries along the northern and eastern sides and a more complex southern boundary. The magnetotelluric surveys defines a very deep conductive zone that rises from 7-8 km to within about 2.5 km depth underling the south-eastern portion of the Rotorua Caldera.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

About 1500 geothermal surface features are recognised in Rotorua. They represent the full range of surface feature types and include some of New Zealand's last remaining geysers. The subsurface processes and pathways result in geothermal fluids and gases reaching the surface to form the wide variety of features seen in Rotorua. There are also three habitats associated with surface geothermal features; the aquatic one (springs and steams), the terrestrial one (warm and heated ground) and the micro-climate atmosphere.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA

USE AND DEVELOPMENT

Shortly after arrival to the Bay of Plenty coast Te Arawa people started to explore inland. The explorer Ihenga discovered the Rotorua lakes area and soon after people settled on the southern shores of Lake Rotorua. Māori consider geothermal a taonga (treasure), being used for cooking, bathing, heating, ceremonial use and healing for generations.

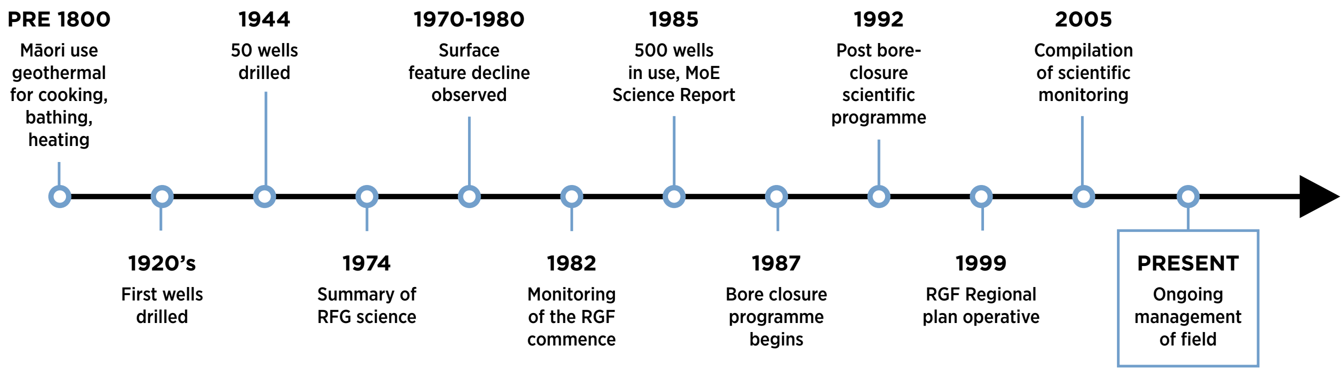
The geysers, flowing springs and other thermal features attracted visitors to the Rotorua area and tourism developed. The New Zealand government leased land from Ngāti Whakaue in the 1880's to establish the town of Rotorua as a European style spa resort for tourists visiting the 'hot lakes'. The spring flows started to be manipulated and modified to provide for bathing and spa development. Demand grew post the 1930's and 40's with tourism, farming and forestry post the second world war seeing bore numbers rise with population growth and power shortages. The first oil shock led to rapid, unregulated, demand growth in the late 1970's.

The decline of surface geothermal activity began as the demand increased. Fluid outflows were severely reduced, and many flowing springs and geysers stopped playing. It became very apparent development was destroying the geothermal surface features of Rotorua. In 1980 the Minister of Energy and the Rotorua District Council announced guidelines for better efficiency and use of geothermal energy, including no new bores with 1.5 km of Whakarewarewa. The Rotorua Monitoring Programme (RMP) was initiated in 1982 to develop a better understanding of the Rotorua system. Many issues were identified around gross inefficiencies and poor licensing.

Action was needed to protect and preserve the Rotorua system. A Government enforced bore closure programme began around 1986; introducing a total ban on geothermal fluid extraction within a 1.5 km radius of Pohutu Geyser and no increased heat take. This change resulted in an estimated 60% reduction in withdrawal of geothermal fluids. The number of shallow bores reduced from about 500 to 140. In 2020 there were over 130 consents for the take and use of geothermal water and energy in Rotorua. Around 90 percent of takes reinject fluid, mitigating depletion of the resource. There are also about forty down hole heat exchangers.

There are several relevant regional planning documents that guide management of the geothermal resource, including the Bay of Plenty Regional Policy Statement and regional plans. The Rotorua Regional Geothermal Plan largely carried over the management regime bought in by the Government. Its purpose is to promote the integrated and sustainable management of the Rotorua geothermal resource. Under the plan the use and discharge of geothermal fluid requires a regional resource consent, unless it is a traditional take for the communal benefit of tangata whenua.

The Rotorua system has a wide range of values. The unique surface features have significant cultural, ecological and landscape values and are a major attraction for tourism in Rotorua. In 2016/17 tourism in Rotorua was a $799 million per annum industry, and indirectly provided about 18% of employment. The continuation of the natural surface activity is vital for Rotorua tourism, a significant sector of the Rotorua economy. Geothermal fluid is directly used for bathing and wellness, including commercial properties and private use. Space and water heating accounts for a significant proportion of the use, including commercial properties, the Rotorua Hospital and municipal facilities. Over 400 homes are heated by geothermal



Rotorua Geothermal System time line

energy in Rotorua. There is currently no geothermal electricity generation or industrial direct heat use.

To quantify the recovery and state of the Rotorua geothermal system the Regional Council in partnership with Crown Research Institutes (GNS, NIWA) and Universities monitor resource consents, the geothermal aquifer, groundwater, surface features, heat flow, fluids and gases. The data is used to assess the management of the geothermal field, monitor the sustainability of current resource use, inform resource management decision making and help develop effective models for long term resource management.

Unique in the world, management regimes introduced in the 1980-90 period and carried over into the Regional Plan have resulted in substantial recovery of the Rotorua Geothermal System. The monitoring data (bores, ground water, surface features) show the system under went aquifer recovery from 1986 to 1994 and has been in a new sustained phase of equilibria where the management regime (extraction and reinjection) and long-term climate are the primary drivers of change.

TE AHUNGA WHAKAMUA
FUTURE DIRECTION

The Regional Council has a robust, scientific consenting and monitoring regime that informs models and the fundamental understanding of the Rotorua system. The Regional Council uses models to help manage the Rotorua Geothermal System.

Modelling is a way of describing the physical features of a geothermal system and predicting the effects of uses. Understanding the interactions between the solid, liquid and gaseous elements of a geothermal field is highly complex. To assist in this understanding and to make predictions of the future behaviour of the Rotorua Geothermal System, computer models have been built that simulate the underground processes. There are two types of model:

- A 'conceptual model' is a representation of a system. The model helps people know, understand, or simulate the geothermal system.
- A 'reservoir' model is a mathematical representation incorporating all the 'characteristics' of the reservoir.

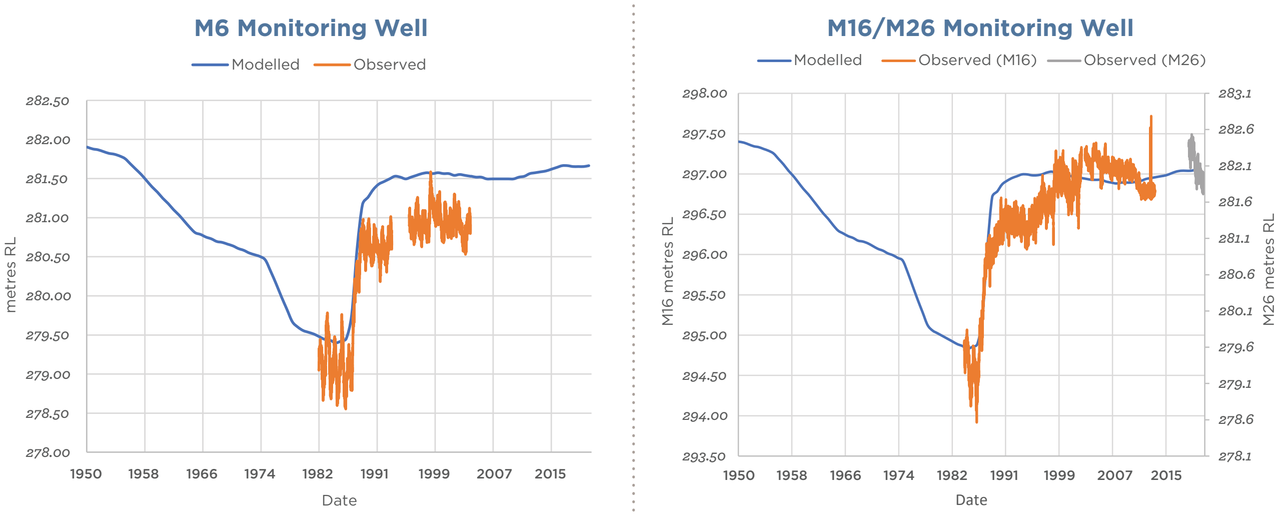
The conceptual model of the Rotorua system was first produced in 1985, with several subsequent revisions. It includes key features like chemistry, fluid flow, geology and energy. The conceptual model is supported by real life data (measured data).

The computational or reservoir model is resolved mathematically by a geothermal simulator or computer program. This calculates the likely pressures, temperatures and flows in a geothermal system based on knowledge of how the system works (i.e. the conceptual understanding). The simulator solves mathematical equations that describe how fluid and heat moves through porous rocks. The output is calibrated by comparing with measured real-life data. Results show the current model to be a good predictor of system response to change.

To improve the fundamental understanding of the Rotorua system, filling some information gaps and shortfalls could improve management of the system. Surface feature monitoring could be improved both through inclusion of more areas, such as Ngāpuna, and by more regular monitoring to investigate shorter term trends.

Changes in groundwater pressure can indicate risk to surface features. Monitoring data on trends in the shallow vs deep aquifers could improve management planning. The Regional Council is also testing ways of measuring the actual use of the geothermal fluid, as opposed to what is consented. Because the fluid is hot, sometimes under pressure and contains gases this is not always easy. The Regional Council has funded development of technology to achieve this and better quantify the actual use.

Geothermal resources have been an integral part of Māori culture in Rotorua. Māori have traditional knowledge of changes and events. Incorporating this knowledge into management of the resource is one of the key future tasks.



Measured (real life data) versus model results for Bores M6, 16 and M26 (source: GNS Science).

Group 3 – conditional development systems

ROTOMĀ-TIKORANGI, TIKITERE-RUAHINE, TAHEKE AND LAKE ROTOKAWA-MOKOIA ISLAND

Varying levels of existing use in these systems. Mainly non-extractive. Some SGFs, where the vulnerability to extractive use is moderate. The values of SGFs have priority over extractive values. System management will provide for use and development, contingent upon the ability to avoid, remedy or mitigate significant adverse effects of development on the SGFs present in these systems. Potential for development of extractive use (heat or fluid).

Rotomā-Tikorangi

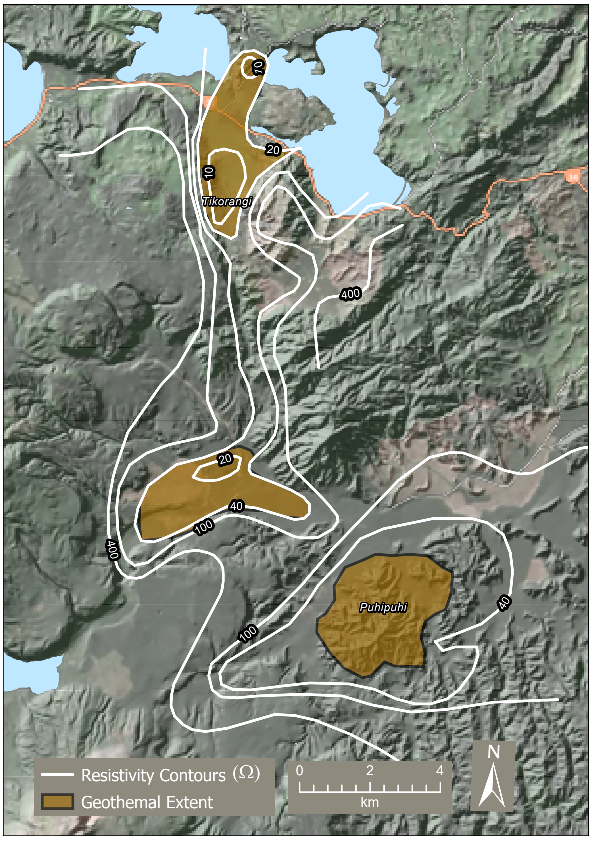
The Rotomā-Tikorangi geothermal system has a small surface expression manifested by few thermal surface features including steaming ground, small fumaroles and warm springs. Located to the south of Lake Rotoehu the field is defined by the low resistivity boundary encompassing an area of around 20 km^2.

MĀTAI ARONUKU ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY AND GEOPHYSICS

The Rotomā-Tikorangi geothermal system is nested within the north-eastern corner the Haroharo-Ōkataina volcanic caldera. This volcanic complex is comprised of young rhyolite lava, volcanic breccia and air-fall tephra within the complex and old rhyolite lavas forming the margins. At Tikorangi, the thermal activity is associated with a small lava dome formed 5500 years ago and characterised by steaming ground, small fumaroles with sulphur sublimates and temperatures of 80–97°C are present.

Geophysical surveys define the extent of the geothermal field in the near surface, and two areas are defined. Aerial magnetic data show a negative magnetic total force anomaly and is interpreted as demagnitised thermally altered rock in the Tikorangi area. Part of the magnetic signature extends north towards the Waitangi Springs and Lake Rotomā, while a second signature extends south to the Mangakotuku Stream.

The resistivity anomaly covers about 40 km^2 and is elongated north-south along the eastern caldera boundary and is over 14 km in length. It is focused on the Tikorangi area. To the north of Tikorangi is the area of lowest apparent resistivity (1.2 km^2) that is interpreted to be a shallow condensate aquifer, which outflows to form the Waitangi and Otei Springs. South of Tikorangi, is a shallow low resistivity layer which is interpreted to represent near-boiling chloride waters and coincides with a demagnetised zone of hydrothermally-altered rocks inferred from the aerial magnetic data. The warm seeps in the Mangakotuku Stream are associated with this signature.



Sketch map showing the resistivity data for the Rotomā-Tikorangi-Puhipuhi area

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Surface features in this area have limited surface expression, although they are spread widely. There is steaming ground and small fumaroles at Tikorangi (80–97°C) and two areas of warm springs 3-4 km further to the north (Waitangi) and northeast (Otei) springs flow into lakes Rotoehu and Rotomā respectively. Warm springs at Mangakotukutuku located about 7 km south of Tikorangi are also considered part of this system.

The Waitangi Spring discharges diluted mixed chloride-bicarbonate waters at 49°C.

Aerial view of steaming ground and small fumaroles at Tikorangi. GNS VML 252644

Waitangi soda spring hot pool

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

Local Māori mined sulphur in this area up until the 1950's. Five shallow exploration bore holes were drilled in 1969 for sulphur prospecting; one bore hole erupted during exploration and measured steam pressure indicated temperatures of 134°C are present.

A few domestic shallow bores are present. The deeper subsurface has been explored by a single exploratory bore (RM1) drilled in 1985. It was drilled near Tikorangi to a depth of 1500 m. The bore encountered rhyolite lava to 650 m that overlies lacustrine sediments and several older ignimbrites. Measured temperatures reveal a high temperature outflow of >220°C around 700 to 1000 m drilled depth. A temperature inversion was found deep in the bore. Subsequent geophysical investigations suggest that the main reservoir is located a little south of RM1 with outflow towards the north.

At Waitangi on the shore of Lake Rotoehu a pool and bath complex has been created to use the warm waters. No routine monitoring of the surface features, outflows or heat are made except for chemical sampling of a spring by the GeoNet project at Waitangi.

Tikitere-Ruahine

The Tikitere-Ruahine geothermal field lies northeast of Rotorua adjacent to the western portion of Lake Rotoiti. Within this area lie Hell's Gate, Maraeroa, Ruahine and the Parengarenga and Manupirua Springs on the shore of Lake Rotoiti. Surface geothermal features also occur in the Rotokawau crater 2 kilometres to the south. The Hells Gate area is a major tourist attraction.

Aerial view of Tikitere (Hells Gate area and mining in background). GNS VML 146268

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

The surface geology is dominated by unwelded ignimbrite and air-fall tephra (20-40 m thick) that overlies the welded Mamaku Ignimbrite. Rhyolite lava also occurs locally to the east. Several hydrothermal eruption breccia deposits occur within the Tikitere-Ruahine geothermal field. Mineralisation of breccia clasts suggest high temperature chloride waters are present at depth. Rhyolite clasts in the breccias are possible indicators of subsurface buried rhyolite domes.

Thermal features also occur 5 km further to the north at Taheke, and it has long been debated if Tikitere-Ruahine and

Taheke are connected at depth and therefore part of the same geothermal system or if they are discrete systems. The near surface extent of the Tikitere-Ruahine geothermal field is poorly defined by the 20 ohm-m resistivity anomaly that covers around 15 km^2. A smaller resistivity anomaly at Taheke covers about 3 km^2.

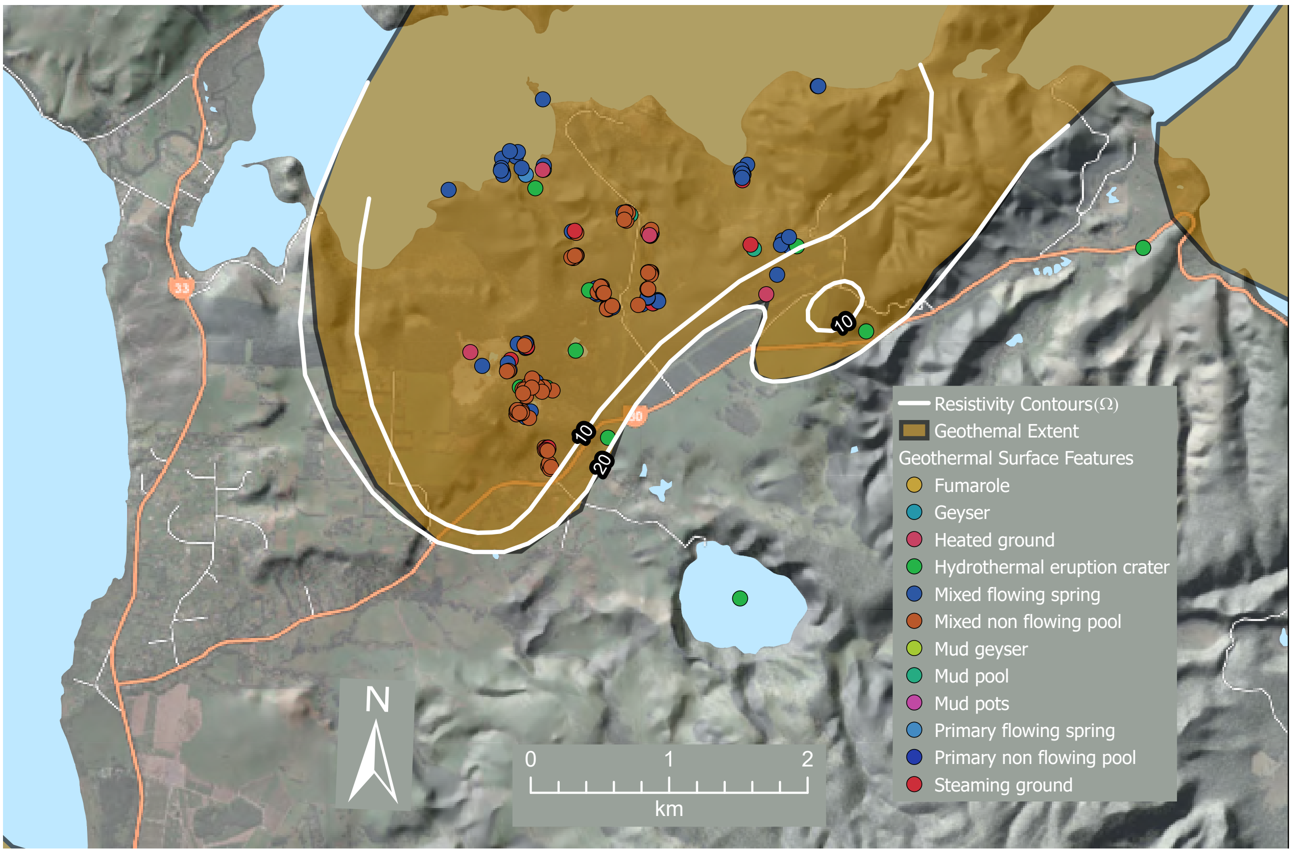
At Tikitere-Ruahine, most springs and pools are acidic and sulphate-rich, with low or no chloride and variable amounts of bicarbonate. The spring flows are small and have relatively high gas emissions. Springs at Manupirua and Parengarenga on the lake edge, and at at Ruahine have up to 308 mg/kg chloride, but steam heated and diluted by groundwater.

Shallow bores have been drilled (70–110 m) near Hell's Gate and discharge diluted chloride waters that have mixed with groundwater and are partly steam-heated. Discharge pressures suggest down-hole temperatures of 140–160°C, while geothermometry temperatures calculated from water chemistry indicate 160–190°C reservoir conditions.

Geochemical models indicate the field is underlain by hot chloride-bicarbonate water with temperatures more than 200°C below about 450 m depth. The current conceptual model for the Tikitere-Ruahine geothermal system consists of a steam-heated cap which extends to around 100 m depth that overlies a two-phase chloride reservoir with temperatures greater than 200°C.

Exploration bore holes have been drilled at Taheke, however these have now been grouted and sealed.

Estimated natural heat output from Tikitere is estimated at 120 MWt (megawatt thermal) and from Taheke is 13 MWt suggesting a significant geothermal reservoir exists.



Tikitere extent based on resitivity and surface features (After Simpson and Bignal 2016 (Geothermics))

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

The Tikitere-Ruahine Geothermal System is classed as Group 3, allowing conditional development. Several shallow wells exist for domestic or minor commercial use. Selected surface features are now monitored by BOPRC while the GeoNet project undertakes chemical sampling of two springs and one bore.

The surface expression is wide spread over an area of about 3 by 2.5 km. Surface activity is dominated by altered heated-steaming ground with diffusive fumaroles that have sulphur sublimates. This is complemented with bubbling to vigorously boiling steam heated clear-muddy pools (30–100°C).

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

The geothermal resource has been used for domestic and bathing purposes for centuries (reportedly 700 years). Tikitere has had a major tourist attraction at Hells Gate for over a century: people were guided through the area from the 1840s.

Geothermal water is used to supply the hot pools at Manupirua Bay on the shores of Lake Rotoiti.

High grade silica used as a pozzolanic cement additive has being extracted from residual amorphous silica deposits near Hell's Gate.

Taheke

The Taheke geothermal field is located adjacent to the north-west shores of Lake Rotoiti and east of the Kaituna River.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

Located predominantly in Rotoiti breccia the Taheke field is underlain by Mamaku and older ignimbrite rock. Structures controlling the Taheke hydrothermal field are not clear, but it may be fed by the same single continuous aquifer at depth as the Tikitere field (Espanola, 1974).

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Surface features in the area are characterised by waters perched in the Rotoiti breccia that are heated by steam containing carbon dioxide, hydrogen sulphide and ammonia. Features emerge from altered breccia and white to grey sinters. Waters range from clear to brown/black emerging at temperatures up to 98°C. There are areas of active steaming ground with sulphur, solfatara, silica residues, weak acid springs (Cody, 2007), and hydrogen sulphide gas detected in the west.

The Taheke Geothermal System classified as Group 3, allowing conditional development. Several shallow bores exist for domestic or minor commercial use. No routine monitoring of the surface features, outflows or heat are made.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

High grade silica used as a pozzolanic cement extracted from residual amorphous silica deposits has been identified at Taheke.

Exploration of the field has been undertaken and is set to be expanded to identify the potential resource in this area

Sulphur deposit around fumarole at Taheke

Lake Rotokawa-Mokoia

The Lake Rotokawa-Mokoia geothermal field lies approximately 7.8 kilometres northeast of Rotorua city. Geothermal bores utilise heat for domestic and commercial use, and some of the hot springs and seeps are used for bathing. Modelling and chemistry indicate these surface features at Mokoia and Rotokawa although separated by the lake are connected at source.

Mokoia Island and Rotokawa area.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

Drilling logs held by BOPRC provide a basic near-surface geological record, suggesting that soils and silty pumice (caldera infill sediments and eruptives) extend to depths of 30 to 85 m, which is underlain by ignimbrite.

Geophysics data sets include a regional investigation of the resistivity in the greater Rotorua area, resistivity traversing survey of the bed of Lake Rotorua and a focussed transient electromagnetic and audio-magnetotelluric survey of Mokoia Island. There has also been a student project targeting resistivity of Lake Rotokawa in the late 1970s. Geochemical analyses of the surface and borehole fluids are also reported.

A conceptual model of the geothermal system around Lake Rotokawa based on the interpretation of shallow resistivity data has been developed. Unfortunately, this conceptual model does not include the area of Mokoia Island.

The conceptual model shows a narrow zone where thermal waters ascend, before mixing with groundwater, and flow west toward Lake Rotorua providing the fluids for the seeps seen at the edge of

Lake Rotorua. Water chemistry shows all the fluids are generally dilute, neutral, sodium chloride waters which suggest that the geothermal fluids probably have been diluted by groundwater. The springs on Mokoia Island also show similar characteristics suggesting that geothermal fluids are mixing with groundwater in this area as well.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Eighteen geothermal surface features were identified in the Lake Rotokawa-Mokoia geothermal system from a surface feature survey of the Bay of Plenty region in 2000-2004.

Surface manifestations in this system occur at three geographic areas: Key surface geothermal features being Lake Rotokawa (east of Rotorua Airport), warm seeps on the lake shore, and several hot springs on Mokoia Island. To the east of Lake Rotokawa discharging spring supplies warm water (~45°C) to the Māori Baths.

On Mokoia Island, the springs lie primarily along the south-east margin of the island. Measured temperatures are up to 61°C and the chemistry is typical of a dilute, neutral pH, sodium-bicarbonate water with a chloride content of 69 mg/kg (Bromley et al., 2006). On the shore of Lake Rotorua, hot seeps occur near Ngunguru Point. At Lake Rotokawa, warm springs and warm ground are documented (40-45°C). There is also a warm spring (23°C) located on the bank of Waingaehe Stream (Wharenui Spring), about 1 kilometre south of Lake Rotokawa.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

The island has a long history of occupation and use of geothermal, and is where Hinemoa warmed herself after swimming to the island guided by Tutanekai's flute according to legend.

Eighteen shallow bores have been drilled in the Lake Rotokawa-Mokoia geothermal system all are located in the proximity to Lake Rotokawa. Bore depths are generally less than 25 m below ground level, with one cold water bore extending to ~100 m.

Consented geothermal water-takes are for domestic use and include the Rotokawa School. The school extracts geothermal water at 115°C and reinjects the same volume at 71°C.

Sampling of Waikimihia Spring (also known as Hinemoa's pool) located on Mokoia Island has been undertaken for research or in response to reported changes.

Waikimihia-Hinemoa's pool, Mokokia Island.

TE AHUNGA WHAKAMUA
FUTURE DIRECTION

An inventory of the uses of surface water, groundwater and geothermal fluids will be important to understanding observed changes in natural geothermal surface features and ground water flows. It is therefore important to maintain an up-to-date record of water-takes and re-injection of geothermal fluids in this system.

An aerial thermal infrared (TIR) survey (Reeves et al. 2014) of the greater Rotorua area includes the Lake Rotokawa-Mokoia geothermal system. It provides a good reference for monitoring the presence and extent of surface geothermal features.

Group 4 – development systems

KAWERAU, LAKE ROTOITI, ROTOMĀ-PUHIPUHI

Varying levels of existing extractive use in these systems. Few or no SGFs with moderate to low vulnerability to extractive use. System management that provides for extractive use, provided significant adverse effects on SGFs are remedied or mitigated. Potential for development of extractive use (heat or fluid).

Kawerau

The Kawerau Geothermal System is located to the north-east of Kawerau within the Bay of Plenty Region, and partially underlies the township of Kawerau. It has been substantially developed for industrial purposes pursuant to resource consents granted by BOPRC under the Resource Management Act 1991 (RMA). This includes geothermal energy being used for electricity generation, industrial processes (direct heat) and cultural purposes.

The Kawerau Geothermal System is based on the inferred resistivity boundary extending over an area of approximately 35 km^2. The system has been developed since the 1950s and understanding of the system has evolved over nearly 70 years. The Kawerau Geothermal System is the only geothermal system in the Bay of Plenty Region that has been the subject of large takes and discharges of geothermal fluid for electricity generation, and industrial direct heat purposes.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

The Kawerau area is part of a rapidly subsiding tectonic fault-graben feature. At around 3 km depth basement greywacke rocks occur. Stacked above is a sequence of locally sourced lavas, distal sourced pyroclastic rocks (some are welded ignimbrite units) with interbedded sands and gravels (alluvium) deposited in the Tarawera River flood plain. Kawerau town sits on sands and gravels (alluvium) deposited by the Tarawera River onto a flood plain. Widely spaced, steeply dipping, northeast-trending normal faults (and cross-cutting northwest-trending faults) and/or fractures occur through the geothermal system from depth to the surface. The faulting and fractures create high local permeability, within otherwise largely impermeable rock.

Hydrothermal eruption breccia deposits are interbedded with Ōkataina Volcanic Centre eruption sequences. This indicates ages of around 16,000 years and 9000 years for the breccias. The Kawerau area is overlooked by the 10,000 year old Pūtauaki (Mount Edgecumbe), a multiple vent dacite-andesite volcano.

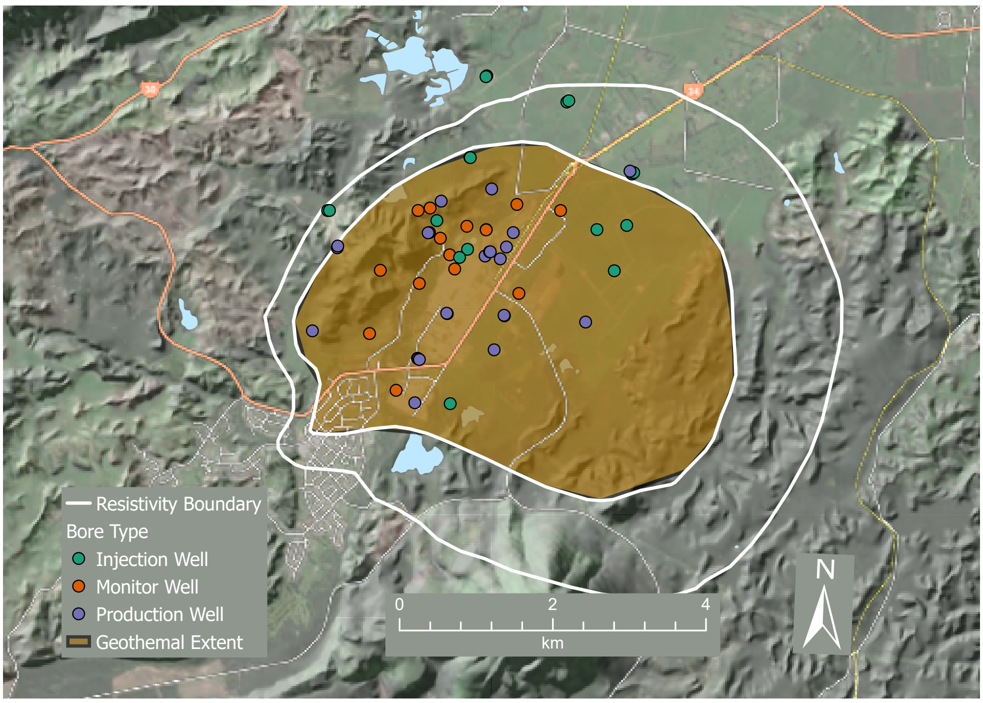
Resistivity surveys reveal an extensive geothermal system at depth. Initial resistivity surveys had shallow penetration, indicating a resource area of 10 km^2 at around 250 m depth. Later surveys with deeper penetration defined the boundary zone of the Kawerau geothermal system to encompasses an area between 19 and 35 km^2. Magnetotelluric (MT) surveys now identify a deeper geophysical field boundary and underlying resistive reservoir to over 1500 m depth.

The geothermal fluids are gas rich and show a wide range in the primary chloride waters and other elements. The chemistry composition of the fluids seen in the bores and groundwater has changed as a response to utilisation of the geothermal system. Changes include dilution and declining temperatures in the shallow reservoir, with precipitation of calcite in bores and associated feed zones. The well temperature data, fluid inclusion data, alteration mineralogy and the MT survey data suggest that the reservoir has been hotter in the past to the north of the field.

Today the highest measured subsurface geothermal fluid temperatures and pressures at Kawerau occur towards the southern part of the system, in the vicinity of the Putauaki volcano. This is consistent with the deep upflow and major heat source occurring in this part of the system.

The major changes seen with time are mixing of cold groundwater and deep production fluids.

The conceptual model of the Kawerau geothermal field indicates that deeply sourced hot water is moving upwards through the basement greywacke via the steeply dipping, normal faults (and cross-cutting faults) and/or fractures. Zones of high local permeability exist. Hot water spreads laterally into permeable zones via the horizontal volcanic and sedimentary layers. The highest measured bore temperatures (>300°C) occur in the southern part of the field. There is also a subsurface outflow extending to the north, mixing with groundwater beneath the Tarawera–Rangitāiki flood plain. This model is supported by measured bore temperature, permeability, fluid chemistry and resistivity/gravity surveys. The conceptual model includes two cool water downflows.



Kawerau geothermal low resistivity contours and well locations.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

Surface geothermal features at Kawerau are concentrated in a 2 km^2 area. Prior to development they included hot springs, seepages, sinters, hydrothermal eruption vents, altered and steaming ground, and small fumaroles. The features were at Onepu, with springs and seepages along the banks of the Tarawera River and around Lake Rotoitipaku, and steaming ground near the township.

Interpretation of early chemical and physical data and feature descriptions indicates the thermal activity suffered decline during the early 1900s, prior to exploitation of the geothermal resource. Latter changes in the surface features is a mix of the exploitation and downcutting by the Tarawera River. Apart from seepages into the Tarawera River most of the features at Kawerau are no longer discharging. Aerial photographs and thermal infrared imagery indicated that areas of bare ground and stressed vegetation decreased in size from 1945 to present.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

Geothermal development started with scientific surveys and shallow drilling in 1951/52. Production was initiated by Tasman Pulp and Paper Company (Norske Skog Tasman-Tasman industrial complex).

Today the timber, pulp and paper factories utilise steam for process heat, electricity generation and timber drying. Bay of Plenty Energy developed two binary plants to generate electricity. Until 2005 the geothermal resource at Kawerau was owned by the Crown. In July 2005 the Crown negotiated a Treaty of Waitangi settlement with Ngāti Tūwharetoa Ki Kawerau, resulting in a transaction between the Crown, Mighty River Power (MRP) and Ngāti Tūwharetoa Settlement Trust (NTST). The Crown transferred the geothermal assets to MRP. MRP then sold most of the geothermal assets to NTST. These assets are managed by Ngāti Tūwharetoa Geothermal Assets (NTGA) along with TOPP1 power station, which generated 24 megawatt electrical power in 2013.

The 100 megawatt Kawerau Geothermal Power Station owned by Mercury (KGL) opened in 2008. The Te Ahi O Māui (TAOM) power station was commissioned in September 2018. New wells have been drilled over the years to replace declining injection wells and to improve production. There are currently four Consent Holders taking geothermal fluid and energy for industrial direct heat uses and for electricity generation, including Mercury (KGL), NTGA, Geothermal Developments Limited (GDL) and Te Ahi O Māui (TAOM). These consent holders report annually to BOPRC on their consented activities and monitoring of the system.

Geothermal use – Kawerau.

Extensive reservoir monitoring is undertaken by consent holders as a condition of their consent in order to detect any changes or responses in the exploited reservoir. This monitoring includes bore testing; groundwater levels, chemistry, temperature; geothermal surface features, photographic survey, vegetation patterns, airborne infrared, levelling surveys, micro-seismicity and air emissions.

The injection of fluids into the greywacke basement provides pressure support to the deep reservoir helping to reduce any changes deeper in the reservoir which could be communicated to the shallow reservoir. Consent conditions generally specify deep injection into the greywacke basement for pressure support.

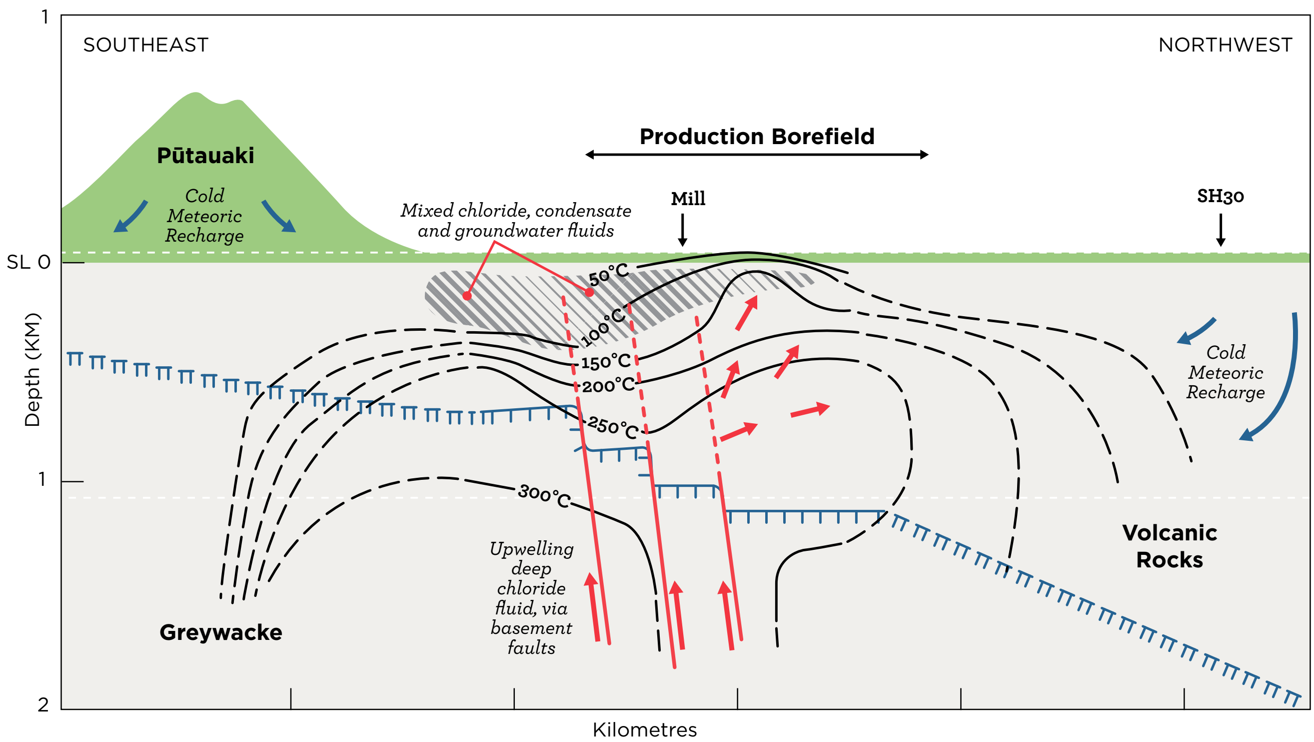
Local surface subsidence has been measured at Kawerau since the 1970s. A broad area of subsidence extends over about 6 km^2, with a smaller localised area within. Subsidence rates range from 1-2cm per year to about 3-5 cm per year. This has been attributed to compaction of rock and fluid extraction.

TE AHUNGA WHAKAMUA
FUTURE DIRECTION

The Kawerau System Management Plan (SMP) has been created to allow for the integrated management of the Kawerau geothermal system in accordance with the Bay of Plenty Regional Policy Statement.

The focus of this SMP is therefore to guide how the Kawerau Geothermal System is managed to meet the needs of current and future generations in a sustainable manner. This includes agreed operational protocols between consent holders and BOPRC to achieve sustainable and integrated development of the Kawerau Geothermal System.

Bay of Plenty Regional Council will continue to manage the Kawerau Geothermal System under the Resource Management Act (RMA) 1991 through resource consents for the taking of geothermal water and heat, and geothermal discharges, and assisted by the Kawerau Geothermal Peer Review Panel. Work will continue to improve monitoring of the geothermal resource and associated features as well as the impacts of resource use.



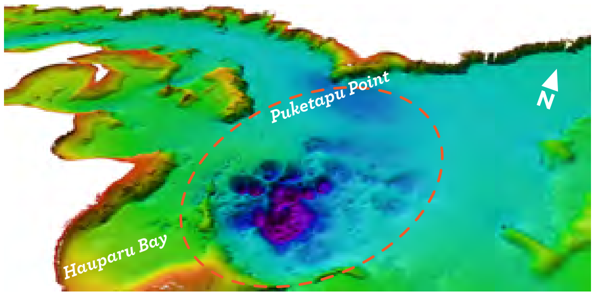
Schematic of the Kawerau Geothermal System (after Christenson, 1997 and Holt, 2007).

Lake Rotoiti

The mesotrophic Lake Rotoiti is the third-largest in the region, occupying in part an old drainage system from the Rotorua basin into the Ōkataina Volcanic Centre (Haroharo Caldera). The lake deepens from west to east, changing from an average of 10 m deep to a maximum of 125 m. Geothermal activity is centred around a deep lake vent in the eastern portion of Lake Rotoiti known as Centre Basin. The basin has formed where margin of the Haroharo Caldera crosses the lake from Ruato Bay to Puketapu Point. The eastern arm of Lake Rotoiti occupies the caldera moat.

Centre Basin is characterised by high heat flow. Elevated temperatures in the sediments around the vent and gas bubbles emanating from the area reveal a geothermal origin. Studies of heat conduction in the lake bed in the 1970's indicated a conductive heat flux of around 140 megawatt from the basin.

Geothermal heating affects water temperature in the hypolimnion of Lake Rotoiti through both conductive exchange with geothermally heated sediments and direct inputs of geothermal waters at different water depths. Hydrodynamic modelling indicates geothermal energy input of 165 megawatt into the bottom of the basin was required to accurately simulate the observed increases in water temperature found in the hypolimnion.



Lake Rotoiti bathymetry showing deep vent at eastern basin of the lake (Source: GNS Science)

Rotomā–Puhipuhi

This poorly known geothermal system is located 10 kilometres south of Lake Rotomā (see Tikiorangi map, page 36) in the Tarawera River valley. The Puhipuhi resistivity anomaly indicates this area is a separate system from the Rotomā-Tikorangi area.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

The Puhipuhi basin is complex and not well understood. It is inferred to have formed during or after an ignimbrite eruption 28,000 year ago (Matahina eruption). The basin has impounded small-moderate size lakes and seen the intrusion and eruption of the Puhipuhi Dacite lavas. It is also infilled by younger pyroclastic material between 60 and 30,000 years ago. Today the Tarawera River valley traverses the eroded basin.

Weakly mineralised (chloride 173 mg/L) warm springs (24°C) occur in this area along with many cold unmineralised springs. The chemistry indicates these springs represent highly diluted geothermal flows from depth under the Haroharo and Tarawera volcanic complexes.

The resistivity anomaly covers about 8 km^2 and is located on the south side of the Tarawera River (see map, page 36), elongated east-west. It is focused on the Puhipuhi area with a smaller anomaly to the north of lower apparent resistivity (1-2 km^2).

Group 5 – low temperature systems

MAYOR ISLAND (TUHUA), TAURANGA-MOUNT MAUNGANUI (MAUAO), PĀPĀMOA-MAKETU, MATATĀ (PROSPECT), AWAKERI, PUKEHINAU AND MANAOHAU.

Varying levels of existing extractive use in these systems which are below temperatures of 70°C. Few or no SGFs vulnerable to extractive use. System management that provides for extractive use, where the adverse effects of the activity can be avoided remedied or mitigated. Discharge of geothermal fluid must be managed to avoid significant adverse effects on surface water and stormwater.

Awakeri

Awakeri hot springs lie about 10 kilometres south-west of Whakatāne on the eastern margin of the Rangitāiki plains. Today there is a motor camp and thermal bathing complex located in the area. Historically, cold and hot springs where channelled to holes in the ground for bathing and customary use.

MĀTAI ARONUKU ME TE MĀTAI MATŪ
GEOLOGY AND CHEMISTRY

The geology of the Awakeri Springs area consists of a greywacke basement rocks forming the Raungaehe Range to the east, overlain by about 50 m of Matahina Ignimbrite and volcanic sediments. The Whakatāne Graben, a deeply faulted and lowered area underling the Rangitāiki plains, is the major landform. A major north-east trending basement fault, bounding the Whakatāne Graben, is thought to be located near State Highway 30 adjacent to the Awakeri Springs. Hot water is thought to ascend this fault, then enter the horizontal aquifers beneath the Matahina ignimbrite, and finally rise up to the surface via another local fault.

Bore water chemistry shows weakly mineralised, neutral, chloride-bicarbonate water. Chemical ratios and silica content are typical of tectonic springs unlike the nearby high temperature Kawerau system of volcanic origin. The origin of the hot waters are therefore inferred to be from deep circulation of meteoric groundwaters along a major basement fault.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

The historically active main spring known as Pukaahu, flowed at around 5 litres per second in the late nineteenth century (Maxwell, 1991). In 1945 two natural and one excavated spring existed. The springs had temperatures ranging from 58°C to 60°C and collectively discharged approximately 2.3 litres per second. The temperature of the main spring at present is around 56°C.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

Currently three bores are in operation in addition to the hot spring, supplying heat to the pool complex via heat exchangers. Use of geothermal water is currently limited to 440 cubic metres per day. Bore water temperature is around 65-68°C.

Tauranga

The Tauranga Geothermal System is a large low-temperature geothermal system (between 30°C and 70°C) that shares similar aquifers as the cold groundwater resource. A few warm springs are found at the surface which have been used for bathing, with the system being tapped by many bores utilising the waters for commercial and domestic purposes.

It extends over 60 km from Katikati-Waihi Beach in the north-west to Te Puke-Maketu in the east, with the dominant heat source appearing to lie near Tauranga city.

MĀTAI ARONUKU, MĀTAI MATŪ ME TE MĀTAI AHUPŪNGAO Ā-NUKU
GEOLOGY, CHEMISTRY AND GEOPHYSICS

The Tauranga geothermal system sits in the Tauranga Basin, a geological depression, forming about 2–3 Ma ago. Bounded to the east by the Pacific Ocean, and to the west by the mountains of the Coromandel and Kaimai ranges. The area forms part of the Coromandel Volcanic Zone (CVZ) which was active between approximately 1.5 to 18 million years ago. During this time, three large scale ignimbrite eruptions occurred and at least 21 dacite-rhyolite domes or dome complexes were emplaced. Rhyolite domes like Mt Maunganui (252m high) and Mt Minden remain dominant landforms in the Tauranga area. These form part of the Tauranga volcanic area (see map, page 7).

In the coastal area, relatively young, eastward-dipping sediments have been deposited on top of the volcanic rocks. Sediments dated at ~6500 years ago overlie some of the rhyolite domes. Tidal sediments are somewhat younger, between 3400 and 700 years old and thicken seawards reaching a thickness of approximately 300m off the coast, but thinning to the west.

Permeability is thought to be lower in deep volcaniclastic lithologies than shallow sediments (e.g. Tauranga Group). Heat is carried by fluid convection or transferred by conduction depending on permeability of the lithological unit. Chemical and isotope analysis of warm waters from this area show waters are generally potable, with no evidence of high-temperature geothermal conditions.

NGĀ ĀHUATANGA NGĀWHĀ O RUNGA
SURFACE GEOTHERMAL FEATURES

There are a few natural warm springs, generally with water temperatures below 35°C. Sapphire Springs south-west of Katikati was sampled at the start of the twentieth century (1904), but there is little observational detail on the spring or its use. Today the spring is diminished with hot pools being sourced from groundwater bores.

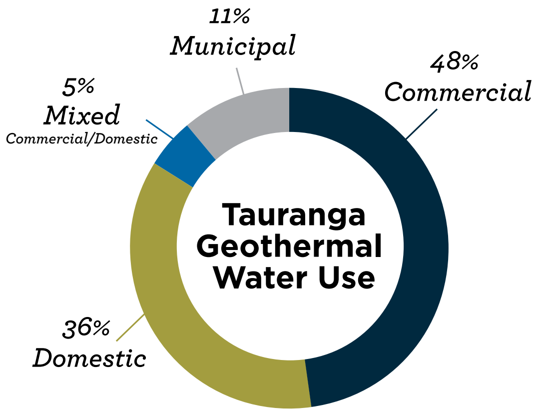
Hot springs located around one kilometre south-west of Maketu have been documented as being bathed in by local Māori in the late 1800s (Matherson, 1998). Springs were likely to have been in a wetland area and may have been reduced with drainage development in the area for farming.

TE WHAKAMAHINGA ME TE WHAKAWHANAKETANGA
USE AND DEVELOPMENT

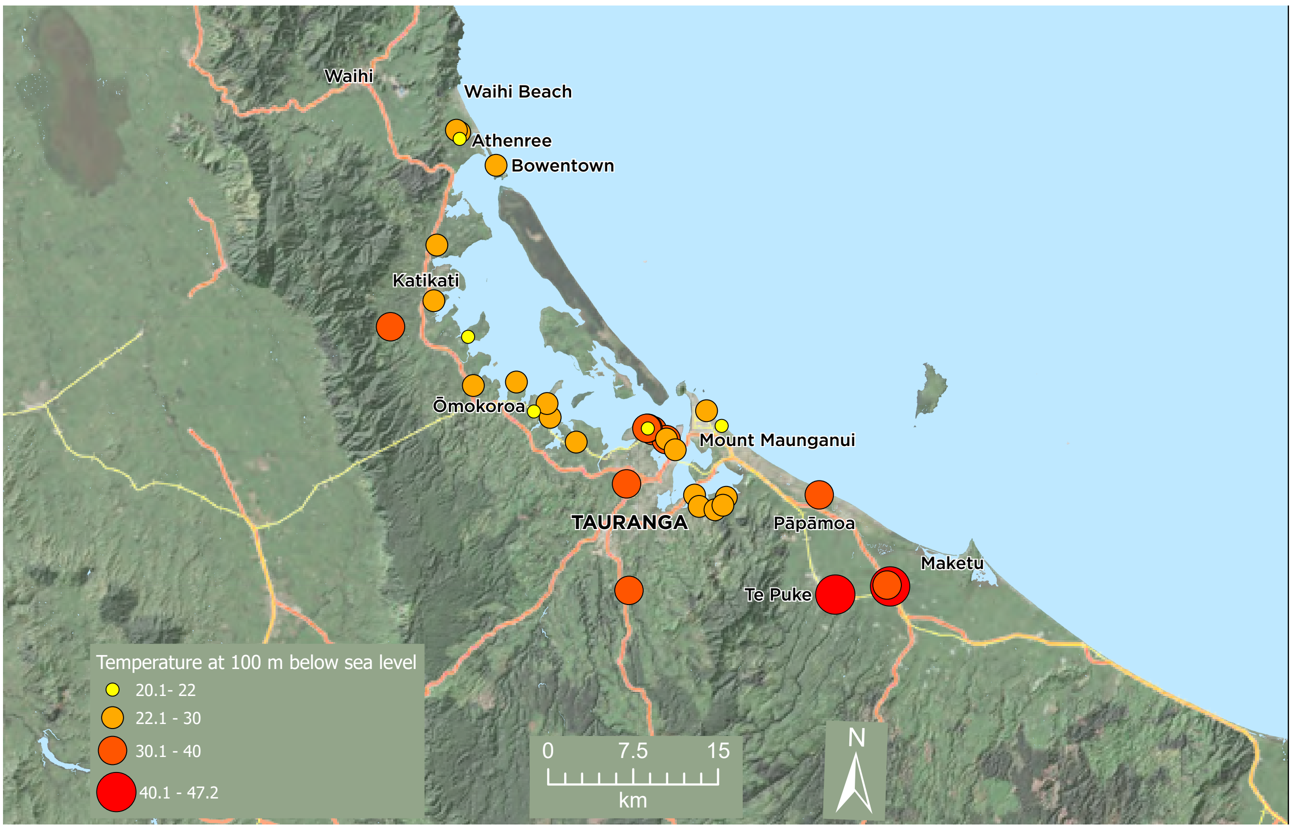
Hot water has been extracted from the system for about the last 40 years for heating, cooling, tropical fisheries, bathing and greenhouses. Water is also extensively used for irrigation and frost protection being the dominant use of the geothermal use in the resource in the commercial sector (see map, page 49). The system has traditionally been monitored for groundwater flow, but increases in use have also caused concern about the management of the heat within the system. Low-temperature (<70°C) geothermal resources are becoming an increasingly attractive energy source as technology improves and traditional energy sources become scarcer.

There is potential that parts of the Tauranga Geothermal System are sensitive to permanent cooling if overused. If too much geothermal water is taken, then cool water may replace the warm, cooling the heat left in the rocks and potentially taking many years to regenerate.

Some waters are potable but can be affected by shallow seawater intrusion, or elevated levels of elements such as arsenic and boron.



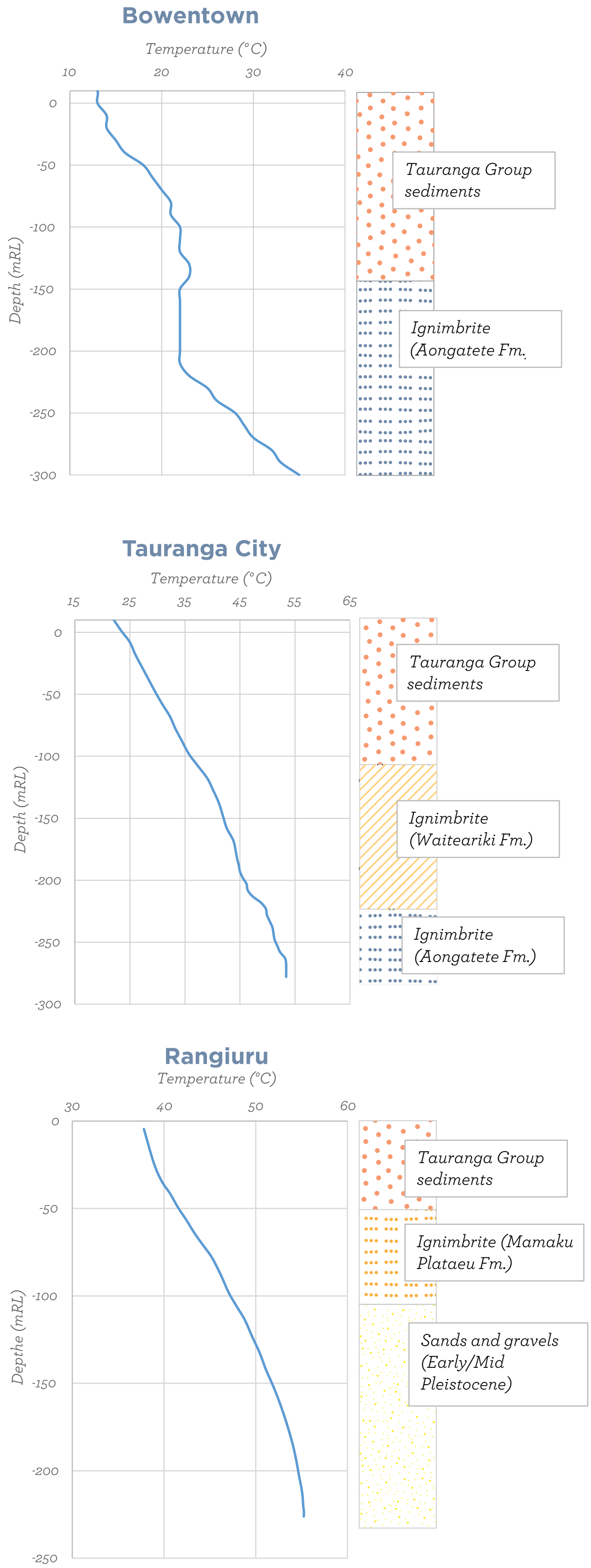
Tauranga geothermal bore water use



Bore water temperatures found at 100m below sea level, through Tauranga area.

TE AHUNGA WHAKAMUA
FUTURE DIRECTION

Council is completing further scientific research in order to better understand the attributes of this geothermal system. To help better model the extent of the Tauranga Geothermal System in terms of its depth and geographic scale, geothermal bores and groundwater takes are being monitored and tested. Once a better understanding of the science is achieved, work will continue with key stakeholders and the community to develop new policies and rules to help ensure the long-term sustainability of the geothermal system.



Downhole temperature and geologic profiles for warm water bores from Bowentown in the north-west, Tauranga City and southeast at Rangiuru.

Pukehinau and Manaohau

A small occurrence of warm geothermal water has been observed near the Rangitāiki River in an isolated area of native forest adjacent to the confluence of the Waikokopu Stream and Pukehinau Stream (see map, page 10).

Kuputaka
Glossary

acidic: relating to fluids with pH less than 7 [acid]

active volcano: a volcano that is currently erupting, or has erupted within the past few thousand years and may do so again in the future

alkaline: relating to [1] fluids with pH greater than 7 [alkali]; [2] igneous rocks with high concentrations of the alkali metals lithium, potassium, sodium, rubidium, caesium and/or radium

andesite/andesitic: volcanic rock (or lava) containing 54 to 62% silica and moderate amounts of iron and magnesium

ash: fine particles of pulverized rock (tephra) erupted from the vent of a volcano. Particles smaller than 2 mm in diameter are termed as ash

ashfall: volcanic ash that has fallen through the air from an eruption plume

basalt: volcanic rock (or lava) containing less than 54% silica, commonly producing more effusive, runny and less explosive lava [basaltic]

caldera: a volcanic depression formed by the collapse of the ground above a magma chamber, which empties during very large volcanic eruptions. The diameter of a caldera many be times larger than the size of the individual vents

carbon dioxide: a gas composed of carbon and oxygen [CO_2] and a key greenhouse gas; the dissolved form is bicarbonate [HCO_3-]. A common volcanic gas

carbon isotopes: there are three naturally-occurring isotopes of carbon (C), the stable isotopes 12C and 13C and the radioactive isotope 14C (radiocarbon)

carbon monoxide: a colourless and odourless gas composed of carbon and oxygen [CO]. A common volcanic gas

chemistry: the study of the elements, the compounds they form and the reactions they undergo [chemical]

chloride: the dissolved form of chlorine, and a common constituent of geothermal fluids [Cl-]

convection: continuous transfer of heat by slow circular movement [convective]

crater: a commonly circular depression formed by either explosion or collapse at a volcanic vent, from which volcanic material is erupted

discharge: the volume of flow of a moving liquid or gas. Examples include a river, a spring, a gas blow from a hydrothermal vent or flow from an artificial channel or pipe. Commonly measured in litres per second or cubic metres per second

earthquake: a sudden motion or trembling in the crust caused by the abrupt release of accumulated stress along a fault

earthquake magnitude: commonly denoted as M; the size of an earthquake based on the original Richter scale

earthquake swarm: a group of many earthquakes of similar size occurring closely clustered in space and time with no dominant main shock

economic minerals: geological materials that can be utilised profitably, including oil, gas, coal, metallic and non-metallic minerals, and water

electrical conductivity measurement: a geophysical method based on the ease with which current can pass through the ground [electrical resistivity]

epicentre: the point on the Earth's surface directly above an earthquake source

eruption: the arrival of fragmented material, the effusion of lava, or both, to the surface of the Earth (or other planetary bodies) by a volcano

fault: a major fracture or dislocation along which the crust has moved

fracture: a brittle crack in the crust

geochemistry: the study of the chemistry of the crust and mantle [geochemical; geochemist]

geothermal system: the natural transfer of heat within a confined volume of the Earth's crust where heat is transported from a 'heat source' to a 'heat sink', usually the ground surface. Types of geothermal systems include hydrothermal systems and magmatic-hydrothermal systems

geological map: a map that contains primarily geological information [geological mapping]

geological structure: the general disposition, attitude, arrangement or relative positions of rock masses

geological time: the time from the formation of the Earth 4.6 billion years ago to the present

geology: the study of the composition, structure and origin of the solid Earth; sub-disciplines include geochronology, engineering geology, mineralogy, petrology, palaeontology and stratigraphy [geological; geologist]

geophysics: the study of the physical properties of the Earth [geophysical; geophysicist]

geothermal: relating to [1] natural heat within the crust; [2] heat from hot groundwater or steam used for power generation

geothermometer: specific chemical compositions in minerals or fluids that indicate the temperature, at equilibrium, of a geothermal system

geyser: an eruption of hot water and steam from a hydrothermal system. It is usually of cyclic occurrence and ejects only small amounts of solid material. The ejection mechanism is volume change due to boiling, as opposed to ejection of water because of artesian pressure alone

gravity measurement: a geophysical method based on measurement of the attractive force of the Earth, which varies with altitude, latitude and the density of local rock masses

gravity anomaly: the difference between measured gravity and the expected (modelled) gravity at a site. Small gravity anomalies can indicate the presence of a subsurface magma body

groundwater: subsurface water contained in pores and fissures in rock beneath soil, most of which is beneath the water table

hot springs: a surface feature of a geothermal system, where warm or hot water flows out of the ground

hydrogen isotopes: the isotopes of hydrogen, namely 1H (hydrogen), 2H (deuterium) and 3H (tritium)

hydrogen sulphide: a poisonous, strongly odorous gas composed of hydrogen and sulphur [H_2S]. A common volcanic gas

hydrology: the study of land-based water systems, including rivers, lakes and groundwater

hydrothermal: relating to naturally occurring hot water—often referred to as 'thermal' at tourist locations—whose minimum temperature is higher than the ambient mean annual temperature

hydrothermal activity: manifestations seen at the surface of geothermal systems. Hydrothermal activity may include hydrothermal eruptions, fumaroles, gas/steam emissions, steaming ground, geysers, hot springs and streams, and hot pools (including mud pools)

hydrothermal eruption: an eruption ejecting steam and some solid material. Energy is derived only from a convecting hydrothermal system, not magma

hydrothermal system: a type of geothermal system where heat transfers from a heat source (e.g., magma) to the surface by 'free convection', involving meteoric fluids, with or without traces of magmatic fluids. Liquids discharged at or near the surface are replenished by meteoric water derived from the outside, that is drawn in by the rising fluids. A hydrothermal system consists of 1) a heat source, 2) a reservoir with thermal fluids, 3) a surrounding 'recharge region', and 4) a heat discharge area at the surface with manifestations (e.g. fumaroles, hot springs)

ignimbrite: a volcanic deposit formed by a pyroclastic flow. Ignimbrite layers can be soft and full of pumice such as the land surface around Taupō (from the Taupō eruption 1800 years ago); or hard rock where the deposit has been thick and hot enough for the particles to fuse together (Mamaku Plateau, Rotorua)

impermeability: the inability of rocks or sediments to transmit fluid [impermeable]

isotopes: forms of an element with differing numbers of neutrons [isotopic]

lava: molten rock that has reached the Earth's surface and been thrown out of or has flowed from a volcano or volcanic vent. Molten rock that is still underground is called magma

lava dome: a steep-sided pile of viscous (i.e. sticky) lava at a volcanic vent. The surface is often rough and blocky because of fragmentation of the cooler outer crust during growth of the dome. Lava domes can collapse and cause block and ash flows

lithological: related to the physical character of a rock [lithology]

magma: molten or partly molten rock beneath the surface of the earth. Magma that reaches the surface erupts as lava or pyroclasts from a volcano

magmatic-hydrothermal system: a type of geothermal system where ascending magmatic (primary) fluids commonly mix with meteoric (secondary) fluids, including sea water

mineral: [1] a constituent of a rock with a specific chemical composition, or range of compositions [mineralogy; mineralogist]; [2] in an economic sense, a profitable geological commodity [mineralised; mineralisation]

mudstone: a fine-grained sedimentary rock of mixed silt and clay-sized grains [mud]

normal fault: a fault in which the upper, hanging wall moves down with respect to the lower, footwall

oxygen isotopes : the stable isotopes of oxygen, expressed as 16O/18O (δ 18O), used either as an indicator of the source of rock material, the temperature of seawater or cave water or, when compared to a calibrated paleo-seawater curve, the age of fossil remains

permeability: the ability of rocks or sediments to transmit fluid through interconnected pores or fractures [permeable]

phreatic eruption: a volcanic eruption that is caused by heating and 'flashing' of water to steam, produced when magma meets water, but only country rock or overburden is ejected (i.e. no juvenile magmatic material). The energy of the eruption comes from magma or magmatic gas

phreatomagmatic eruption: an explosive volcanic eruption that results from the sudden interaction of surface or subsurface water and magma. Magma or lava may contact water, or water may be introduced during an eruption. Fragments of fresh magma (i.e. juvenile igneous material) are erupted, and ashfall is usually wet and sticky

physics: the study of the properties and interaction of matter and energy [physical]

plume: [1] a body of convecting fluid travelling upward through the mantle or crust; [2] a dense cloud of black, mineral-laden 'smoke' expelled from hydrothermal vents on the seafloor; [3] a suspension of muddy sediment discharged onto the continental shelf by rivers; [4] a concentration of pyroclastic (tephra) particles, aerosols and gases from an erupting volcano

pumice: a light-weight volcanic rock (usually pale-coloured), formed by the expansion of gas in frothy lava during an eruption. Pumice commonly floats on water due to the high number of bubbles (vesicles) in each rock and can travel further than other rocks of a similar size during an eruption due to its low density. It is often composed of rhyolite

reservoir: a porous volume within a rock formation containing fluids

resource(s): [1] economic mineral reserves plus all other known mineral deposits that may eventually become available; [2] mineral and energy sources that may be of economical use to society

rhyolite: volcanic rock or highly viscous magma, light coloured, with a high silica content (typically more than 69%). It is found as pumice, ignimbrite, lava or obsidian.

seal: a natural layer of impermeable rock that prevents seepage of oil, natural gas, water or other fluids from an underground hydrocarbon reservoir

seismicity: Seismic activity; earthquakes and other shaking (tremors)

silica: the common name of silicon dioxide (SiO_2). Typically, it is found as the mineral quartz. Where silica crystals are very fine grained (cryptocrytalline), they form minerals such as opal and the chalcedony group, including agate. Sinters around hydrothermal vents are rich in silica. Organisms such as diatoms and radiolarian have silica skeletons. Accumulations of their remains (biogenic silica) form deep sea-floor oozes and where compacted into rock are called chert, or diatomite if composed mainly of diatoms. In magma, silica content has a great influence on the viscosity of the molten rock; basalt is poor in silica and is very hot and flows freely, while rhyolite is rich in silica, is cooler and more viscous. Erupting rhyolite is more prone to violent explosions as gas struggles to escape from the sticky lava [siliceous, silicic]

solfatara: a natural volcanic steam vent in which sulfur gases are the dominant constituent along with hot water vapour.

steam eruption: usually small eruptions consisting mostly of steam. Rocks and ash might also be erupted, but no fresh magma is involved. Steam eruptions include hydrothermal eruptions

sublimates: A volcanic sublimate or fumarolic sublimate is a mineral which forms directly from volcanic gas, by the process of deposition usually the discharge from a fumarole

sulphur: a yellow non-metal often found in volcanic or geothermal areas [S]; compounds are sulphides [S6-] or sulphates [SO_{42}-]

sulphur dioxide: a colourless, choking poisonous gas often associated with volcanic or geothermal areas [SO_2]

Taupō Volcanic Zone: the c. 100 kilometre wide by c. 350 kilometre long volcanic region of central North Island extending north from Ruapehu volcano to beyond White Island volcano; the 'older TVZ' was active from c. 2 Ma to 340 ka, and the 'younger TVZ' has been active since c. 340 ka

tectonic: relating to the formation of large-scale structural features [tectonism; plate tectonics]

volcanic centre: a group of volcanoes that are related to each other, and are clustered in space (e.g. Ōkataina Volcanic Centre, Taupō Volcanic Centre)

volcanic gases: magma deep in the earth contains dissolved gases. As the magma rises closer to the ground surface, these gases are released and, because they are so mobile when compared to the sluggish liquid magma, they rise to the surface and are discharged through vents, fumaroles, and the soil. The gas temperatures, absolute amounts, and relative proportions of different gases give information on the state of the magmatic system. There are many types of volcanic gases, with the most common being water vapour (H_2O); sulphur as sulphur dioxide (SO_2) or hydrogen sulphide (H_2S); nitrogen, argon, helium, methane, carbon monoxide and hydrogen

water table: the upper surface of a zone of water saturated rock or sediment

Ngā tohutoro
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