Geothermal Systems of the Bay of Plenty Region, Aotearoa New Zealand - Inventory and Systems Extent

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ABSTRACT

The Bay of Plenty Regional Council (BOPRC) is in the process of reviewing its inventory of natural geothermal resources of the region and their geographical extent. This work provides the science base-knowledge for identifying and mapping the systems for the sustainable management of the geothermal resources through its planning framework, as well as to inform work for other Council areas like Consents and Compliance. This work identifies the key sources of information publicly available and outlines the methodology developed to identify and propose the geothermal system' extent of the Bay of Plenty region. Two types of extents are suggested, tailored to the level of certainty around their geographical extent. Approximate extents are suggested when there is a reasonable level of certainty around its location, and inferred extents for when the level of certainty is moderate or low. Those different levels of certainty arise from variable levels of data availability, data quality and appropriateness of the data available for the purpose of this mahi. A high certainty is not considered achievable given the intrinsic complex hydrodynamics of geothermal systems and gradual lateral transition into cold groundwater systems, therefore none of the systems are proposed to be mapped with accurate extent. A distinction between geothermal systems and geothermal occurrences is also proposed and recommended, as well as the inclusion, exclusion and merging of some of the geothermal systems identified in the planning framework of the Bay of Plenty Regional Natural Resources Plan and Regional Policy Statement. This paper also highlights that a significant heterogeneity in the level of knowledge and data availability exists across the various geothermal systems of the region. Geothermal systems with high commercial and scientific interest like Kawerau, Rotorua and Waimangu, for example, have been extensively studied over time, while a lower level of knowledge exists for some of the other systems, like the offshore Moutohorā Island (Whale Island), the low-temperature systems like the Tauranga-Mount Maunganui (Mauao)-Pāpāmoa-Maketū system and, to some extent, most systems with significant environmental constraints for development, like Tikitere.

1. INTRODUCTION

The Regional Policy Statement (RPS) identifies 17 systems or geothermal areas in the Bay of Plenty region (Table 1). These are mapped at a broad regional scale in the RPS and the Regional Natural Resources Plan (RNRP).

The Plan Change 11 (PC11) of the RNRP is currently being progressed with a draft for consultation scheduled to be released early-2024. It is therefore timely to review how the geothermal systems will be included in planning maps, and to provide more guidance for consenting processes. This paper addresses the issues below to support PC11 and is based on Zuquim (2023):

- Discuss whether there is scientific merit in mapping the extent of the geothermal systems, including potential connections between different systems.
- Develop an inventory of areas with geothermal activity in the region and a scientific methodology to define their extent.
- Propose geothermal system's extent in a geographic information system (GIS).
- Discuss and address uncertainty around those spatial extents.

Note that advice on system classification for the BOPRC RPS and/or RNRP, and a Mātauranga Māori lens on system boundaries, is beyond the scope of this paper. Seabed hydrothermal occurrences in the coastal area (e.g. the Calypso vents; e.g. Botz *et. al.*, 2002) were not assessed at this stage. Those occurrences are managed under the Bay of Plenty Regional Coastal Environmental Plan (2019) therefore outside the of scope of this work for PC11, but might be assessed in further stages.

2. METHODOLOGY

The methodology to develop the system's extent followed the main stages below:

1) Development of a stocktake of the data and reports available to Council that can be made publicly available.
2) High-level discussion on:
   a) Constraints of those datasets and reports.
   b) Measures to mitigate those constraints.
   c) Weigh the scientific value of the datasets for setting system's extent, based on the degree in which the dataset reflects the extent of the geothermal system.
3) Classification of the different types of data into 'reasonably high', 'moderate' and 'low' quality or suitability for this work.
4) For each geothermal system and occurrence, outline the exact criteria applied to draw the system's extent.
5) Provide a recommendation on the type of extent (approximate or inferred) based on the resulting degree of confidence on those geographical extents.
6) Propose potential extents for when the scientific data or knowledge points towards potential connections between different geothermal systems or for the existence of a warm resource beyond the hot(ter) areas.

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Table 1: Methods for different levels of metering requirements and production systems.

Management Group	Group name (RPS)	Geothermal systems included
1	Protected	(a) Waimangu-Rotomahana-Tarawera (b) Whakaari (White Island) (c) Moutohorā Island (Whale Island)
2	Rotorua (special group)	Rotorua
3	Conditional development	(a) Tikitere-Ruahine (b) Tāheke (c) Rotokawa-Mokoia Island (d) Rotomā-Tikorangi
4	Development	(a) Kawerau (b) Lake Rotoiti (c) Rotomā-Puhi Puhi
5	Low-temperature	(a) Tūhua (Mayor Island) (b) Tauranga-Mount Maunganui (Mauao) (c) Pāpāmoa-Maketu (d) Matatā (e) Awakeri (f) Pukehinau (g) Manaohau
6[1]	Research	None at the time of writing

Different methodologies were developed and applied for high-temperature systems (RNRP and RPS Groups 1-4), low-temperature systems (RNRP and RPS Group 5) and geothermal occurrences (not in the RNRP and RPS so far). Those methodologies are presented in sections 2.3 to 2.5.

2.1 Data

The following sources of information were used for this work, when available:

- Geoscience data – geology, geochemistry, geophysics.
- Geothermal vegetation map.
- Surface feature locations and the feature-type.
- Current and past exploratory and production wellbore locations and wellbore data.
- Published peer-reviewed research.
- Technical reports.

A summary of the sources of data and information per geothermal system is presented in Table 1 to Table 5 of the Appendix. The key references and publications were selected based on the relevance of their content, the quality and completeness of the results, as well as whether the data obtained or compiled by the authors is validated by other datasets (e.g. geophysics validated by wellbore data).

2.2 Data limitations and weight of the data for the definition of the systems' extent

All the datasets provide valuable information but also have limitations due to a variety of reasons for the purpose of this work (Table 2). Limitations for those datasets specific to each geothermal system are reflected in the level of confidence and/or ability to define potential on the system's extent, and are discussed in Section 3.

2.3 High-temperature systems

2.3.1 High-temperature systems extent

In New Zealand, the shallow (< 1 km) extent of the geothermal systems is typically defined by apparent DC resistivity < 20-30 Ω m (Stagpoole & Bibby, 1998). This approach to define the extent of the geothermal systems is widely adopted in Aotearoa and proved reasonably accurate, at least at regional scale, but also is known to produce some spurious results, therefore require validation by other datasets (e.g. wellbore data). Those low resistivity zones are a product of the presence of hydrothermally altered or clay-rich rocks filled with reasonably warm (≈70 ˚C) to hot (e.g. > 350 ˚C) geothermal fluids (Ussher *et. al.*, 2000).

The typical 2D resistivity structure of a high-temperature geothermal system in New Zealand is presented in Figure 1. The deeper geothermal reservoir is slightly more resistive than the shallowest parts of the geothermal system, with resistivities up to ~60 Ω m due to propylitic alteration. A clay cap typically overlies this reservoir, with resistivities of the magnitude of ~10-30 Ω m due to illite or interlayered illite-smectite hydrothermal alteration assemblage. The cooler and shallowest portion of the system is typically

[1] The Group 6 in the RPS applies to systems yet to be discovered, or for when more information is required before the system can be classified into groups 1 to 5.

characterised by the presence of smectite clay, reflected on the more conductive top layer of the system.

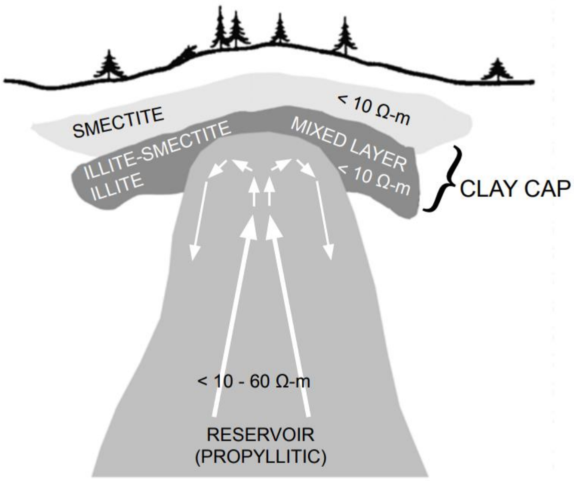

Figure 1: Schematic resistivity versus clay alteration structure of a high-temperature geothermal system. After Johnston *et. al.* (1992).

An important consideration is that those broad geophysical layers have in fact a complex 3D geometry, and temporal changes (e.g. waning) can create further complexities (e.g. high-temperature mineral assemblages overprinted by lower temperature ones). The resistivity maps available are essentially a 2D representation of the resistivity structure at subsurface ('slices') for reasonably shallow depths (< 1 km), while most geothermal systems would extend well beyond this depth (at least a few kilometers scale).

DC resistivity is also superseded by magnetotellurics. However, for most geothermal systems of the Bay of Plenty region, such survey has not been carried out so far. For those with MT data, in most cases the results are either not available to Council, cannot be used for this work due to confidentiality or commercial sensitivity, or do not have the required spatial resolution for the purpose of this mahi (i.e. regional MT survey to image the roots of the geothermal systems).

Nonetheless, while the system's extent could be greatly refined with detailed MT data, DC resistivity data is considered fit-for-purpose for this work and was widely adopted to inform the geographical extents. This is because, in all systems other than the ones with potential for power generation, only the shallowest part (< 1 km) of the systems is tapped or expected to be tapped. Therefore, the system's extent, which is heavily based on DC geophysics in most cases, effectively reflects the areas where warm or hot water is most likely to be encountered and produced from, thus where the effects of the activities will likely happen and be limited to.

Regional resistivity data from Stagpoole & Bibby (1998) is used unless data from the specific system and/or area is available and provide a more accurate picture of the resistivity structure than the regional dataset. When available, the DC resistivity data is used in conjunction with other geophysical methods (e.g. interpreted gravimetry).

The extent of the geothermal systems is typically defined by the location of the steepest resistivity gradient. Those areas reflect the edge of the saline aquifer or reservoir and its associated hydrothermally altered rocks. This criterion was used to locate the likely system extent, but the actual 'choice' of the isoresistivity contour was defined in a case-by-case basis, based on results from various geoscientific datasets (e.g. wellbore data, geothermal surface features location).

Relict or waned geothermal systems often leave a gradational rather than steep resistivity signature, therefore this steep gradient is a distinct feature of the active systems. West Lake Rotorua to the west of Mokoia Island, for example, is characterised by a deep area of very low resistivity with a smooth, rather than a steep, resistivity gradient (Bibby *et. al.*, 1992). This geophysical signature coupled with minor enhanced conductive heat flow at the bottom of the lake (Whiteford, 1992) leads to the interpretation that the deep low resistivity anomaly is likely a waning, warm geothermal system.

As much as possible, the mapped extents of the geothermal systems are not tailored to any specific use (e.g. extent of the resource suitable for electricity generation). However, the data available is invariably biased towards the high(er)-temperatures areas of the systems. This is because the main drivers for the geothermal science and commercial projects are invariably related to the 'core' of the geothermal system (e.g. hot reservoir for power generation or geothermal surface features of scientific interest). Nonetheless, where possible, potential extents were suggested to delineate cooler outflows/fringes.

The level of certainty on the system's extents are reflected on the type of extent, whether approximate or inferred. An approximate extent is adopted when there is a reasonably high level of certainty on its extent, while an inferred extent is adopted for when there is a moderate to low degree of certainty. A high certainty is not considered achievable or realistic, given the intrinsic complex hydrodynamics of geothermal systems and reasonably gradual lateral transition into cold groundwater systems, therefore none of the systems are proposed to be mapped with accurate extent.

For the geothermal systems associated with offshore volcanoes (e.g. the active Whakaari volcano and the remnant Moutohorā volcano), the broad approach was that the geothermal system area shall cover the edifice of the volcano, above and below sea level. This is consistent with the conceptual model for active volcanic field play-type (Moeck, 2014) and the broad conceptual model for Whakaari (Kilgour *et. al.*, 2021).

Finally, consideration was given on whether recent MT work by Bertrand *et. al.* (2022), which identified a potential blind system underneath the Makatiti Dome, should be considered for the purposes of this work. This is because this potential blind system ~ 3 km depth may be viable for developments (Kissick *et. al.*, 2023), thus of relevance for the Bay of Plenty Regional Council. An option to map the system from a scientific rationale is provided, but further consideration on the appropriateness from a policy development perspective is beyond the scope of this paper.

Table 2: Limitations of the different datasets used to inform this work and the high-level weight of the dataset to define the extent of the geothermal systems' extent and potential extents.

Type of data	Limitations or constraints	Measures to mitigate the limitations	Weight of the data for setting systems extent
DC resistivity	• Requires interpretation of the results by a subject matter expert. • Interpretation of the data and results publicly available is biased towards the 'hotter' parts of the geothermal system. The 'hotter' areas are the main targets for commercial viability of development projects or research projects, but this does not reflect the RMA definition of geothermal water. • Low-resistivity zones may reflect relict alteration, sediment clays or weathered tuffs for example, and not the extent of the currently active geothermal system. In most cases this would result in extents larger than the actual size which can be misleading for determining hydrogeological connections. • The geothermal aquifer/reservoir has a complex 3D geometry unique to each geothermal system. The data available does not capture this complex resistivity structure and other hydrological controls like topography. • In most cases is limited to the shallower ~500 m depth which significantly constrains the method in areas with thick recent volcanic deposits, like around the Ōkataina Volcanic Centre. • Should be validated by another geophysical method (e.g. magnetics, gravimetry) for robustness, but often this is not the case.	• Use interpreted results from peer-reviewed publications. • Validate with other data from subsurface (e.g. wellbore data). • Augment with MT/deeper data if available. • Assign a lower level of confidence if other surveys/data sources are not available for validation or the survey was not 'bespoke' to the geothermal system (regional surveys vs local surveys).	**HIGH**
Resistivity – Magnetotellurics	• Requires interpretation of the results by a subject matter expert. • Data available to BOPRC designed to understand regional scale processes and the deeper parts of the crust (the 'roots' of the geothermal system). • Limited coverage of the Bay of Plenty region.	• Only used to understand the heat sources of the geothermal systems, but not for defining extent, unless it is the only dataset available.	**LOW TO HIGH**
Other geophysical methods: gravimetry, magnetics	• Generally, the surveys do not provide enough resolution for defining system's extent, but are useful for validating resistivity data. • Requires interpretation of the results by a subject matter expert.	• Use the data to validate DC resistivity results.	**LOW**
Geothermal surface features databases	• The BOPRC Geothermal surface features inventory and the GNS GGW database have some significant issues: - Location accuracy. - Generally outdated (30+ years for most of the data outside Rotorua) with no or limited subsequent ground-truthing after the initial survey of the ~1980s. • The 'expression' of the geothermal system at surface. However: - Surface features may be offset from the geothermal aquifer/reservoir at depth.	• Cf. the data against other geoscientific data and conceptual model for the geothermal system. Apply discretion on the surface feature type versus what it represents in terms of the current surface expression of the geothermal system (e.g. old hydrothermal eruption craters, relict sinter deposits).	**HIGH**

Type of data	Limitations or constraints	Measures to mitigate the limitations	Weight of the data for setting systems extent
	- The geothermal system may have little or no surface expression. - Relict surface features may not necessarily reflect current thermal activity (e.g. sinter, hydrothermal eruption crater).	• Apply discretion, particularly if outside the geophysical extent. • Undertake field investigations to validate and update historical data.	
Heat flow maps	• Requires interpretation of the results by a subject matter expert.	• Use interpreted results only from peer-reviewed publications.	**HIGH**
Geothermal vegetation map	• Not all areas have been ground-truthed. • Geothermal vegetation is not exclusive to geothermal areas. • Might contain relict vegetation in a waned system.	• Cf. the data against other geoscientific data and conceptual model for the geothermal system. • Assign a lower level of confidence if other surveys/data sources are limited.	**MODERATE**
Geothermal wells	• A direct measure of the subsurface conditions. The main constraints are: - The limited number of wells available. - Limited data available particularly for smaller and shallower wells, for wells in developed systems and for exploration wells. - Limited data quality particularly for smaller and shallower wells.	• Apply discretion on the data available and utilise the data within its intrinsic limitations.	**HIGH**
Cold groundwater bores	• A direct measure of the subsurface conditions which can help to constrain the geothermal systems. The main limitations are: - Limited confidence on the temperature data, particularly for deeper bores assigned as cold in warm areas. - Typical shallow depth. Cooler temperatures do not preclude the existence of the thermal resource at a greater depth.	• Apply discretion on the data available and utilise the data within its intrinsic limitations.	**MODERATE**
Geothermal vegetation map	• Not all areas have been ground-truthed. • Geothermal vegetation is not exclusive to geothermal areas. • Might contain relict vegetation in a weaned system.	• Cf. the data against other geoscientific data and conceptual model for the geothermal system. • Assign a lower level of confidence if other surveys/data sources are limited.	**MODERATE**

2.3.1 High-temperature systems potential extent

A potential extent for the high-temperature geothermal systems is proposed in two instances:

(i) To define areas where a low-temperature resource associated with the high-temperature systems may occur, particularly in the outflow/fringes of the systems.
(ii) Where there is evidence that two systems can be hydrogeologically connected at reasonably shallow, currently exploitable depths (up to ~ 3 km).

No potential extent has been suggested when it was considered that there was not enough robust information to substantiate them, or when it was not considered scientifically justifiable or appropriate.

For (i) a low-temperature resource (warm water) likely occurs for a substantial distance in the outflows of the high-temperature geothermal systems, which can be reflected both in the groundwater chemistry and temperature. For example, warm bores occur to northeast of the Kawerau Geothermal Field and a boron anomaly is identified in several canals, drains and streams to north and northeast of Kawerau in the Rangitaiki Plains (BOPRC Tarawera Catchment Regional Plan).

Another example is a site south of Rotorua, where an exploration well encountered bottom of hole temperature of 91 °C at 200 m depth, giving a high conductive temperature gradient of 340 °C/km [Brown, 2010]. This well was drilled by the isoresistivity contour of 70 Ω m (AB/2 = 500 m), again highlighting how a geothermal resource is likely to be encountered for quite a distance from the typical DC resistivity extent of ~30-50 Ω m.

For (ii), the level of hydrogeological connection in those cases is unknown, but it is assumed that it is to a level that there is a possibility that a reasonably large stressor/perturbation in one system (e.g. a large power plant) could potentially affect the neighbour system. The potential extent, in this case, will reflect the likely subsurface area of hydrogeological connection projected to surface. Additionally, within the potential extent, low-temperature geothermal water can be, or may already be tapped into by shallow geothermal wells, for example, for domestic or light commercial use.

2.4 Low-temperature systems

2.4.1 Low-temperature systems extent

Four low-temperature systems are proposed to be defined for the Bay of Plenty region: Awakeri, Tūhua (Mayor Island), Tauranga-Mount Maunganui (Mauao) + Pāpāmoa-Maketū and West Lake Rotorua, with the first three systems already identified in the operational RNRP and RPS. A different methodology was applied to each of those four systems, given their distinct nature. The Pukehinau-Waikokopu and Manaohau systems are proposed to be reclassified as an occurrence rather than a system and are covered in Section 2.5. The Matatā system is proposed to be removed from the inventory due to the lack of supporting evidence for a thermal resource.

The Tauranga geothermal system is an extensive warm system bounded to northeast by the Pacific Ocean and by the Kaimai Range to west. A few warm springs are known to occur in areas where the aquifer is known to be reasonably warm, like in Tauranga City, Maketū and around Katikati (Zuquim *et. al.*, 2022; Pearson-Grant & Burnell, 2018).

The thermal structure of the Tauranga system is highly complex laterally and vertically, and still not fully understood. Broad areas of enhanced temperature gradients exist (Zuquim *et. al.*, 2022), but there is very limited data coverage to the south and west of the system (Janků-Čápová *et. al.*, 2022). Nonetheless, there is a good match between identified areas of enhanced temperature gradient with the location of warm bores and historic and current warm springs.

Part of the Tauranga Geothermal System is covered by the regional DC resistivity survey. However, saltwater and connate water affects the resistivity results, so there is little confidence on whether the low resistivity zone around Maketū reflects a large zone of enhanced aquifer temperatures indeed (Janků-Čápová *et. al.*, 2022).

The geothermal-groundwater chemistry for the Tauranga Geothermal System is not particularly distinct from the chemistry of the cold groundwater (White *et. al.*, 2008), thus chemistry data is of limited use for outlining the system extent.

Finally, the main datasets used to outline the extent of the Tauranga-Mount Maunganui (Mauao) + Pāpāmoa-Maketū system are location of the warm and cold bore occurrences augmented by the location of warm springs and broad areas of enhanced thermal gradient.

The Awakeri system is reasonably hotter than the Tauranga system, with shallow wells (~60 m depth) tapping into a ~70 ˚C geothermal-groundwater aquifer. It also includes the existence of a reasonably hot (55 ˚C) spring, the Pukaahu Spring. More hot springs are believed to exist in the area but were destroyed by land development (Bromley *et. al.*, 2003).

A reasonably detailed exploratory survey was undertaken in Awakeri in the early 2000s by Bromley *et. al.* (2003), resulting in a reasonably high level of understanding of this unique geothermal system. The system has limited lateral extent and is strongly controlled by the extent of the Awakeri fault and the intersection with an inferred cross fault (Bromley *et. al.*, 2003). The aquifer temperatures are sufficiently high to cause clay alteration and induce a distinct geophysical signature/response. Warm and cold bores are used to further constrain the warm water anomaly/resource.

Tūhua (Mayor Island) is a dormant volcano off the Bay of Plenty coast (Houghton *et. al.*, 1992). Likewise, for the offshore volcanos of Whakaari and Moutohorā (extinct), the broad approach to define the system extent to cover the edifice of the volcano, above and below sea level.

Finally, West Lake Rotorua, to the west of Mokoia Island, is likely a waning, warm geothermal system, even though this has not been tested by drilling. While a warm geothermal system may still exist beneath the lakebed, it is unlikely to be of significant size or extent, thus it is highly unlikely to be economically feasible for extractive uses. Nonetheless, it is considered that such system shall still be identified and mapped for the purpose of this work.

2.4.2 Low-temperature systems potential extent

A scientific justification or rationale could not be identified to inform the development of potential extents for low temperature systems. As such, no system's extents are proposed for those system-types.

2.5 Geothermal occurrences – Tectonic springs, other warm springs and isolated warm wells

Warm springs and bores that could not be directly linked to any known geothermal system of the Bay of Plenty region are known to occur particularly in Te Urewera and the volcanic lakes associated with the Ōkataina Volcanic Centre (Nairn, 2002). Currently, it is considered that there is a lack of robust supporting evidence that those isolated occurrences are directly fed by a more extensive geothermal resource at depth, and, as such, were classified as geothermal occurrences in this work. Further research and exploration could identify a linkage with a wider geothermal aquifer in the future, and this classification might be reviewed.

Two geothermal springs in the Te Urewera fall into this setting: Manaohau and Pukehinau-Waikokopu. The Manaohau and Pukehinau-Waikokopu springs are likely warm tectonic springs associated with the North Island Fault System or North Island Dextral Fault Belt (NIFS or NIDFB; Beanland, 1995; Litchfield *et. al.*, 2014). The faults of the NIFS have both strike-slip and normal components, which is an ideal setting to create good, highly localised vertical permeability in releasing bends or damage zones (e.g. Rowland & Sibson, 2004).

This deeply circulating geothermal-groundwater is heated by the naturally occurring thermal gradient which increases with depth. As this slow-moving water intercepts permeable vertical fluid pathways like fault zones, it ascends to surface and discharges as warm springs. Currently, no supporting evidence was identified that suggests that the thermal springs at Te Urewera are the surface expression of a wider geothermal system at depth.

Warm springs also occur in the shores of Lake Tarawera and Ōkataina. Currently, no supporting strong evidence was identified that indicates an interconnection of those springs to the Waimangu-Rotomahana-Tarawera system to south (other than the springs in Te Rata Bay in Lake Tarawera).

Recent work by Caratori-Tontini *et. al.* (2023) concluded that the warm springs in Kanaehapa Bay and Humphries Bay (Lake Tarawera) and in Otangimoana Bay (Lake Ōkataina) are possibly a result of circulation of meteoric water through permeable rhyolitic rocks driven by gravity, discharging at the lakes shore where it intersects the water table, and not associated with a wider geothermal system. Therefore, the warm springs in Kanaehapa Bay and Humphries Bay (Lake Tarawera) and Otangimoana Bay (Lake Ōkataina) are also suggested to be classified as geothermal occurrences (Caratoni-Tontini *et. al.*, 2022).

Likewise, no strong evidence was identified that points towards the existence of a plume feeding a more extensive geothermal system underneath Mount Tarawera (Bertrand *et. al.*, 2022). Therefore, the area encompassing the fumaroles and steaming ground located around the top of the maunga are proposed to be classified as geothermal occurrences, at least until further evidence gathered points towards a linkage to a wider, established geothermal system.

One 'isolated' warm bore also occurs around 8 km to the south of the proposed Tauranga Geothermal System extent. This well is located 2.5 km to southwest of the Ōtamarākau fault in Pongakawa and is considered an isolated occurrence. It is possible and likely that other warm wells drilled within the wider Central Volcanic Zone (CVZ; Wilson *et. al.*, 1995), like this bore, will encounter warm water given the broadly enhanced thermal gradient of the CVZ.

3. RESULTS

Based on the analysis carried out and described in Section 2, the results show that, from a science perspective, there is merit in mapping system's extent or potential extent (Section 1). This is because:

- While there is a range in the level and quality of information on the geothermal systems of the region, which creates a range in the level of certainty around their extension at depth, the data available is confirmed of sufficient quality and coverage to inform the system's extent at depth projected to surface.
- The various levels of certainty around the system's extent can be effectively communicated and reflected in the type of extent (approximate or inferred). None of the geothermal systems are proposed to have an accurate extent.

It is considered that the issues with data quality, quantity and uncertainty of their location and extent have been appropriately addressed and mitigated. Therefore, those issues do not preclude mapping the geothermal systems and occurrences of the Bay of Plenty region and defining their geographical extent.

The scientific criteria applied to outline the extent and potential extent of the geothermal systems and occurrences of the Bay of Plenty region is summarised in Tables 6 to Table 9 of the Appendix. The level of confidence applied to the system extent used to inform the recommendation for an approximate or inferred extent and rationale for the potential extent is presented in Table 10 to Table 14 of the Appendix. A regional map is presented in Figure 2.

4. CONCLUSIONS

This work presented and applied a consistent methodology to identify and map the extent of the geothermal systems identified and not yet identified in the policy framework for the Bay of Plenty region (RPS and RNRP). It also recommended the inclusion and reclassification of some systems into geothermal occurrences.

The work also addressed the level of certainty on the data used to inform the systems extent and proposed a residual uncertainty on the systems geographical extent, after measures to minimise issues of data uncertainty were applied when possible. This residual uncertainty is reflected in the type of extent: approximate or inferred, when there is a higher or lower level of certainty, respectively.

This work also proposes the follow changes to the BOPRC inventory of geothermal resources of the Bay of Plenty region to better reflect the current level of understanding of those geothermal systems/occurrences:

- Tauranga-Mount Maunganui (Mauao) and Pāpāmoa-Maketū systems: Merge into one low-temperature geothermal system and remove the sea drape i.e. adopt the coastline for the system extent.

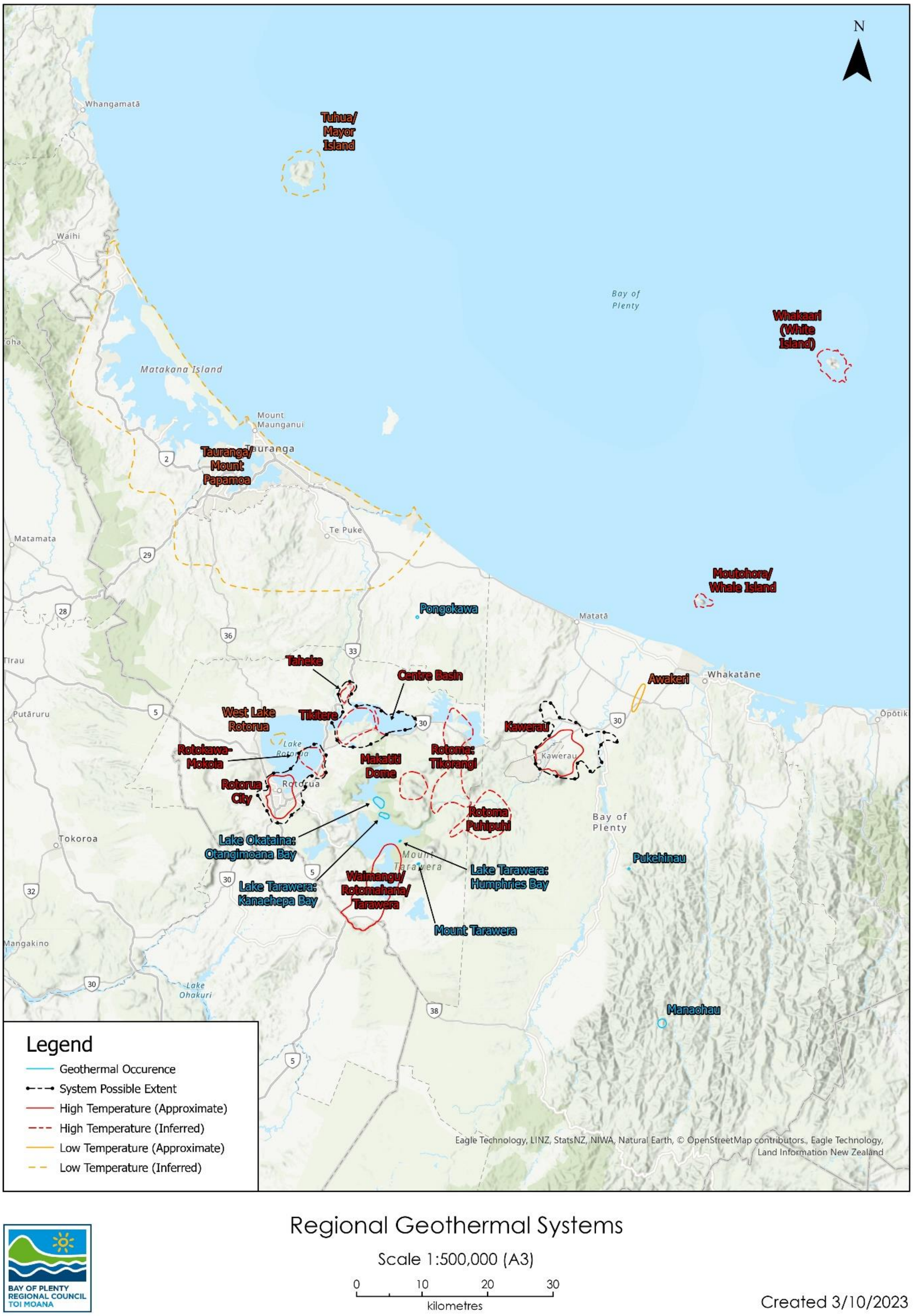

Figure 2: Proposed extent and potential extent for the geothermal systems and occurrences of the Bay of Plenty region.

- Separate the RNRP and RPS low-temperature systems into geothermal systems and geothermal occurrences, as below:
  a) Low-temperature systems:
     i) Awakeri
     ii) Tūhua (Mayor Island)
     iii) Tauranga-Mount Maunganui (Mauao) + Pāpāmoa-Maketū
  b) Geothermal occurrences (regardless of the temperature):
     i) Lake Tarawera - Humphries Bay
     ii) Lake Tarawera - Kanaehepa Bay
     iii) Lake Ōkataina - Otangimoana Bay
     iv) Mount Tarawera
     v) Manaohau, Pukehinau-Waikokopu, Pongakawa
- Add one new high-temperature system: Makatiti Dome.
- Add one new low-temperature system: West Lake Rotorua.
- Remove Matatā from the list of geothermal systems for the Bay of Plenty region.
- Accept the location, extent and potential extent as per Section 3 and presented in in Figure 2, from a scientific perspective.
- Accept the type of extent and potential extent as either approximate or inferred to reflect the level of certainty on those areas, from a scientific perspective.

Those proposed changes might be adopted by the reviewed Bay of Plenty Regional Natural Resources Plan through the Plan Change 11, but further work might be required as part of the process of building the knowledge-base for the plan change.

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REFERENCES

Allis, R. G., Christenson, B. W., Nairn, I. A., Risk, G. F., & White, S. P. (1993). The natural state of Kawerau geothermal field. In Proc. of the 15th New Zealand Geothermal Workshop (pp. 227-233).

Bay of Plenty Regional Council. 1991. Geothermal overview report. Bay of Plenty Regional Council Technical publication number 4. August 1991.

Bay of Plenty Regional Natural Resources Plan 2008 (amended). Regional Natural Resources Plan | Bay of Plenty Regional Council | Toi Moana (boprc.govt.nz)

Bay of Plenty Regional Policy Statement 2014 (amended). Regional Policy Statement | Bay of Plenty Regional Council | Toi Moana (boprc.govt.nz)

Bay of Plenty Regional Coastal Environmental Plan 2019. Regional Coastal Environment Plan | Bay of Plenty Regional Council | Toi Moana (boprc.govt.nz)

Beanland, S. 1995. The North Island Dextral Fault Belt, Hikurangi Subduction Margin, New Zealand. PhD Thesis, Victoria, University of Wellington.

Bertrand, E. A., Kannberg, P., Caldwell, T. G., Heise, W., Constable, S., Scott, B., ... & Palmer, N. (2022). Inferring the magmatic roots of volcano-geothermal systems in the Rotorua Caldera and Ōkataina Volcanic Centre from magnetotelluric models. Journal of Volcanology and Geothermal Research, 431, 107645.

Bibby, H. M., Dawson, G. B., Rayner, H. H., Bennie, S. L., & Bromley, C. J. (1992). Electrical resistivity and magnetic investigations of the geothermal systems in the Rotorua area, New Zealand. Geothermics, 21(1-2), 43-64.

Bibby, H. M., Bennie, S. L., Stagpoole, V. M., and Caldwell, T. G. (1994). Resistivity structure of the Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, New Zealand. Geothermics, 23(5-6), 445-471.

Botz, R., Wehner, H., Schmitt, M., Worthington, T. J., Schmidt, M., & Stoffers, P. (2002). Thermogenic hydrocarbons from the offshore Calypso hydrothermal field, Bay of Plenty, New Zealand. Chemical Geology, 186(3-4), 235-248.

Stagpoole, V. M., & Bibby, H. M. (1998). Shallow resistivity of the Taupo volcanic zone, New Zealand. In Proc. 20th New Zealand Geothermal Workshop (pp. 303-309).

Bromley, C. J., Bottomley, J. J., & Pearson, C. F. (1988). Geophysical exploration for prospective geothermal resources in the Tarawera Forest. In Proceedings lOth NZ Geothermal Workshop (pp. 123-128).

Bromley, C. J., Bennie, S., & Graham, D. (2003). Geophysical methods for shallow geothermal exploration and assessment of sustainable resource utilization–an example from Awakeri, Whakatane. In Proceedings of the 25th NZ Geothermal Workshop (pp. 107-112).

Brown, I. R. (2010). Geothermal potential at Red Stag site, Rotorua. Report for East Harbour Energy Ltd. IRBA project 1077. April, 2010.

Caratori-Tontini, F., de Ronde, C. E. J., Black, J., Stucker, V. K., & Walker, S. L. (2023). The geology and geophysics of Lake Tarawera, New Zealand: Implications for sublacustrine geothermal activity. Journal of Volcanology and Geothermal Research, 433, 107731.

Cave, M. P., Lumb, J. T., & Clelland, L. (1993). Geothermal resources of New Zealand. Resource Information, Energy and Resources Division, Ministry of Commerce.

de Ronde, C.E.J., Walker, S.L., LeBlanc, C., Davy, B.W., Fornari, D.J., Tontini, F.C., Scott, B.J., Seebeck, H., Stewart, T.J., Mazot, A. and Nicol, A., 2016. Reconstruction of the geology and structure of Lake Rotomahana and its hydrothermal systems from high-resolution multibeam mapping and seismic surveys: Effects of the 1886 Tarawera Rift eruption. Journal of Volcanology and Geothermal Research, 314, pp.57-83.

de Ronde C.E.J., Caratori Tontini F., Walker S.L., Stewart T.J., Fornari D.J., Stucker, V.K., Black J. 2022. The geology and geophysics of Lake Rotoiti, New Zealand: Implications for sublacustrine geothermal activity. Journal of Volcanology and Geothermal Research. In press.

Giggenbach, W.F., Shinohara, H., Kusakabe, M., Ohba, T. 2003. Formation of Acid Volcanic Brines through Interaction of Magmatic Gases, Seawater, and Rock within the White Island Volcanic-hydrothermal System, New Zealand. Society of Economic Geologists, Special Publication 10, p. 19-40.

GNS Science. (2016). New Zealand Active Faults Database 1:250,000 scale [Data set]. GNS Science.

Geothermal and Groundwater Database. 2021 –. Release 3.1.26.115. Lower Hutt (NZ): GNS Science. [updated 2021 Nov 11; accessed February 2022]. https://doi.org/10.21420/9QTA-4884

Hedenquist, J. W. (1991). Boiling and dilution in the shallow portion of the Waiotapu geothermal system, New Zealand. Geochimica et Cosmochimica Acta, 55(10), 2753-2765.

Hochstein, M. P., Yamada, Y., Kohpina, P, and Doens, E. F. 1987. Reconnaissance of the Tikorangi geothermal prospect (Haroharo-Ōkataina caldera), New Zealand. In Proc. 9th NZ Geothermal Workshop, pp. 31-36.

Janků-Čápová, L., Zarrouk, S.J., Zuquim, M.P.S (2022). Tauranga Geothermal System: Temperature Distribution. In Proc. 44th New Zealand Geothermal Workshop, Auckland, New Zealand.

Johnston, J.M., Pellerin, L. and Hohmann, G.W. (1992). Evaluation of Electromagnetic Methods for Geothermal Reservoir Detection. Geothermal Resources Council Transactions, Vol 16. pp 241–245.

Kilgour, G., Kennedy, B., Scott, B., Christenson, B., Jolly, A., Asher, C., Rosenberg, M. and Saunders, K., 2021. Whakaari/White Island: a review of New Zealand's most active volcano. New Zealand Journal of Geology and Geophysics, 64(2-3), pp.273-295.

Kissick, D., Carey, B., Alcaraz, S. (2023). Geothermal: The Next Generation Deep Geothermal Exploratory Drilling and Testing in the Taupō Volcanic Zone. Traverse Environmental Ltd report. May 2023.

Leonard, G. S., Begg, J. G., Wilson, C. J. N., & Leonard, G. S. (2010). Geology of the Rotorua area. Lower Hutt, New Zealand: GNS Science.

Milicich, S. D., Chambefort, I., Wilson, C. J. N., Charlier, B. L. A., & Tepley, F. J. (2018). The hydrothermal evolution of the Kawerau geothermal system, New Zealand. Journal of Volcanology and Geothermal Research, 353, 114-131.

Mouslopoulou, V.; Nicol, A.; Little, T.A.; Walsh, J.J. 2007. Displacement transfer between intersecting regional strike-slip and extensional fault systems. Journal of Structural Geology 29, 100–116.

Nairn, I. A. 2002. Geology of the Okataina volcanic centre, scale 1: 50,000 (Institute of Geological and Nuclear Sciences geological map No. 25).

Pearson-Grant, S.C., Burnell, J.G. (2018). Update of the Tauranga Basin geothermal reservoir model. GNS Science Consultancy Report 2018/102.

Reeves, R., Scott, B.J., Hall, J. 2014. 2014 Thermal infrared survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields. GNS Science Consultancy Report 2014/57.

Rowland, J. V., & Sibson, R. H. (2004). Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. Geofluids, 4(4), 259-283.

Scott, B.J., Kissling, W.M., Moreau, M., Sajkowski, L., Burnell, J.G., Brakenrig,

T., Reeves, R.R. 2021. Assessing the Rotorua Geothermal System: a review of data sets. GNS Science Consultancy Report 2020/84.

Seward, A.M., Reeves, R.R., Scott, B.J. 2018. Proposed monitoring options for Lake Rotokawa-Mokoia and Tikitere geothermal systems. GNS Science Consultancy Report 2018/212.

Seward, A., Reeves, R., & Alcaraz, S. (2022). Assessment of the surface heat loss from Waimangu Geothermal Valley: Comparison of terrestrial based assessment techniques with remote sensing. Journal of Volcanology and Geothermal Research, 430, 107630.

Simmons, S. F., Stewart, M. K., Robinson, B. W., & Glover, R. B. (1994). The chemical and isotopic compositions of thermal waters at Waimangu, New Zealand. Geothermics, 23(5-6), 539-553.

Stagpoole, V. M., and Bibby, H. M. Electrical resistivity map of the Taupo Volcanic Zone, New Zealand; nominal array spacing 500 m, 1:250 000, version 1.0. Institute of Geological & Nuclear Sciences geophysical map 11. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (1998a).

Ussher, G., Harvey, C., Johnstone, R., & Anderson, E. (2000, May). Understanding the resistivities observed in geothermal systems. In proceedings world geothermal congress (pp. 1915-1920). Japan: Kyushu.

White, B. (2006). An assessment of geothermal direct heat use in New Zealand. New Zealand Geothermal Association Inc.

White, P. A., Meilhac, C., Zemansky, G., & Kilgour, G. (2008). Groundwater resource investigations of the Western Bay of Plenty area stage 1 – conceptual geological and hydrological models and preliminary allocation assessment. GNS Science consultancy report, 240, 221.

Whiteford, P.C. 1992: Heat flow in the sediments of Lake Rotorua. Geothermics 21: (1/2), 75-78.

Wilson, C. J. N., Houghton, B. F., McWilliams, M. O., Lanphere, M. A., Weaver, S. D., & Briggs, R. M. (1995). Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. Journal of volcanology and geothermal research, 68(1-3), 1-28.

Yang, T. H. J., Chambefort, I., Mazot, A., Rowe, M. C., Scott, B., Macdonald, N., ... & de Ronde, C. E. (2023). Understanding caldera degassing from a detailed investigation at Lake Rotoiti, Ōkataina Volcanic Centre, New Zealand. Journal of Volcanology and Geothermal Research, 433, 107716.

Zuquim, M.P.S., Zarrouk, S.J., Janků-Čapova, L. (2022). Tauranga geothermal system – an overview. In Proc. 44th New Zealand Geothermal Workshop, Auckland, New Zealand.

Zuquim, M.P.S. (2023). BOPRC Environmental Publication 2023-03 - Geothermal Systems of the Bay of Plenty region – Inventory and Extent.

APPENDIX

Table 1: Summary of the data and information sources utilised to inform the extent of the high-temperature geothermal system of the Bay of Plenty region identified in the RNRP and RPS.

Geothermal system	Geophysics	Surface data	Wellbore data	Geochemistry
Kawerau	Allis *et. al.* (1993). Milicich *et. al.* (2018).	BOPRC geothermal surface features database. BOPRC geothermal vegetation layer.	Milicich *et. al.* (2018).	Milicich *et. al.* (2018).
Lake Rotoiti – Centre Basin	Stagpoole & Bibby (1998). de Ronde *et. al.* (2022). Bertrand *et. al.* (2022).	BOPRC geothermal surface features database. de Ronde *et. al.* (2022). Yang *et. al.* (2023).	BOPRC wells database.	Yang *et. al.* (2023).
Moutohorā Island (Whale Island)	N/A.	BOPRC geothermal surface features database. BOPRC geothermal vegetation layer. Bathymetry.	N/A.	N/A.
Rotokawa-Mokoia Island	Bibby *et. al.* (1992). Whiteford (1992). Bertrand *et. al.* (2022).	Reeves *et. al.* (2014). BOPRC geothermal surface features database.	BOPRC wells database.	Seward *et. al.* (2018).
Rotorua City	Bibby *et. al.* (1992). Whiteford (1992). Bertrand *et. al.* (2022).	Reeves *et. al.* (2014). BOPRC geothermal surface features database. BOPRC geothermal vegetation layer.	BOPRC wells database.	Scott *et. al.* (2021).
Rotomā-Tikorangi	Hochstein *et. al.* (1987). Bromley *et. al.* (1988).	BOPRC geothermal surface features database. BOPRC geothermal vegetation layer. Bromley *et. al.* (1988).	Cave *et. al.* (1993). BOPRC wells database.	Bromley *et. al.* (1988).
Rotomā-Puhipuhi	Hochstein *et. al.* (1987). Bromley *et. al.* (1988).	BOPRC geothermal surface features database. Bromley *et. al.* (1988).	BOPRC wells database.	Bromley *et. al.* (1988).
Tikitere-Ruahine	Stagpoole & Bibby (1998). Bertrand *et. al.* (2022).	BOPRC geothermal surface features database. Yang *et. al.* (2023).	BOPRC wells database.	Seward *et. al.* (2018).
Tāheke	Stagpoole & Bibby (1998).	BOPRC geothermal surface features database. Yang *et. al.* (2023).	BOPRC wells database.	BOPRC consents reports.
Waimangu-Rotomahana-Tarawera	Bibby *et. al.* (1994). Seward *et. al.* (2022). de Ronde *et. al.* (2016). Caratoni-Tontini *et. al.*, 2023. Bertrand *et. al.* (2022).	BOPRC geothermal surface features database.	Hedenquist (1991).	Simmons *et. al.* (1994)
Whakaari (White Island)	N/A.	BOPRC geothermal surface features database. Giggenbach *et. al.* (2003). Kilgour *et. al.* (2021). Bathymetry.	N/A.	Kilgour *et. al.* (2021).

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Table 2: Summary of the data and information sources utilised to inform the extent of the potentially new high-temperature geothermal system of the Bay of Plenty region not identified in the RNRP and RPS.

Geothermal system	Geophysics	Surface data	Wellbore data	Geochemistry
Makatiti Dome	Bertrand *et. al.* (2022).	N/A	N/A	N/A

Table 3: Summary of the data and information sources utilised to inform the extent of the low-temperature geothermal system of the Bay of Plenty region identified in the RNRP and RPS. It also includes the geothermal occurrences.

Geothermal system	Geophysics	Surface data	Wellbore data	Geochemistry
Awakeri	Bromley *et. al.* (2003).	Bromley *et. al.* (2003). BOPRC geothermal surface features database. BOPRC geothermal vegetation layer. GNS Science active faults database.	Bromley *et. al.* (2003)	Awakeri
Manaohau	N/A.	Cave *et. al.* (1993). Natural Thermal Feature/Springs of New Zealand (GNS GGW database).	N/A.	Manaohau
Matatā	N/A.	White (2009) GNS Science active faults database.	Cave *et. al.* 1993.	Matatā
Tūhua (Mayor Island)	N/A.	BOPRC geothermal surface features database. Bathymetry.	N/A.	Tūhua (Mayor Island)
Pukehinau-Waikokopu	N/A.	BOPRC Geothermal overview report (1991). Natural Thermal Feature/Springs of New Zealand (GNS GGW database).	N/A.	Pukehinau-Waikokopu
Tauranga-Mount Maunganui (Mauao)-Pāpāmoa-Maketū	N/A.	BOPRC geothermal vegetation layer. Leonard *et. al.* (2010). Natural Thermal Feature/Springs of New Zealand (GNS GGW database) + BOPRC data on warm springs.	BOPRC wells database. Pearson-Grant & Burnell (2018). Zuquim *et. al.* (2022).	Tauranga-Mount Maunganui (Mauao)-Pāpāmoa-Maketū

Table 4: Summary of the data and information sources utilised to inform the extent of the potentially new low-temperature geothermal system, of the Bay of Plenty region not identified in the RNRP and RPS.

Geothermal system	Geophysics	Surface data	Wellbore data	Geochemistry
West Lake Rotorua	Bibby *et. al.* (1992). Whiteford (1992).	N/A.	N/A.	West Lake Rotorua

Table 5: Summary of the data and information sources utilised to inform the extent of the potentially new geothermal occurrences of the Bay of Plenty region not identified in the RNRP and RPS.

Geothermal system	Geophysics	Surface data	Wellbore data	Geochemistry
Lake Tarawera - Humphries Bay	Stagpoole & Bibby, (1998). Caratori-Tontini *et. al.* 2023.	BOPRC geothermal surface features database. Nairn (1981). Caratori-Tontini *et. al.* (2023).	N/A	Lake Tarawera - Humphries Bay
Lake Tarawera - Kanaehepa Bay	Caratori-Tontini *et. al.* (2023).	BOPRC geothermal surface features database. Caratori-Tontini *et. al.* (2023).	N/A	Lake Tarawera - Kanaehepa Bay
Lake Ōkataina – Otangimoana Bay	Stagpoole & Bibby (1998).	Nairn (1981).	N/A	Lake Ōkataina – Otangimoana Bay
Mt Tarawera	Stagpoole & Bibby (1998). Bertrand *et. al.* (2022).	BOPRC geothermal surface features database.	N/A	Mt Tarawera
Pongakawa	N/A	N/A	BOPRC wells database.	Pongakawa
Pukehinau-Waikokopu	Refer to Table 3 (appendix).			
Manaohou	Refer to Table 3 (appendix).			
Matatā	Refer to Table 3 (appendix).			

Table 6: Data/criteria applied to delineate the extent and potential extent of the high-temperature geothermal systems of the Bay of Plenty region identified in the RNRP and RPS.

Geothermal system	System extent	Potential extent
Kawerau	Regional resistivity survey – 70 Ω m (AB/2 = 500 m nominal spacing) + 30 Ω m (AB/2 = 1000 m nominal spacing) (smoothed). Hot and warm wells (KA49 included). Cold bores to constrain extension. Geothermal surface features – all. Geothermal vegetation – all.	Include system extent. Regional resistivity survey – 70 Ω m (AB/2 = 500 m nominal spacing) + 50 Ω m (AB/2 = 1000 m nominal spacing) (smoothed). Hot and warm wells (KA49 excluded).
Moutohorā Island (Whale Island)	Bathymetry at 20 m below sea level. Geothermal surface features - all. Geothermal vegetation – all.	N/A.
Rotokawa-Mokoia Island	Regional resistivity survey – 100 Ω m (AB/2 = 500 m nominal spacing) (smoothed). Heat flow contour 0.5 W/m^2 (approximate). Hot and warm wells. Cold bores to constrain extension. Geothermal surface features - all.	Include system extent. Cover Waikare-Hinemoa Point spring. Regional resistivity survey (smoothed): • 150 Ω m (AB/2 = 500 m nominal spacing) in Rotokawa-Mokoia Island area. • 70 Ω m (AB/2 = 1000 m nominal spacing) in Rotorua area. Heat flow contour 0.25 W/m^2 (approximate).
Rotorua city	Regional resistivity survey – 30 Ω m (AB/2 = 500 m and AB/2 = 1000 m nominal spacing) (smoothed). Heat flow contour 0.5 W/m^2 (approximate). Hot and warm wells. Cold bores to constrain extension. Geothermal surface features - all. Geothermal vegetation – all.	

Geothermal system	System extent	Potential extent
Rotomā-Tikorangi	Regional resistivity survey – 50 Ω m (500 m nominal spacing) (smoothed). System limits of Bromley *et. al.* (1988). Including the area with high chloride flux between the Tarawera Falls and the Waterfall Road bridge, and the warm swamp. Encompass all geothermal surface features and mapped geothermal vegetation.	N/A
Rotomā-Puhipuhi	System limits of Bromley *et. al.* (1988). Encompass all geothermal surface features and mapped geothermal vegetation.	N/A
Lake Rotoiti – Centre Basin	Heat flow anomalies. Include areas with indication of degassing by hydrothermal activity in the bottom of Lake Rotoiti (moderate-high CO2 flux and pockmarks). Surface features inventory. Ōkataina Volcanic Centre boundary.	Include Tikitere-Ruahine, Taheke and Lake Rotoiti - Centre Basin systems' extent. Regional resistivity survey (smoothed) - 50 Ω m (AB/2 = 500 m and AB/2 = 1000 m nominal spacing) Include areas with indication of degassing by hydrothermal activity in the bottom of Lake Rotoiti (low-moderate CO2 flux and pockmarks). Warm wells. Relict hydrothermal eruption occurrence.
Tikitere-Ruahine	Regional resistivity survey - 30 Ω m (AB/2 = 500 m nominal spacing). Hot wells. Cold bores to constrain extension. Geothermal surface features - all. Geothermal vegetation – all.	
Tāheke	Regional resistivity survey - 30 Ω m (AB/2 = 500 m nominal spacing). Hot wells. Cold bores to constrain extension. Geothermal surface features - all. Geothermal vegetation – all.	
Waimangu-Rotomahana-Tarawera	Regional resistivity survey – 50 Ω m (500 m nominal spacing) (smoothed). Conductive heat flow >2 W/m^2 and > 1 W/m^2 for Lake Rotomahana. Geothermal surface features - all. Geothermal vegetation – all.	N/A
Whakaari (White Island)	Bathymetry at 150 m below sea level, excluding the neck to NW. Geothermal surface features - all. Geothermal vegetation – all.	N/A

Table 7: Data/criteria applied to delineate the extent and potential extent of the high-temperature geothermal system of the Bay of Plenty region not identified in the RNRP and RPS.

Geothermal system	System extent	Potential extent
Makatiti Dome	MT survey - 10 Ω m at 3 km depth.	N/A

Table 8: Data/criteria applied to delineate the extent and potential extent of the low-temperature geothermal system of the Bay of Plenty region identified in the RNRP and RPS.

Geothermal system	System extent	Potential extent

Awakeri	Include the resistivity low (30 Ω m) of Bromley *et. al.* (2003) and the west limit of the regional resistivity survey (AB/2 = 500 m nominal spacing). Include warm wells and warm spring. Follow the Awakeri fault trend of the active faults database and of Bromley *et. al.* (2003).	N/A
Tūhua (Mayor Island)	Bathymetry at 70 m below sea level. Geothermal surface features - all. Geothermal vegetation – all.	N/A
Tauranga-Mount Maunganui (Mauao) plus Pāpāmoa-Maketu	Encompass all warm wells and springs. Informed by the temperature gradient contours (Zuquim *et. al.*, 2022) Informed by the location of the concealed faults in Maketū (Leonard *et. al.*, 2010).	N/A

Table 9: Data/criteria applied to delineate the extent and potential extent of the low-temperature geothermal system of the Bay of Plenty region not identified in the RNRP and RPS.

Geothermal system	System extent	Potential extent
West Lake Rotorua	Regional resistivity survey - 30 Ω m (AB/2 = 500 m nominal spacing). Heat flow data points of 0.12 W/m^2.	N/A

Table 10: Summary of the availability and suitability of data used to inform the extent and potential extent of the high-temperature geothermal system of the Bay of Plenty region and the resulting level of confidence on their extent. Geothermal systems identified in the RNRP and RPS only. This resulting level of uncertainty informs the recommendation of an approximate or inferred extent, and the suitability for an associated potential extent. Green cells are for data sources assessed to have a high level of quality and appropriateness to inform system extent. Orange cells are for when the quality/appropriateness is moderate, and red cells are for low. The resulting level of confidence for the system extent follows the same colour code.

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Kawerau	Detailed local resistivity survey.	Geothermal surface features mapped and representative of the deeper system.	Several hot, warm and cold wells/bores with quality data.	Reasonably high. NE geophysical extent of the field not fully constrained. **Recommend an approximate extent.**	**Recommend including a potential extent** to reflect evidence that the geothermal system may extend further to NE.
Lake Rotoiti – Centre Basin	Regional resistivity data does not outline a system area or extent. Bottom of lake geophysics and CO_2 flux only insufficient for system extent delineation.	Surface expression under the water, with quality lake-bottom surveys available. No data on an inland extension identified.	Few shallow wells in the system inland. Most of the system is untapped, at the lake bottom.	Low. **Recommend inferred extent.**	**Recommend including a potential extent** Cf. Taheke - Tikitere-Ruahine
Moutohorā Island (Whale Island)	N/A	Geothermal surface features mapped but data is particularly outdated, due to limited research carried out in this geothermal system. Little known about subaquatic thermal activity.	No wells drilled to test the system.	Low. **Recommend an inferred extent covering the volcano edifice.**	Not enough information to inform a potential extent.
Rotokawa-Mokoia Island	Regional resistivity data but no local resistivity survey.	Geothermal surface features mapped and representative of the deeper system.	Some hot wells and cold bores to constraint the system.	Moderate. Limited subsurface information/testing and lack of local resistivity surveys. **Recommend an inferred extent**.	**Recommend including a potential extent** to reflect the potential hydrological connection between

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Rotorua City	Local, integrated geophysical investigations via various methods (gravity, magnetics, MT, resistivity, seismic).	Geothermal surface features mapped and representative of the deeper system.	Extensive wells database.	Reasonably high. Extensively researched system. **Recommend an approximate extent.**	Rotokawa-Mokoia Island and Rotorua City at depth.
Rotomā-Tikorangi	Local, integrated geophysical investigations via various methods (gravity, magnetics, and resistivity).	Geothermal surface features mapped and representative of the deeper system. Complemented with data from literature.	Only one exploration well (RM1) with presumably quality data, but confidential and not accessible. Published papers indicate high subsurface temperatures. A reasonable number of warm wells at the BOPRC database. Limited subsurface data to inform the system extent.	Moderate. Limited subsurface data and the system has limited surface expression. **Recommend an inferred extent**.	Not enough information to inform a potential extent.
Rotomā-Puhipuhi	Local, integrated geophysical investigations via various methods (gravity, magnetics, and resistivity).	Geothermal surface features mapped and representative of the deeper system. Complemented with data from literature.	No wells to test the anomaly.	Moderate. No subsurface data and the system has limited surface expression. **Recommend an inferred extent.**	Not enough information to inform a potential extent.
Tikitere-Ruahine	Regional resistivity data but no local resistivity survey available.	Geothermal surface features mapped but features-type not fully representative of the deeper geothermal reservoir/aquifer.	Deeper system not tested/drilled into.	Moderate. **Recommend an inferred extent.**	**Recommend including a potential extent** to reflect the potential hydrological connection between Tāheke, Tikitere-Ruahine and Lake Rotoiti - Centre Basin systems at depth.

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Tāheke	Regional resistivity data but no local resistivity survey available to Council. Previous MT survey confidential.	Geothermal surface features mapped but features-type not fully representative of the deeper geothermal reservoir/aquifer.	Deep drilling carried out recently for exploration. Part of the drilling data not available to Council.	Moderate. **Recommend an inferred extent.**	
Waimangu-Rotomahana-Tarawera	Regional resistivity data but no local geophysical survey on land. Quality bottom of lake surveys. TIR flight but results constrained by extensive vegetation cover. Collectively good information.	Surface features extensively mapped and studied. Detailed lake-bottom survey. Warm springs at lake shore mapped.	Only one exploration well.	Reasonably high. Extensively researched system. **Recommend an approximate extent.**	Not enough information to inform a potential extent.
Whakaari (White Island)	No geophysical studies suitable for the purposes of this work.	Geothermal surface features extent probably does not reflect the subsurface limits of a geothermal system and the volcano. A significant part of the volcano edifice is underwater.	No geothermal wells drilled.	Low. **Recommend an inferred extent covering the volcano edifice.**	Not enough information to inform a potential extent.

Table 11: Summary of the availability and suitability of data used to inform the extent and potential extent of the high-temperature geothermal system of the Bay of Plenty region and the resulting level of confidence on their extent. Geothermal systems not identified in the RNRP and RPS. This resulting level of uncertainty informs the recommendation of an approximate or inferred extent, and the suitability for an associated potential extent. Green cells are for data sources assessed to have a high level of quality and appropriateness to inform system extent. Orange cells are for when the quality/appropriateness is moderate, and red cells are for low. The resulting level of confidence for the system extent follows the same colour code.

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Makatiti Dome	Not well constrained yet. Deep MT survey integrated with other geoscientific studies leave an open possibility of the occurrence of a blind system.	N/A but might be linked to springs at surface offset to the reservoir. Requires further studies to confirm.	No wells drilled to test the system.	Low. Speculative stage, but with some reasonably strong evidence of a blind system. **Recommend an inferred extent.**	Not enough information to inform a potential extent.

Table 12: Summary of the availability and suitability of data used to inform the extent and potential extent of the low-temperature geothermal system of the Bay of Plenty region and the resulting level of confidence on their extent. Geothermal systems identified in the RNRP and RPS only. This resulting level of uncertainty informs the recommendation of an approximate or inferred extent, and the suitability for an associated potential extent. Green cells are for data sources assessed to have a high level of quality and appropriateness to inform system extent. Orange cells are for when the quality/appropriateness is moderate, and red cells are for low. The resulting level of confidence for the system extent follows the same colour code.

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Awakeri	Detailed local resistivity but does not cover the wider area and location of warm wells to northeast. Resistivity data validated by seismic and gravimetry surveys. Regional DC resistivity not fit-for-purpose.	The only geothermal spring is mapped and representative of the deeper system.	Location of warm wells well defined and cold wells provide a constraint to the warm area. Some quality data for the Awakeri hot pools wells.	Reasonably high. **Recommend an approximate extent.**	Not enough information to inform a potential extent.

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Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
Tūhua (Mayor Island)	Not available.	A few warm springs mapped along the coast, but might have some surface features underwater.	N/A	Low. **Recommend an inferred extent covering the volcanic edifice.**	Not enough information to inform a potential extent.
Tauranga-Mount Maunganui (Mauao) **plus** Pāpāmoa-Maketu	Regional DC resistivity survey not fit-for-purpose as the results are likely affected by saltwater intrusion and does not cover most of the system.	Warm springs reasonably well mapped but does not provide constraints on the extent of the geothermal system.	Location of warm wells well defined and cold wells provide a constraint to the warm aquifer area, but there is some uncertainty on the quality of the temperature bore data (i.e. whether cold bores could be warm bores). Temperature profile data with limited coverage to west and south.	Moderate. **Recommend an inferred extent.** **Recommend remove sea drape and use the coastline as the system limit.**	Not enough information to inform a potential extent.

Table 13: Summary of the availability and suitability of data used to inform the extent and potential extent of the low-temperature geothermal system of the Bay of Plenty region and the resulting level of confidence on their extent. Geothermal systems not identified in the RNRP and RPS. This resulting level of uncertainty informs the recommendation of an approximate or inferred extent, and the suitability for an associated potential extent. Green cells are for data sources assessed to have a high level of quality and appropriateness to inform system extent. Orange cells are for when the quality/appropriateness is moderate, and red cells are for low. The resulting level of confidence for the system extent follows the same colour code.

Geothermal system	Geophysics	Surface expression of the geothermal system	Wellbore data	Level of confidence for defining an extent and recommendation for an approximate or inferred extent	Potential extent – rationale
West Lake Rotorua	Regional resistivity data and historical bottom of lake heat flow survey.	Surface expression under the water if at all.	No wells to test the anomaly.	Low. Geophysics indicate a relict system but very minor conductive heat flow still present. **Recommend an inferred extent.**	Not enough information to inform a potential extent.

Table 14: Summary of the availability and suitability of data used to inform the extent and potential extent of the low-temperature geothermal system of the Bay of Plenty region and the resulting level of confidence on their extent. Geothermal systems not identified in the RNRP and RPS. This resulting level of uncertainty informs the recommendation of an approximate or inferred extent, and the suitability for an associated potential extent. Green cells are for data sources assessed to have a high level of quality and appropriateness to inform system extent. Orange cells are for when the quality/appropriateness is moderate, and red cells are for low. The resulting level of confidence for the system extent follows the same colour code.

Geothermal occurrence	Summary of data used to inform the location or extent of the occurrence	Level of certainty and/or error	Approach for defining the location or extent of the occurrence
Lake Tarawera - Humphries Bay	Geothermal surface features inventory and Caratori-Tontini *et. al.* (2023).	Reasonably high	Location of surface features and high conductive heat flow (approx. > 2 W/m^2). **Recommend an approximate extent.**
Lake Tarawera - Kanaehepa Bay	Geothermal surface features inventory and Caratori-Tontini *et. al.* (2023).	Reasonably high	Geothermal surface features – occurrence broad area. **Recommend an approximate extent.**
Lake Ōkataina – Otangimoana Bay	Nairn (2002). Regional resistivity survey – 30 Ω m (500 m nominal spacing) from Stagpoole & Bibby 1998.	Low	Exact location of warm springs and their correlation with resistivity data unknown. **Recommend an inferred extent.**
Mount Tarawera	Geothermal surface features inventory.	Moderate	Location of geothermal surface features. Constraints due to the limited correlation between the geothermal surface features' types (steam-fed) and an underlying geothermal system. **Recommend an inferred extent.**
Pukehinau-Waikokopu	Reports of warm seeps adjacent to Waikokopu Stream at Pukehinau Stream confluence.	Moderate. 140 m coordinates error.	Geographical coordinates as per database with a circle of 140 m radius around the location. **Recommend an inferred extent.**
Manaohou	Report of a warm seep in the area.	Moderate. 650 m coordinates error.	Geographical coordinates as per database with a circle of 650 m radius around the location. **Recommend an inferred extent.**
Matatā	Locals are aware of springs (White, 2009). Geophysics affected by salt/connate/brackish water. Report stating that exploratory well did not find geothermal water (White, 2009), but no data available. Set of active faults (Matatā fault system).	Low certainty. No records on the location of the springs or the exploratory well. Drilling raw data could not be accessed to check the results.	**Not enough information to define a system or an occurrence.**

Geothermal occurrence	Summary of data used to inform the location or extent of the occurrence	Level of certainty and/or error	Approach for defining the location or extent of the occurrence
		Extent inland completely unknown.	
Pongakawa	One isolated warm well (BN20-0256). No data to inform an area.	High certainty on the location of the well as per drilling report.	**Recommend the location of the well BN20-0256 plus a 200 m potential extent.**

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