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1.2 THE RANGE OF GEOTHERMAL FEATURES FOUND IN THE TVZ

In a geothermal field, what appears at the surface reflects both the surface topography and the processes occurring underground. A quick summary of the processes and their associated features is provided here, so that readers can follow the assessment process described later in this report. More detailed information, including some very helpful diagrams, is available at www.nzgeothermal.org.nz and www.nzic.org.nz/ChemProcesses/water/13A.pdf.

The very hottest fluids from the deepest parts of a geothermal system are typically of near neutral pH chloride composition. These hot fluids cause significant alteration to rocks that they pass through, and minerals such as silica become dissolved in them. As these hot fluids reach the upper parts of the system, pressure reduces and the water may boil. This separates dissolved gases, particularly carbon dioxide (CO_2) and hydrogen sulphide (H_2S) into a vapour phase with steam, which then moves independently towards the surface where it may form fumaroles and steaming ground. Where the steam phase meets cold, near-surface groundwater, it condenses, forming steam-heated waters. If the accompanying H_2S becomes oxidised, acid-suphate waters form. These highly acidic waters cause extensive alteration to rocks. Where CO_2 becomes dissolved in condensate waters, CO_2-rich steam-heated or bicarbonate waters form. These steam-heated waters are low in chloride. Some of the remaining deep chloride waters may reach the surface, forming features such as boiling alkaline springs and geysers, usually associated with silica sinter deposition. They may also become cooled and diluted, forming dilute chloride waters. The upflowing waters may be deflected horizontally by groundwater movement, so that chloride springs may discharge at some distance from steam-related features such as fumaroles. This effect may be most marked where the ground surface of the field has a varied topography or spans a wide altitudinal range (e.g. on the side of a hill or mountain).

Geothermal fields vary considerably in the extent and variety of geothermal surface features they exhibit. Some have a full range or sequence of the generalised features described above, whereas others only have some. In addition, geothermal fields vary in their biodiversity. The natural vegetation in and around geothermal fields in the TVZ has, like much of the rest of New Zealand, been modified to a greater or lesser extent by activities such as land clearance, farming and forestry, and associated impacts such as fire and weeds. Geothermal areas also contain organisms that have evolved to withstand high temperatures, which are generally unique to these areas.

2. Work requested

This study was commissioned by the Tongariro/Taupo and Rotorua Conservancies of the Department of Conservation (DOC). It involved the production of three spreadsheets. The first two summarise physical and chemical aspects of geothermal fields in the TVZ and individual features within those fields. Data in the spreadsheets have largely been compiled from existing published or unpublished sources, with additional information from the author based on personal familiarity with sites and observations made during site visits associated with other fieldwork. Following the compilation of the first two spreadsheets, a third spreadsheet was developed, which incorporates a scoring system to rank various attributes of the geothermal fields. To augment these spreadsheets, a separate Geothermal Bibliography was compiled. Copies of this have been lodged with both the Tongariro/Taupo and Rotorua Conservancies.

Only high-temperature geothermal fields in the TVZ were included in this study. It omitted some minor, localised warm-water occurrences in the TVZ, e.g. Awakeri springs, Motuoapa springs and Maketu. The excluded features are mostly small scale with minor surface expression, and are not directly related to volcanic activity. The author believes that they would have achieved very low scores in this exercise and therefore their omission does not constitute a gross oversight in the establishment of a hierarchy of high-temperature geothermal sites in the TVZ based on their geodiversity values.

This work on geothermal geodiversity was guided by a set of required outputs and prepared questions to be answered. These are listed below, together with brief comments about where each is addressed in the report.

A. *Compile a list of types of features (geodiversity) in geothermal areas, from the rarest to most common, including physical thermal features (e.g. geysers, fumaroles, hot springs, hot seeps, active silica terraces, active silica sinter deposits, mud volcanoes, mud pools and pots, hot lakes, hot ponds and pools, steaming ground, inactive but intact silica terraces, extinct silica deposits, explosion craters, collapse craters); and chemical characteristics of geothermal water (e.g. alkaline, neutral, bicarbonate or acid waters). Use temperature characteristics where practical.*

   This information has been presented in the spreadsheet 'Geothermal Fields Inventory', which is Appendix 1 of this report. It enables ready comparisons between the range of features and characteristics present in each geothermal system studied.

B. *Prepare a spreadsheet showing representation of each geothermal feature type in each geothermal area, including extant and extinct or destroyed examples. Indicate approximate numbers and area of features (absolute, indicative or relative scales) where possible.*

   This is presented in the spreadsheet 'Individual Geothermal Features Inventory', which is Appendix 2 of this report.

C. *Summarise the data compiled in spreadsheets 1 and 2 and then rank the geothermal fields according to the natural features they contain, and their degree of modification.*

   This summary and ranking is presented in 'Geothermal Field Rankings', which is Appendix 3 of this report.

The preparation of these spreadsheets was guided and informed by the following questions:

1. *What criteria should/could be used to rank the relative quality of extant examples of each feature type for conservation purposes (e.g. intactness, size, recent natural or induced change of temperature of surrounding vegetation, degree of existing impact, proximity to sources of direct or indirect disturbance, proximity to extant ecological sequences, and indigenous vegetation)?*

   The answer to this question is addressed in the range of headings and criteria used in the spreadsheets summarising geothermal fields (Appendices 1 and 2), and in section 3. The physical, chemical and geographical features all contribute to the ranking of the relative qualities of geothermal areas, and are parameters that can also be robustly assessed and audited by independent people.

2. *Can it be demonstrated that there are extensive geothermal sequences showing geophysical integrity or coherence which, if protected from development, would encapsulate significant systems or proportions of geothermal diversity?*

   The data in the three spreadsheets illustrate how it is practical to objectively compile summaries that show extensive geothermal sequences within contiguous areas. Waiotapu, Waihi-Hipaua and Te Kopia all score highly as sites of uncommon continuity and diversity. See sections 5.1 and 8.

3. *Are there particular features outside these sequences that are important contributors to New Zealand's remaining geothermal geodiversity (e.g. that are unique, of significant scientific value or one of only a few such features in the TVZ)?*

   There are features that are presently outside formally protected geothermal areas, which also represent outstanding geothermal attributes. Notable in this regard are the Red Hills and Waipapa Valley of Orakeikorako; the hydrothermal eruption craters of southern Ngatamariki and Horohoro; and the sinter-depositing springs of Reporoa. See section 5.2.

4. *What relationships between geodiversity and biodiversity are known or suspected in geothermal systems (e.g. macroscopic algae and water temperature, thermal ferns, and water chemistry)?*

   These relationships are discussed later in the text, but geothermal biodiversity is generally greatest in and around hot water features, as hot water tends to be more benign than steam. This is because steam features usually result from boiling, which also separates acidic gases that are more aggressive to life forms. See section 4.1.

5. *What types of geodiversity have proven to be or are likely to be most vulnerable to the effects of geothermal energy utilisation?*

   Geodiversity types that are dependent solely or largely upon upflows and surface outflows of deep geothermal fluids are most critically vulnerable to loss resulting from energy utilisation. Boiling springs, silica sinter deposition and geysers are particularly at threat. The loss of geysers, alkaline hot springs and actively depositing sinter from Wairakei, Taupo and Ohaaki soon after electricity generation started all illustrate this. See section 6.

6. *Given the analysis based on the required outputs A, B and C (above) and questions 1-5, what is the significance of Te Kopia geothermal area (i.e. not only the reserve) and the potential loss resulting from energy utilisation in the context of geodiversity in the TVZ?*

   Te Kopia has a very diverse topography and the most unmodified natural vegetation of all the TVZ geothermal areas. The area has a wide variety of geothermal phenomena that remain in largely natural conditions. Geological investigation indicates that flows of hot alkaline springs at Te Kopia were once much greater, depositing silica over large areas. Energy utilisation could dramatically degrade the geodiversity and biodiversity at Te Kopia. See section 7.

3. Details of spreadsheet preparation, including description and qualification of terms used

The spreadsheets (Appendices 1, 2 and 3) use the geothermal field names that are most commonly used, and self-explanatory terms and measurements as much as possible. However, some of the terminology is subjective, and the range of conditions or sizes that each adjective describes is discussed in more detail below. Single-word adjectives are used instead of actual measurements to provide groups or classes of features that can be easily understood at a glance.

Selection of terms used was the result of considerable discussion between the author and Dr Harry Keys (DOC, Tongariro/Taupo Conservancy), and other DOC staff.

These terms are described below. The term ‘feature’ is commonly used in geothermal science, because it can encompass the entire range of geothermally produced surface structures and phenomena.

3.1 TYPE AND SIZE OF FEATURE

The type of feature is based upon the nature of the fluid, steam or gas upflow that supports its existence. Neutral pH or alkaline chloride waters occur deep in the geothermal field where there is very little or no input of other fluids, steam or gas. Dilute chloride water is deep geothermal fluid diluted with groundwater. Acid sulphate and bicarbonate waters form when the gases H_2S and CO_2, respectively, dissolve in surface waters. Mixed waters may have varying amounts of these fluid types and groundwater.

Following identification of their chemical type, features are then described by size. A large-sized geothermal spring is > 5 m diameter (dia.), moderate size is 1–5 m dia. and small is < 1 m dia. Water bodies are termed lakes when > 20 m dia., pools when 5–20 m dia. and small pools when < 5 m dia.

Mud cones occur where mud ejecta builds up conical structures. Mud lakes are > 20 m dia., mud pools are 5–20 m dia. and mud pots < 5 m dia.

Steam-heated ground includes fumaroles, solfatara (where heated surficial liquids may be present in minor amounts), steaming ground, barren ground and altered ground.

3.2 MAIN FEATURES AND GROUPS OF FEATURES

Main features are listed by their name and/or catalogue or mapping reference number (if they have one). Important features or those that are good examples of their types in each geothermal field are presented either as separate entries (e.g. Champagne Pool, Ohaaki Pool, Te Kopia and Hipaua fumaroles) or as cumulative groups for features of the same type (e.g. three springs of same general chemistry and flow types; five mud pools of same general chemistry, colour and nature).

3.3 STATUS AND QUALITY

Status is given as: A = active at present in geothermal field; Hn = historically active but now inactive or lost due to natural causes; Hh = historically active but now inactive due to human causes; P = prehistorically active; and N = never present.

Quality is described as follows: O = outstanding example in its natural state; G = good example in natural state; M = modified; and D = severely degraded.

3.4 REPRESENTATION

This is given as an indication of how important the feature is in representing its type, including how rare it is in New Zealand and elsewhere. That is: I = internationally important, if it is the only one of its kind or the best in New Zealand; R = regionally important, if it is one of the best examples in the TVZ; and L = locally important, if it is one of the best examples in its geothermal field.

3.5 HYDROLOGICAL AND GASEOUS CHARACTER

This description involves surface flow rate and type of activity, together with a term to describe the state of any ebullition (i.e. bubbling activity, whether boiling or not).

Strong flow is > 3 litres per second (L/s), moderate is 1–3 L/s, weak is < 1 L/s and nonflowing means that there is no surface flow. Note, however, that a nonflowing clear spring with a neutral or alkaline pH will probably have a subsurface outflow into the surrounding ground or groundwaters, otherwise a static nonflowing body of such water will rapidly oxidise and become turbid and acidic.

Flow types are: periodic = geyser or cyclical flow; irregular = varying and aperiodic; steady = essentially nonvariable; and intermittent = sometimes inactive.

Gaseous ebullition is described as being either strong, moderate, weak or absent (i.e. mud or water is calm), with a mean height estimate for ejected mud or water. It is a relatively common phenomenon for pools and springs to have a bubbling surface that superficially appears to be boiling, although no steam is freely generated and the surface temperatures can be well below true boiling point.

3.6 BULK CHEMISTRY

This summarises the chemistry of the water, gas or solids. Odours may also be recorded.

Water type is described as: chloride, bicarbonate, chloride-sulphate, acid sulphate, sulphate, or other (see sections 1 and 3.1).

Where known, pH has been included. Otherwise, it has been categorised as: neutral to alkaline = pH > 6.6; weakly acidic = pH 6.6–4.5; moderately acidic = pH 4.5–3.0; and strongly acidic = pH < 3.0.

3.7 PHYSICAL CHARACTER

This summarises known details of normal temperature, heatflow (megawatts, MW), clarity (clear or turbid) and colour, including any suspended sediment evident. Temperature may be described as: superheated = > 100°C; boiling = 97–100°C; hot = 61–97°C; warm = 35–61°C; tepid = 25–35°C; and cold = < 25°C. Note that boiling point varies a few degrees within the TVZ according to altitude and also the quantity of dissolved solids and/or gases.

Fumarolic energy output may be described as: strong = > 2 MW; moderate = 2–0.5 MW; and weak = < 0.5 MW.

3.8 SINTER DEPOSITION

This classifies various characteristics including:

- The amount of deposition: active, minor or nil.
- The type of sinter: amorphous silica, calcite, calcite-silica intergrowths, and other.
- The form of deposition: dense, laminated, algal or residue.
- The structure of deposition: terraces, aprons, cascades, rims, sheets, mats, films, crusts and rinds.

3.9 LANDFORM TYPES

These include hydrothermal eruption craters (HEs), breccia deposits, dissolution craters or dolines, wetlands, hillslopes, terraces, gullies, ridges and flats.

3.10 SIGNIFICANCE

This score ranks the overall importance of a geothermal field in terms of its geodiversity. This is based upon the number of different types of individual geothermal features, the total number of features, their quality (including extent of naturalness/intactness/degradation as given in section 3.3 above), representation (i.e. rarity, etc.) and the range of characteristics likely to be important for biodiversity (including factors such as flow, chemistry, pH, temperature, colour, sinter deposition, altitude range and landform diversity).

It is notable that geothermal features related to steam and gas upflows tend to be the most common features recorded in geothermal fields, and these features tend not to have well-defined structures (e.g. hot ground, solfatara, warm ground). The smaller in size these features are, the more commonly they are recorded and thus the less significant they become. Hence, they generally have a low score in terms of geodiversity.

4. Using the information collated to rank geothermal fields and features according to their geodiversity

To compare geothermal fields based on their geodiversity, a ranking system was required to give scores for feature types, rarity, intactness or lack of modification, and representation of geothermal features within each field. The Geothermal Field Rankings spreadsheet (Appendix 3) uses a scoring system that gives 1–10 points to each type of geothermal feature present according to its intactness (i.e. natural, modified or degraded) and rarity.

Additional weighting has been given to all types of geysers (by doubling their ranking score), because of their exceptional rarity compared with all other types of geothermal features in particular and geological features in general (< 1000 worldwide; see, for example, www.teara.govt.nz/EarthSeaAndSky/HotSpringsAndGeothermalEnergy/HotSpringsMudPoolsAndGeysers for more detail).

To score altitudinal range in each geothermal field, the total altitudinal range (in metres) was divided by 100, to provide a value that was in proportion to scores for other features by preventing the large variations in altitude that occurred in some fields from dominating these fields' total scores.

The ranking scheme for individual geothermal features is provided in Table 1.

TABLE 1. RANKING SCHEME FOR INDIVIDUAL GEOTHERMAL FEATURES IN THE TAUPO VOLCANIC ZONE.

RANK	DESCRIPTION
0	Not present in this particular geothermal field or, if ever present, it has now been irretrievably lost.
1	Very poor example of geothermal feature but is the only or best remaining example in the geothermal field. Severely degraded by human activity.
2	Poor or only local example of its type but degraded by human activity.
3	Good local example in modified condition.
4	Good local example in natural condition.
5	Good regional example in modified condition.
6	Good regional example in natural condition.
7	Good national example in modified condition.
8	Good national example in natural condition.
9	Outstanding national example in natural condition.
10	Outstanding international example of its type in natural condition.

In each geothermal field, a score was given for intactness of vegetation, landscape and geothermal features (Table 2). These three scores were then averaged to produce a multiplier that was applied to the sum of geodiversity types scored above. Land-use activities were distinguished from fluid-extraction effects because the latter are generally more destructive and more likely to be irreversible, especially at the rates required for power generation. Note that land-use or geothermal field changes considered to result from entirely natural processes have not been included.

TABLE 2. RANKING SCHEME FOR LANDSCAPE AND LAND USE FEATURES OF GEOTHERMAL FIELDS IN THE TAUPO VOLCANIC ZONE.

RANK	DESCRIPTION
1.0	Intact, natural and unmodified geothermal field (incl. vegetation).
0.9	Largely intact and only slightly modified by land use effects (incl. vegetation).
0.8	Some feature types degraded by land use effects.
0.7	Some feature types now destroyed by land use effects.
0.6	Some feature types slightly modified by fluid extraction effects.
0.5	Some feature types degraded by fluid extraction effects.
0.4	Some feature types destroyed by fluid extraction effects.
0.3	Features, vegetation and landscape highly modified by land use effects.
0.2	Features, vegetation and landscape highly degraded by human activities including extraction of fluids as well as land use effects.
0.1	Features, vegetation and landscape destroyed by human activities including extraction of fluids as well as land use effects.

4.1 HOW DOES GEODIVERSITY INFLUENCE BIODIVERSITY IN GEOTHERMAL FIELDS?

Appendix 3 presents geodiversity information for each geothermal field. It also includes a general score for vegetation intactness around the geothermal fields surveyed. It does not, however, include a detailed ranking of botanical or biological features or aspects. This component will require further work from specialist scientists and is a key aspect intended for eventual inclusion in this ranking system.

Geothermal fields and features exhibit extreme variations of temperature, acidity and other environmental factors that would seem to make them unlikely places for plants, animals and microorganisms to exist. However, many species do survive these conditions, and some very rare and specialised species are found in geothermal areas. Table 3 shows the temperature ranges at which particular life forms can survive, providing an example of how geodiversity (in this case temperature) can influence biodiversity in geothermal fields.

The amount and extent of oxidation of H_2S gas is thought to have a highly significant influence on the abundance and diversity of biota in geothermal fields and may explain some of the differences in biota that occur between fields.

It appears that thermophilic (heat-loving) plants and animals, some of which are of tropical origin (e.g. clubmoss *Lycopodium cernuum*), require very stable conditions of warmth with high humidity (but low acidity). This is most likely to be attained where warm or hot springs are reliably present, as these have a greater intensity of concentrated heatflow than steam without the evolution of acid gases. For example, Waikite Valley, which contains mainly hot alkaline-chloride-bicarbonate springs, has abundant thermophilic ferns and native snail populations.

Similarly, the hot alkaline-neutral springs of Te Kopia host tropical ferns and snails, although little silica is presently being deposited there. Recent studies indicate that silica deposition is of little importance to biota other than for providing suitable anchor points on which to grow (Handley et al. 2003). The presence of thermophilic plants is probably related to the consistently warm conditions, however they are achieved, without excessive acidity.

Several factors operate to produce unique biotic environments in geothermal fields. Diversity in gas chemistry and fluid dynamics, acidity, alkalinity, oxygen or sulphur availability, light, temperature, moisture, substrate, altitude and landform can lead to high biodiversity.

Wherever boiling conditions exist in a geothermal field, evolved gases play a major role in the creation and maintenance of the surface thermal environment. If boiling is occurring at shallow depths (< 200 m) and gas upflows are rapid without any interaction with oxygenated groundwaters or entrained air, there may be insufficient residence time in which sulphides may oxidise. The extent to which oxidation occurs and what oxidation state is achieved also depends upon the abundance of an oxygen supply, e.g. does the H_2S oxidise to sulphur, sulphur dioxide or sulphate?

TABLE 3. UPPER TEMPERATURE LIMITS FOR LIFE (ADAPTED FROM BROCK 1994).

LIFE FORMS	TEMPERATURE LIMIT (°C)
Eukaryotes	
Animals	
Fish	38
Insects	45–50
Ostracods (crustaceans)	49–50
Plants	
Vascular plants	45
Mosses	50
Eukaryotic microorganisms	
Protozoa	56
Algae	55–60
Fungi	60–62
Prokaryotes	
Bacteria	
Cyanobacteria (blue-green algae) (oxygen-producing photosynthetic bacteria)	70–73
Other photosynthetic bacteria	70–73
Heterotrophic algae	90
Archaea	
Methane-producing bacteria	110
Sulphur-dependent bacteria	115

The extent or absence of this oxidation process in a geothermal field has vital repercussions for biota, as it influences both the nature and abundance of airborne emissions and condensates. The resulting inertness or chemical aggressiveness of moisture and air then plays a key role in determining the variety and extent of thermophilic biota that may be hosted by a field. Where sulphur formation occurs at the ground surface, condensates and air at the surface are generally highly acidic, imposing severe constraints on what life forms can exist in these areas.

Strong acids also dissolve ground materials to produce turbid waters, muddy waters and muds. The resulting suspended solids block penetration of strong sunlight, so that no UV light is available for photosynthesis, meaning that algae are also excluded.

The abundance of water plays a significant role in the determination of biotic diversity and abundance. Water dilutes acid condensates and hence reduces acidity, so that fluids become more benign to biota.

Temperature limits what photosynthesis can occur, and higher temperatures lead to a reduction or absence of soil microorganisms, so that processes such as symbiotic root nitrogen fixing and enzyme production cannot take place. This severely restricts the number of species of vascular plants that can exist in thermally heated ground. However, some microorganisms can thrive in temperatures up to 115°C

Despite, or in some cases because of, the extreme conditions, some very specialised microorganisms have been found in high-temperature geothermal fields. In recent years, these have been studied by scientists because of the insights they provide to the earliest life on earth and possible life forms on other planets. One microorganism (recovered from Yellowstone National Park in the USA) is now a vital component of DNA analysis. Others, including some obtained from geothermal areas in the TVZ, are being used or investigated for use in a variety of industrial applications. For more information on this aspect of geothermal areas (especially microorganisms), see Brock (1994; www.bact.wisc.edu/Bact303/b1). The Environment Waikato website (www.ew.govt.nz/enviroinfo/geothermal/geobiodiversity.htm) also provides useful information.

The life forms that live in and around geothermal areas require the same degree of consideration in protection efforts as the geothermal features that host them.

5. Which geothermal fields exhibit the greatest geodiversity?

The total scores for each geothermal field are given in Table 4. The four highest scoring fields are Waiotapu (340), Te Kopia (294), Waimangu (290) and Tokaanu-Waihi-Hipaua (199).

It is important to regard these scores for geothermal fields as being relative to each other, rather than absolute values to the exclusion of other considerations. Although the relative intactness and diversity of each geothermal field is considered to be reasonably reflected by its score, there are a few obvious anomalies. For example, Tikitere has a score of 151 and Rotorua a score of 127, yet Rotorua contains features of international significance (two large geysers) while Tikitere has no geysers at all and no features of either international or national significance. Instead, Tikitere has a wide variety of many individual geothermal feature types and has also been less severely modified by human activity.

Similarly, Orakeikorako (130) might be expected to rank more highly than some of the fields that scored higher, because of its large number of active geysers and the rarity of these features. However, refinement of the ranking system to address such issues is beyond the scope of this first attempt and will require a great deal more discussion and planning to achieve. It is also possible that the

TABLE 4. GEODIVERSITY RANKINGS OF GEOTHERMAL FIELDS IN ORDER OF DECREASING SCORES. SEE APPENDICES 1, 2 AND 3 FOR DETAILED SCORES FOR EACH GEOTHERMAL FIELD.

GEOTHERMAL FIELD	GEODIVERSITY RANKING
	>300
Waiotapu	340
	200–300
Te Kopia	294
Waimangu (incl. Rotomahana)	290
	100–200
Tokaanu (incl. Waihi, Hipaua)	199
Tikitere	151
Whakaari	136
Orakeikorako	130
Rotorua	127
Waikite Valley	109
Rotoma	103
	50–100
Tarawera	89
Tongariro	79
Ruapehu	78
Reporoa	69
Ngatamariki	68
Rotokawa (Taupo)	67
	10–50
Moutohora (Whale Island)	47
Mokai	40
Kawerau	36
Taheke	23
Tauhara	22
Wairakei (excl. Tauhara)	14
Rotoiti	14
Whangairorohea	11
Atiamuri	10
	<10
Ongaroto (Whakamaru)	9
Okataina	8
Horohoro	8
Ohaaki (Broadlands)	7
Rotokawa (Rotorua)	5
Mangakino	2

inclusion of biodiversity values in the ranking system may change the scores and hence the placement of fields in Table 4. The addition of biodiversity values would certainly produce more robust scores.

Given the limited amount of biodiversity information presently available for use in the ranking system, several geothermal fields clearly stand out in terms of the range and quality of their geothermal features and the naturalness of adjoining land. Some fields do not score highly because they do not contain extensive geothermal sequences, yet they have particular geothermal features that are unique and exceptional worldwide. Both these categories are discussed more fully below.

5.1 FIELDS WITH EXTENSIVE GEOTHERMAL SEQUENCES

The underground extent of the geothermal fields assessed in this study have all been defined by robust and accepted means, such as resistivity surveys. Geothermal reservoirs show up as areas of low resistivity (contours of < 20 ohmmetres) compared with the ground around them.

Although the underground extent of geothermal fields can be very large (c. 10 km × 10 km), not all of the land surface above the reservoirs exhibits heating or geothermal activity, because impermeable surface rocks and strong horizontal flows of underground cold water can block access of hot water and steam to the ground surface. The surface extent of areas of geothermal activity above reservoirs varies considerably from large (e.g. Waiotapu) to small (e.g. Mangakino) or non-existent.

Altitudinal range commonly affects the variety of natural features that occur in a geothermal area. Generally, the greater the altitudinal range in a geothermal field, the greater the variety of features. This is mostly because large altitudinal ranges can allow the separation of steam- and gas-related features (at higher altitudes) from hot-water features (at lower altitudes).

Te Kopia (260 m), Tokaanu (356 m), Waiotapu (370 m), Tarawera (650 m) and Ruapehu (1170 m) each have large altitudinal ranges. However, Ruapehu, Tarawera and Tokaanu do not show a continuum of geothermal features throughout their altitudinal range, as each has large areas without any surface expression of the underlying geothermal activity. Waiotapu has a nearly continuous sequence of geothermal features above its geothermal reservoir, but still contains large areas of ground at ambient ground temperature, that contains non-thermal vegetation and can be used for roads and forestry tracks, plantation forest blocks, and buildings, farmland, power lines, etc.

Te Kopia has a good continuity of geothermal features that occur within an area of rural and natural forested land. The Scenic Reserve adjoining and partially enclosing Te Kopia comprises about 1700 ha of largely unmodified forest. Geothermal features are present from 360 m a.s.l. c. 500 m west of Te Kopia Road, to 620 m a.s.l. c. 300 m east of the Paeroa Fault scarp summit.

In historical times (pre-1950s), Wairakei had a large variety and number of geothermal features and outstanding geothermal values. However, these have all been irreversibly destroyed by extraction of fluid from the field for electricity generation and subsequent land changes. Wairakei is now known worldwide for its large amount of land subsidence (> 15 m) induced by ongoing fluid removal from the field (Allis 2000). The natural features formed from outflows of the deep hot water (geysers, boiling springs and silica sinter deposition) have gone, but steam-related activity has increased in some areas. Similarly, Orakeikorako was highly significant for its abundance of large and frequently active geysers until these were mostly destroyed in January 1961 by flooding associated with the formation of Lake Ohakuri (Lloyd 1972).

5.2 GEOTHERMAL FIELDS WITH INDIVIDUAL FEATURES OF OUTSTANDING IMPORTANCE

Several New Zealand geothermal fields contain features that are of international significance. Some are in fields that score highly in terms of the range of features they contain, while others are in fields that have been modified by human activity or have few other features of significant value.

Examples of fields that contain individual features of international significance are:

- Waimangu: Frying Pan Lake and Inferno Crater, two interconnected, large and sympathetically interactive flowing springs.
- Waiotapu: Champagne Pool for its large size and brightly coloured mineral deposits together with the associated Primrose Terrace, also known as Artist's Palette, for its extent of actively growing silica terrace, now the largest of its type remaining in New Zealand, and Hakareteke Geyser, the only clear acid water, sinter-depositing geyser in New Zealand.
- Te Kopia: for its unique and long-active mud geyser, the only one of its type in New Zealand and, possibly, the world; also, its large and powerful Te Kopia fumarole, now considered to be the most powerful geothermal fumarole remaining in New Zealand.
- Orakeikorako: Waipapa Valley for its extent of actively forming silica terraces, and Artist's Palette Terrace for its active geysers.
- Rotorua: Whakarewarewa for its frequently active large geyser Pohutu and an extinct geyser that is readily accessible to people (the only example of such a feature known in the world today; Cody & Lumb 1992).

Other geothermal fields in the TVZ that historically had internationally significant geothermal features are:

- Ohaaki (or Broadlands): Ohaaki spring and silica terraces. Deep hot water ceased flowing to these features after electricity generation started in 1989. The spring was subsequently irreversibly changed when its vent was concreted-up. The pool that remains is now fed by geothermal bore water.
- Wairakei: Geyser Valley had 22 geysers that were active daily until they all dried up (by the early 1960s) following commissioning of the Wairakei geothermal power station.
- Tokaanu: Once had an extensive silica sinter terrace. Growth ceased at an unknown date, possibly before Europeans arrived in New Zealand.

6. Geothermal features most vulnerable to effects of geothermal energy utilisation

The geothermal features most at risk from energy utilisation are the boiling alkaline-chloride water springs and geysers, and associated silica sinter deposits derived directly from the deep hot reservoir fluids. Wells may directly compete with these natural features by extracting water from the same conduits as supply them. It is also well established that the extraction of fluids from anywhere in the reservoir invariably causes drawdown (i.e. lowers the water level in the reservoir). This has two effects: a reduction in the amount of hot water available to flow to the surface; and boiling at the top of the reservoir as a result of the pressure drop caused by the reduction in water level. Extraction does not need to be very substantial before changes occur. Once boiling conditions develop, great quantities of steam and other gases are evolved. This leads to an increase in the amount of steam flowing to the ground surface. The chloride water features then either die and become cold, or become increasingly steam-heated. Existing steam-heated features may increase in activity, and new hot and steaming ground can form. Hydrothermal eruptions may also occur. Exploited geothermal fields commonly produce hydrothermal eruptions and sometimes these can produce craters in excess of 100 m diameter with the catastrophic eruption of ejecta volumes of >10 000 m^3.

However, it is the geysers, flowing alkaline springs and silica sinter deposits that are most vulnerable to loss when a geothermal field is exploited. Geysers typically operate at very low pressures, perhaps rarely > 30 KPa and typically < 10 KPa. Therefore, a pressure fall of a few KPa may be sufficient to permanently stop boiling from ever commencing at the critical depth where a stored chamber of water underneath a geyser can be induced to boil and erupt. It is well known in New Zealand and other countries that air pressure fluctuations can sometimes start and stop geysers erupting, indicating that driving pressures are only c. 5 KPa or less.

Similarly, by experimental sandbagging of outflows, it has been found that most hot flowing springs also operate at very low pressures, typically of only c. 3 KPa. By contrast, most exploited geothermal fields undergo pressure drops in the order of 20 atmospheres (or 2000 KPa); e.g. Ohaaki and Wairakei have undergone this scale of pressure drop (Allis 2000).

At Wairakei and Ohaaki, well drawoff rates of 160 000 and 120 000 tonnes per day (tpd) occur, while natural spring outflows were 10 000 and 500 tpd respectively. After geothermal power stations went into production on these fields, all spring flows quickly ceased (within 2 years at Wairakei and within 2 weeks at Ohaaki). At Rotorua, where natural outflow was estimated at 17 500 tpd before many wells began exploiting the field (for heating purposes, rather than electricity generation), well drawoff of 35 000 tpd severely impacted on flows of all hot springs and geysers (Cody & Lumb 1992). Some of the decline of activity has been reversed since many wells were closed in the 1990s (see www.envbop.govt.nz/water/geothermal for more details about the Rotorua geothermal field).

At Wairakei, new areas of hot ground formed at Craters of the Moon (Karapiti) and new hot ground is still being formed at Ohaaki.

It is also important to recognise that some geothermal fields are linked, so that the effects of exploitation in one field can be observed in the linked field. This has occurred in Wairakei/Tauhara, where exploitation at Wairakei has affected conditions in Tauhara. Other fields that are believed to be linked are Waimangu/Waiotapu/Waikite/Reporoa and Orakeikorako/Te Kopia.

7. Significance of Te Kopia geothermal field

Te Kopia is significant because its surrounding landscape is still in a mostly natural condition. This has been a largely fortuitous consequence of its location on the steeply faced Paeroa Fault scarp, which has made the land less suitable for farming use, rather than a result of any foresight in preservation of natural landscapes. The relatively intact natural vegetation at Tokaanu and Tarawera similarly results from these areas' unsuitability for other land uses.

While Te Kopia has suffered some land clearing for pastural use and some early logging of native trees, it still contains a substantial tract (c. 1700 ha) of largely natural native forest. In contrast, Tarawera, Waimangu and Waiotapu were denuded in AD 1886 by the volcanic eruption of Mount Tarawera, so that vegetation in those areas has still not fully recovered to a mature or climax forest; more recently, they have also been subject to exotic plant invasion.

Te Kopia has a varied topography. There are gullies and valleys with surface streams, small marshes and wetlands, hillslopes, and steep faces on an active fault scarp and its associated splinter faults. The field's altitudinal range and exposed setting at higher altitudes provide a progression of geothermal features and growing situations for both ambient and thermophilic plants. Such sequences of geothermal activity and associated vegetation are now rare in the TVZ because of land-use practises. One particular feature of the geothermal activity in Te Kopia has been the formation of landforms associated with hydrothermal eruptions. These include a wetland enclosed by a low arcuate ridge of eruption ejecta, as well as other ridges and lakes.

Ruapehu, Tarawera, Tokaanu and Waiotapu all have large altitudinal ranges, but they all lack the continuity of geothermal features throughout that range, and/or have significant human disturbance. For example, Ruapehu and Tarawera do not have a continuity of geothermal features across the length and breadth of their fields, and Tokaanu and Waiotapu have roads, housing and (at Waiotapu) plantation forestry on areas of ambient temperature ground between the thermal areas. In contrast, Te Kopia has a very good continuity of geothermal areas without large tracts of ambient ground dissecting them. It also has only one road (near to its western flank), with few access ways such as farm or logging tracks fragmenting the natural vegetation.

Examination of the geodiversity spreadsheet (Appendix 3) shows that Te Kopia scores low for alkaline and boiling springs, although it has a good range of acidic geothermal water bodies, mud features and types of hot ground. It has deposits of silica sinter from prehistoric times (C^{14} dated at 3000 years old; Browne et al. 1994). In recent times, it has been an area of ongoing change, with the formation of new hot ground associated with local earthquake activity.

There is a general paucity of sulphur deposition at the ground surface at Te Kopia and very little smell of H_2S, although sulphates and alums are common. This indicates that most H_2S is being oxidised deeper within the ground, rather than at the surface. As a result, the steam-heated surface features at Te Kopia may be less acidic than in some other fields. The hot alkaline-neutral springs of Te Kopia host tropical ferns and snails.

Fluid extraction at Te Kopia would lead to the cessation of alkaline–neutral hot spring flows and quickly modify fumarole outputs. Hydrothermal eruptions would be likely to occur. In the past, hydrothermal eruptions at Te Kopia have produced craters ≤ 300 m dia. Ground heating would reduce in some places but could also increase in others. Since heated ground is the most common geothermal feature type, an increase in its extent at the expense of less common features such as hot alkaline-neutral springs would reduce geodiversity.

Use of Te Kopia geothermal field for energy production would result in a loss of geodiversity and an associated loss of biodiversity.

8. Summary

The ranking of high-temperature geothermal fields in this study according to their individual geothermal features and other characteristics has been done using a judgement of size, representativeness, natural quality and adjoining natural values. It is an attempt to assess geothermal fields in a transparent and quantitative manner and is, as far as we know, the first such ranking attempted in New Zealand or elsewhere. At the time of writing this report, the author was not aware that any significant scoring system had been compiled anywhere else in the world. A rudimentary first attempt at such a system had been made by the Geological Society of New Zealand (Houghton et al. 1989), but that work was incomplete in that it considered only flowing springs and geysers that had already been mapped and described in written reports and papers. It did not consider the significance of any geothermal features that were not already documented.

The goal of this study was to establish a procedure by which high-temperature geothermal fields in the TVZ could be ranked on the basis of the geodiversity of their geothermal features. It is acknowledged that this is a first effort that could be greatly improved with further inputs to develop more rigour in the scoring procedure; it particularly needs to incorporate measures that assess biodiversity.

It should be noted that the two regional councils responsible for managing the land encompassed by the TVZ—Environment Waikato and Environment Bay of Plenty—have systems of their own for classifying the geothermal fields in their areas. Details of these can be found at www.ew.govt.nz/envioinfo/geothermal/classification/index.htm and www.envbop.govt.nz/media/pdf/PRWLP9.7May9-7.pdf.

8.1 ASSESSMENT OF RELIABILITY OF GEODIVERSITY SCORES OBTAINED BY THIS PROCESS

The geodiversity scores calculated for geothermal fields in this exercise (Appendix 3) are generally in keeping with informal rankings made by the author based on personal experience and impressions and similar assessments from other informed people. Therefore, although it is apparent from this exercise that some geothermal fields score higher than others because of clusters of characteristics rather than because the individual features in the clusters are all of outstanding merit, the rankings are considered to provide a fair and robust comparison.

9. Acknowledgements

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The bibliography that has been independantly submitted to Tongariro/Taupo and Rotorua Conservancies was created by a great deal of work carried out by University of Auckland students and staff. It was specifically prepared for Waikato Regional Council (Environment Waikato; EW), who have willingly allowed its distribution to DOC. I am grateful to Katherine Luketina, Environmental Scientist at EW, for permission to pass this on.

Map 1 was produced by Louise Cotterall, School of Geography, Geology and Environmental Science, Auckland University. EW provided information for the map, and Dr Manfred Hochstein, Geothermal Institute, Auckland University, also provided assistance.

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Appendix 1

GEOTHERMAL FIELDS INVENTORY

This comprises a large spreadsheet split into a number of tables to enable reproduction in this report. To reconstruct the spreadsheet, the tables need to be viewed as follows:

A1.1a	A1.1b	A1.1c	A1.1d
A1.2a	A1.2b	A1.2c	A1.2d
A1.3a	A1.3b	A1.3c	A1.3d

HE = hydrothermal eruption.

TABLE A1.1a

Field name	Surface area (km²)	Geographical setting	Altitude range min. (m a.s.l.)	Altitude range max. (m a.s.l.)	Altitude range total (m)	Natural heatflow (MW)	Stored heat (PJ)	Max. reservoir temp. (°C)	Surface characteristics
Atiamuri	8	Lake terraces, alluvial plains.	270	360	90	c. 5	1900	165	2 large flowing springs (Whangapoa); > 5 small springs some drowned by Lake Atiamuri.
Broadlands (Ohaaki)	15	Old lakebed plains and river terraces.	285	328	43	100	6900	308	Large Ohaaki spring (12 L/s) and sinter terraces of c. 2 ha; small geyser active until 1950s.
Crater Lake (Ruapehu)	0.5	Crater of active andesite volcano.	1360	2530	1170	300			Very acidic lake in crater; lake varies with volcanic activity; removed during 1995–96 eruptions.
Golden Springs	0.5	Lakebed and alluvial plain.	292	300	8	2.5			3 turbid warm springs, 9–40 L/s, 40–50°C.
Hipaua (see Tokaanu)									
Horohoro	1	Unwelded ignimbrite fan, lakebed plains and terraces.	335	360	25	5		> 160	1 large hot spring, 2 small springs, extinct sinters and spring vents, HE craters.
Horomatangi Reef	0.5	Lava dome on lakebed.	150	350	200	120			Gas and hot water vents on lakebed.
Humphrey's Bay	0.5	Margin of rhyolite lava flows, lake edge shoreline.	295	300	5				Widespread gas bubbling into lake, extensive flocculation of iron, warm lake margins.
Kawerau	12	Alluvial plains, hill slopes, lakelets.	20	120	100	100	7700	> 315	Hot altered ground, small springs, fumaroles, turbid lakelets, solfatara, mudpools.
Mangakino (excl. Whakamaru or Ongaroto)	6	River valley gorge, drowned by hydroelectric dam.	160	225	65	> 10			Hot springs underneath lake Maraetai.
Mokai	40	Gentle hill country.	280	526	246	100	10 000	324	Large mud pools, muddy lakelets, hot ground; also small hot springs along Waipapa Stream.
Moutohora (Whale Island)	1	Island, extinct andesite volcano.	0	353	353				Hot altered ground, hot water seeps, sulphur and silica residues.
Ngatamariki	7	Stream valley alluvial terraces, river banks.	290	330	40	38	900	???	Alkaline flowing springs, sinter terraces, warm acid turbid pools, HE crater, hot barren ground.
Ohaaki (see Broadlands)									
Okataina	0.1	Toe of lava flow on lakeshore.	315	316	1	< 0.2			2 small warm spring outflows along NE shoreline.
Ongaroto (excl. Mangakino)	0.5?	Lakeshore at base of rhyolite hill; river terrace.	235	280	45	5			Warm spring encountered when drilling piles for bridge. Warm spring and hot ground on western shore of Lake Whakamaru.
Orakeikorako	12	River valley hillsides, adjoining margins of hydroelectric dam (filled January 1961).	290	375	85	34	1700	265	Geysers, alkaline and acid springs, hot altered and barren ground, fumaroles, steaming cliffs, mud pools, sinters.

TABLE A1.1b

Field name	Feature types (no. of diff. types from Table 1)	Flow rates (L/s)	Ebullition height (m)	Water chemistry	pH	Temp. (°C)	Clarity/colour	Sinter types	Sinter structures	Sinter forms
Atiamuri	4	< 0.5	Nil	Neutral chloride	7	65	Clear green	Amorphous silica	Aprons, cone, vent	Algal, massive
Broadlands (Ohaaki)	10	Nil	Nil	Alkaline chloride	< 3–8	98	Milky turbid, grey	Amorphous silica	Large terrace, rims	Dense, massive
Crater Lake (Ruapehu)	3	100	> 25	Acid sulphate	< 3	35–98	Turbid grey	Nil	Nil	Nil
Golden Springs	2	50	Nil	Neutral bicarbonate	6.5–7	60	Turbid fawny grey, clear	Nil	Nil	Nil
Hipaua (see Tokaanu)										
Horohoro	4	0.5	Nil	Alkaline chloride	8.5	82	Clear	Amorphous silica	Rims, terrace, walls	Dense, massive
Horomatangi Reef	2									
Humphrey's Bay										
Kawerau	10	0.2	0.3	Alkaline chloride, acid sulphate	< 2–8	98	Clear	Amorphous silica	Crusts, rinds	Residues, dense
Mangakino (excl. Whakamaru or Ongaroto)	1	2	Nil	Alkaline chloride	8.5	98	Clear	Nil	Nil	Nil
Mokai	10	10	1.5	Alkaline chloride bicarbonate, acid sulphate	< 2–7.6	98	Clear, grey milky	Amorphous silica	Rinds and rims	Dense, algal
Moutohora (Whale Island)		5	0.2	Acid sulphate	< 4	98.5	Clear	Amorphous silica		Residues
Ngatamariki										
Ohaaki (see Broadlands)										
Okataina										
Ongaroto (excl. Mangakino)	1	1? (dispersed)	Nil	Neutral chloride				Nil		Nil
Orakeikorako	15	Up to 20	Geysers to 20 m	Alkaline chloride Acid sulphate	7–9.2 2–3.5	65–98 40–90	Clear, turquoise blues, grey turbid, muddy	Dense, massive, algal	Terraces, aprons, rims, cascades, cones	Algal, dense, microbial

TABLE A1.1c

Field name	Age range of features	Geothermal landforms	Pre-historic characteristics	Exploration	Human impacts (effects of extraction and other human impacts)
Atiamuri	All < 26 500 y?	HE crater, algal sinter terraces	Flowing springs more numerous	One well to 605 m; max. temp. 165°C at 550–590 m; geophysical, chemical, geological surveys. MRP applied for drilling consents in early 2005.	Spectacular HE crater infilled with logs.
Broadlands (Ohaaki)	< 26 500 y	Very large sinter terrace	Large area of silica sinter terrace grown around Ohaaki Pool	> 44 wells 776–2420 m; 3 wells > 3500 m; geological, chemical, geophysical surveys.	Loss of Ohaaki Pool and growth of silica terraces (note outflow over terraces diverted by Maori); land subsidence of c. 0.4m/y. Total subsidence c. 3 m over c. 1.5 km^2. Newly forming boiling ground and subsidence fissures.
Crater Lake (Ruapehu)	c. 375 000 y?	Large crater lake	Lahars down Whangaehu River, ash and block eruptions	Scientific and volcano surveillance.	Nil
Golden Springs	< 26 500 y		Unknown	Regional geophysical, chemical surveys.	Minor/nil? Farmland to pool margins.
Hipaua (see Tokaanu)					
Horohoro	< 26 500 y	Large HE craters, extinct springs	More numerous flowing springs, 3 large HE craters c. 100 m dia., extensive sinters	3 wells, resistivity, chemical, geological surveys; 1 well to 60 m, max. temp. 86°C at well bottom.	Farmland to spring margins; outflows diverted.
Horomatangi Reef				Gas and water chemistry, resistivity, submarine.	Nil
Humphrey's Bay			Unknown	Chemistry, geology. Part of Okataina GF? (but not included in Okataina details).	Nil
Kawerau	Holocene; < 20 000 y		More abundant spring outflows and sinter deposition	Geophysical, chemical, geological surveys; > 27 wells drilled 433 m to > 1600 m.	Loss of nearly all springs; sinter terraces no longer growing; landfill of warm lakes; ground subsidence.
Mangakino (excl. Whakamaru or Ongaroto)	?		Unknown?	Geophysical surveys. 1 well drilled to 600 m.	Springs drowned by formation of Lake Maraetai.
Mokai	Holocene	HE craters	Unknown	Chemical, geophysical, geological surveys; 6 wells 609–2600 m deep.	Large mud craters used as rubbish dumps; farmland to margins; animals walking through thermal features.
Moutohora (Whale Island)	Postdate ????		Unknown	Water chemistry.	Sulphur mining; vegetation cleared; now DOC reserve.
Ngatamariki		HE crater lake, silica sinter terrace	Unknown	Chemical, geophysical, geological surveys; 4 wells up to c. 3000 m deep.	Farmland eroded and filled in hot lake; pine plantation planted over thermal area.
Ohaaki (see Broadlands)					
Okataina				Probably includes Humphrey's Bay as one GF but not included here.	
Ongaroto (excl. Mangakino)			Unknown	Resistivity surveying, chemistry of fluids. Mighty River Power intend deep well (c. 2500 m) in 2005. Ongaroto-Whakamaru is actually SE part of this GF also, but regarded separately in this table.	Lake Whakamaru has drowned some of springs.
Orakeikorako	< 26 500 y	Large silica terraces, large alkaline springs	Umukuri sinters area of active hot springs	Four deep drillholes, geophysics, chemistry.	Filling Lake Ohakuri in January 1961 drowned geysers.

TABLE A1.1d

Field name	Exploitation	Extraction (tonnes/day)	References*
Atiamuri	None, during c. 1970–1995 one spring diverted into swimming pool but this was bulldozed and buried in 1995.	Nil	Mongillo & Clelland 1984; Allis et al. 1987.
Broadlands (Ohaaki)	Power station was first commissioned at 114 MWe, but is now producing 50 MWe because of field limitations.	120 000	Mongillo & Clelland 1984; Allis et al. 1995. www.geothermal.org.nz (viewed April 2007)
Crater Lake (Ruapehu)	None	Nil	Mongillo & Clelland 1984; H. Keys, pers. comm.
Golden Springs	1 spring used for bathing; 3 springs in RDC Recreation Reserve.	Nil	
Hipaua (see Tokaanu)			
Horohoro	1 well heating glasshouses for flowers, spring diverted to bathtub for marae use.	120	Mongillo & Clelland 1984; Allis 1987.
Horomatangi Reef		Nil	
Humphrey's Bay (see Tarawera)			
Kawerau	≥ 6 MWe electricity production; direct heat use in paper production, timber processing; heating of public hall and baths.	7200	Mongillo & Clelland 1984; Allis et al. 1993. www.nzgeothermal.org.nz (viewed April 2007).
Mangakino (excl. Whakamaru or Ongaroto)	None	Nil	Mongillo & Clelland 1984
Mokai	Electricity generation since 2000. Expanded in 2005 to total of 94 MWe. Heat used in large greenhouse complex.	28 000	Bibby et al. 1981; Mongillo & Clelland 1984; Webster 1987. www.nzgeothermal.org.nz (viewed April 2007).
Moutohora (Whale Island)	Nil	Nil	NZGS Report 38D 1974; Mongillo & Clelland 1984.
Ngatamariki	None to date, proposed electricity use.		Mongillo & Clelland 1984.
Ohaaki (see Broadlands)			
Okataina			
Ongaroto (excl. Mangakino)	Nil as at December 2004.	Nil	Mongillo & Clelland 1984.
Orakeikorako	Nil, protected status for tourism.	Nil	Mongillo & Clelland 1984.

* References in bibliography lodged in Tongariro/Taupo and Rotorua Conservancies.

TABLE A1.2a

Field name	Surface area (km^2)	Geographical setting	Altitude range min. (m a.s.l.)	Altitude range max. (m a.s.l.)	Altitude range total (m)	Natural heatflow (MW)	Stored heat (PJ)	Max. reservoir temp. (°C)	Surface characteristics
Reporoa (excl. Golden Springs)	15	Caldera, drained lake basin, now farmlands.	290	330	40	155		240	Boiling alkaline springs, mud pools, acid turbid pools, barren hot ground, warm seepages, sinters.
Rotoiti	2	Lake shorelines, lakebed, cliffs along lake edge (unwelded ignimbrites).	155	170	15	140	Unknown	130	Gas bubbling to lake surface, occasional muddy upwellings.
Rotokawau (Rotokawa) (Rotorua)	2	Lakebed and adjoining shores.	280	295	15	5		155	Areas of gas bubbling into lake, hot spring under Maori baths.
Rotokawa (Taupo)	10	Rolling hill slopes, stream valley, lakebed and shores.	290	405	115	210		300?	HE craters, acid springs, fumaroles, hot barren altered ground.
Rotoma		Marshland, lakeshores, alluvial plains.	290	420	130	20			Alkaline springs, solfatara and warm altered ground, turbid pools, fumaroles, steaming cliffs.
Rotomahana (see Waimangu)	c. 18								
Rotorua	12	Lakebed plains and terraces, lakeshore and lake, rhyolite lava hillsides.	210	400	190	470	3400?	250	Geysers, alkaline and acid flowing springs, turbid warm pools and lakelets, solfatara and altered hot ground, fumaroles.
Taheke	2	Steep hillsides, stream valley floors.	285	325	40	13			Hot steaming ground, solfatara, silica residues, sulphur, weak acid springs.
Tarawera	c. 0.5	Lakeshores, stream delta, cliffs on margin of rhyolite lava flows, volcano crater.	300	950	650	25			Hot steaming ground, flowing hot springs, minor sinters, warm seepages, gas upflows, iron flocculants.
Tauhara (excl. Wairakei)	20	High terrace slopes, incised valleys, lakeshores.	357	500	143	250		279	Neutral and acid springs, warm and altered ground, eruption craters, salt deposits, steam vents.
Te Kopia	15	Steep hillsides, valley floors, gullies all associated with Paeroa Fault scarp.	360	620	260	150	2300	241	Steaming cliffs and ground, fumaroles, solfatara, turbid pools, HE craters. Neutral and acid springs, mud geyser and mud pools.
Tikitere (Hell's Gate, Ruahine Springs)	10	Rolling high terraces, HE craters, lakeshores.	279	406	127	120	6230	230	Acid springs, pools and lakelets, HE craters, solfatara, hot barren and altered ground, turbid pools, mudpools.
Tokaanu	7.5	Base of andesite volcano, alongside shores of Lake Taupo. Hipaua extends to upper north and eastern slopes of andesite dome.	357	713	356	80	3200	250	
Tokaanu-Hipaua	2	Steep hill slopes.	480	713	233				Steaming altered hill slopes, acidic seeps.
Tokaanu-Tokaanu	5		357	420	63				Alkaline springs, hot ground, acid pools.
Tokaanu-Waihi	0.5	Hill side and lakeshore.	< 357	420	30				Alkaline springs, warm ground.

TABLE A1.2b

Field name	Feature types (no. of diff. types from Table 1)	Flow rates (L/s)	Ebullition height (m)	Water chemistry	pH	Temp. (°C)	Clarity/colour	Sinter types	Sinter structures	Sinter forms
Reporoa (excl. Golden Springs)	8	5	0.3	Alkaline chloride	< 3–8.7	98	Clear, grey, black	Amorphous silica, chrystobalite	Cones, terraces, aprons, rinds	Dense, algal
Rotoiti										
Rotokawau (Rotokawa) (Rotorua)	3	< 0.2	< 0.1	Weakly acidic chloride	6.5	50	Clear	Nil	Nil	Nil
Rotokawa (Taupo)	8	< 30	< 0.5	Acid sulphate, chloride	2.5–5.5	40–90	Turbid grey, clear	Amorphous silica	Rims, small sheets, spicules	Spicular, microbial
Rotoma										
Rotomahana (see Waimangu)										
Rotorua	13	25	21	Alkaline chloride, bicarbonate, acid sulphate	< 2–9	98	Clear, milky, blue, green	Amorphous silica, chrystobalite	Terraces, aprons, rims, cascades, mounds	Dense, residues, algal
Taheke	5	< 10	< 0.5	Acid sulphate	2.8–5	to 99	Clear to grey turbid	Amorphous silica	Crusts	Residues
Tarawera	7	≤ 0.5	< 0.2	Alkaline chloride		to 98.6	Clear	Amorphous silica	Rims, crusts	Algal, dense
Tauhara (excl. Wairakei)	8	10	Nil	Alkaline chloride, acid sulphate	2.5–7.8		Clear	Amorphous silica	Terraces, rinds	Algal
Te Kopia	13	3	2	Acid sulphate	< 2–7.5	105	Clear, blue, milky	Amorphous silica, chrystobalite, tridymite	Crusts, rims, banks	Algal, laminated dense
Tikitere (Hell's Gate, Ruahine Springs)	8	1	0.5	Acid sulphate, alkaline chloride	2.5–7.6	98	Clear, milky, grey	Amorphous silica	Crusts	Residues
Tokaanu	7	8	1.5	Alkaline chloride	3.5–8.7	98	Clear, turbid grey	Amorphous silica	Aprons, terraces, rims, cones	Dense
Tokaanu-Hipaua										
Tokaanu-Tokaanu										
Tokaanu-Waihi										

TABLE A1.2c

Field name	Age range of features	Geothermal landforms	Pre-historic characteristics	Exploration	Human impacts (effects of extraction and other human impacts)
Reporoa (excl. Golden Springs)	< 26 500 y		More flowing springs and outflows.	1 well to 1338 m; geophysical, chemical surveys.	Drainage of land for farming has stopped flows from many springs at Opaheke and Longview Roads.
Rotoiti					
Rotokawau (Rotokawa) (Rotorua)	All < 7500 y	Perched shallow lake, expansive sinters	Hot alkaline spring sinters deposited over several hectares.	Many wells < 160 m; geophysical, chemical surveys.	Lowered geothermal water levels.
Rotokawa (Taupo)	< 250 000 y?	Large HE crater, dolines	More widespread solfataric activity to west.	Many wells to c. 1800 m; geophysical, chemical surveys.	Sulphur mining damage to land.
Rotoma					
Rotomahana (see Waimangu)					
Rotorua	All < 65 000 y	HE craters, silica deposits	HE blowouts, widespread terraces and aprons, flowing springs at higher altitudes.	Chemical, geophysical, botanical surveys, drilling.	Loss of many geysers and flowing springs, drainage of hot pools and marshes.
Taheke	< 65 000 y	Solfatara		Water and gas chemistry, resistivity.	Sulphur mining, surface stripping, roading.
Tarawera	Post date AD 1886		Nil? All present-day forms postdate AD 1886.	Water and gas chemistry, includes SE and NE shores of Lake Tarawera and volcano crater.	Nil
Tauhara (excl. Wairakei)	< AD 180		Abundant spring outflows and silica terraces.	Chemical, geophysical surveys; drilling.	Ground subsidence, springs drying up, infilling of thermal ground.
Te Kopia	3000	Breccia hills, HE lakes, teaming cliffs	HE blowouts, alkaline springs.	Chemical, geophysical, botanical surveys; 2 drillholes to 950 m.	Nil
Tikitere (Hell's Gate, Ruahine Springs)	65 000 y	HE craters, solfatara; breccias	HE craters.	Chemical, geophysical surveys; 6 wells drilled to < 503 m depth.	Denudation of landscape, re-contouring, roading.
Tokaanu		Steaming hillslopes; silica aprons	Geysers and hot flowing springs more numerous, large silica terrace.	Chemical, geophysical surveys; drilling.	Lowering of water levels, cessation of spring flows.
Tokaanu-Hipaua					
Tokaanu-Tokaanu					
Tokaanu-Waihi					

TABLE A1.2d

Field name	Exploitation	Extraction (tonnes/day)	References*
Reporoa (excl. Golden Springs)	Nil as at March 2005.	Nil	Mahon 1966; Bromley 1993; Jones et al. 1998.
Rotoiti			
Rotokawa (Rotokawau) (Rotorua)	Spring captured for Maori bath, c. 8 wells in use.	< 250	Glover 1974; Mongillo & Clelland 1984.
Rotokawa (Taupo)	Wells supply two power developments generating 35 MWe.	c. 10 000	Mongillo & Clelland 1984.
Rotoma			
Rotomahana (see Waimangu)			
Rotorua	450 wells extracting hot water until 1987; management plan implemented in 1995.	10 500	Mahon 1985; Scott & Cody 2000.
Taheke	Sulphur mining, under investigation for possible power generation (Trust Power).	Nil	NZGS Report 38d 1974; Sheppard & Lyon 1979; Mongillo & Clelland 1984.
Tarawera	Nil (tourism only).	Nil	Mongillo & Clelland 1984.
Tauhara (excl. Wairakei)	Many shallow wells for domestic uses.	1500	Donaldson 1982; Grant 1985.
Te Kopia	Nil	Nil	Mongillo & Clelland 1984; ‘probably connected to Orakeikorako’ Bignall & Browne 1994; MacKenzie et al. 1994; Newson et al. 2002.
Tikitere (Hell's Gate, Ruahine Springs)	Sulphur and silica mining.	Nil	Bromley 1993; Meza 2004.
Tokaanu	Spring flow diverted to baths, private hot water wells.	500	Mahon & Klyen 1968; Robinson & Sheppard 1986; Reyes 1987; Severne 1995.
Tokaanu-Hipaua			
Tokaanu-Tokaanu			
Tokaanu-Waihi			

* References in bibliography lodged in Tongariro/Taupo and Rotorua Conservancies.

TABLE A1.3a

Field name	Surface area (km^2)	Geographical setting	Altitude range min. (m a.s.l.)	Altitude range max. (m a.s.l.)	Altitude range total (m)	Natural heatflow (MW)	Stored heat (PJ)	Max. reservoir temp. (°C)	Surface characteristics
Tongariro	2	Andesite volcano	1300	1790	490	200			
Ketetahi	1	North flank of Tongariro	1340	1440	100	130		> 250	Vapour-dominated system, many small boiling steam vents and heated surface waters, hot ground
Te Mari	0.5	Crater on north flank of Tongariro	1420	1500	80	20			Steaming vents, salt deposits, and altered warm ground
Emerald Lakes	0.5	Within volcano crater	1680	1790	110	50			Steaming altered ground, solfatara, warm acid lakelets
Waihi (see Tokaanu)	< 1	Hillside lakeshore margins and lakebed							
Waikite Valley	5	Base of Paeroa Fault scarp	340	540	200	70		200	
Baths Gully	0.1	Deeply incised gully							Boiling alkaline springs, hot altered ground
Te Waro Scarp	0.003	Marshland along base of hillslope							Warm neutral springs in marsh
Puakohurea	4.9	Hillsides, valley flats, stream valley							Alkaline springs, hot ground, steaming cliffs, algal sinters
Waimangu (and Rotomahana)	18	Deeply incised valley, lakebed and shores, rhyolite dome margins, HE and volcanic craters	< 337	440	103	250	5400	270	HE and volcanic craters, hot to boiling springs, crater lakes, steaming cliffs, geysers
Waiotapu	17	Unwelded ignimbrite terraces, stream valleys, hillsides and marshland	310	680	370	545	6100	295	Mudpools and cones, geysers, collapse holes, acid altered ground, HE craters
Wairakei	15	Rolling hills, stream and river valleys, high terraces	340	550	210	530	6700	271	Steaming hot altered ground, mudpools, turbid warm lakes, barren ground, salts, geysers, alkaline springs
Whakaari (White Island)	4.8	Active andesite volcano island	0	321	321	120		800	Hot solfatara, fumaroles, active volcanic vent
Whakamaru (see Ongaroto)	c. 1	Rhyolite lava dome, lake and river terraces				30			
Whale Island (see Moutohora)									
Whangairorohea	< 0.005	Alluvial valley terrace in rolling hills	290	300	10	< 1			Clear hot pool, hot springs inundated by stream and river, prehistoric silicified sediments
White Island (see Whakaari)						120			

TABLE A1.3b

Field name	Feature types (no. of diff. types from Table 1)	Flow rates (L/s)	Ebullition height (m)	Water chemistry	pH	Temp. (°C)	Clarity/colour	Sinter types	Sinter structures	Sinter forms
Tongariro	4	Nil	Nil	Acid sulphate	< 2.5	70	Turbid, blue and green	Nil	Nil	Nil
Ketetahi	5	6	2	Acid sulphate	2.0–6.5	138	Dark grey turbid	Nil	Nil	Nil
Te Mari										
Emerald Lakes		Nil	Nil	Acid sulphate	< 3		Turbid, blue and green	Nil	Nil	Nil
Waihi (see Tokaanu)										
Waikite Valley	7	20	2	Alkaline bicarbonate	8.7	98	Clear, milky blue	Amorphous silica	Rims, cascades	Dense, algal
Baths Gully								Calcite	Terraces, rinds	
Te Waro Scarp										
Puakohurea										
Waimangu (and Rotomahana)	9	40	2.5	Alkaline chloride	< 3–9.5	98	Clear, sky blue, green	Amorphous silica	Minor terraces	Dense, algal
Waiotapu	13	5	12	Acid sulphate, sulphate chloride, chloride and chloride bicarbonate	1.8–8	98	Clear, lime green, black, yellow	Amorphous silica only	Terraces, cascades, aprons	Residues, massive and dense, spicular
Wairakei	12	3	1	Acid sulphate	< 3	98	Grey turbid, milky	Amorphous silica	Cones, aprons, terraces, rims	Dense
Whakaari	7	1	1	Acid sulphate	< 2	800	Clear, green, yellow	Anhydrite	Vent crusts	Residues
Whakamaru (see Ongaroto)										
Whale Island (see Moutohora)										
Whangairorohea	2	< 1?	Nil	Neutral chloride	7.4	38	Clear	Amorphous silica	Silicified sediments	Dense
White Island (see Whakaari)										

TABLE A1.3c

Field name	Age range of features	Geothermal landforms	Pre-historic characteristics	Exploration	Human impacts (effects of extraction and other human impacts)
Tongariro	> 20 000 y			Chemical, geological surveys.	Nil
Ketetahi	Holocene	Intensely altered valley	Unknown, modified by volcanic eruptions?	Chemical, geophysical surveys.	Nil
Te Mari					
Emerald Lakes				Gas and water chemistry.	
Waihi (see Tokaanu)					
Waikite Valley	Holocene < 20 000 y	HE craters, large silica	Large silica terrace and flowing springs; broad.	Chemical, botanical surveys.	Drainage of land for farming has destroyed silica aprons.
Baths Gully		Terrace, steaming cliffs	Silica aprons.		
Te Waro Scarp					
Puakohurea					
Waimangu (and Rotomahana)	All post date volc. eruption of Mt Tarawera on 10 June 1886.	Volcanic craters, hot lakes, steaming cliffs	Only GF in world to form in historical record. Prior to AD 1886, no geothermal activity in Waimangu Valley.	Chemical and physical monitoring.	DOC Scenic Reserve. Warbrick Terrace was built with sandbags to form terrace, c.1890s.
Waiotapu	Holocene to present (> 26 000 ybp to present)	Huge silica terrace, many large HE craters, large collapse holes, acid geyser	Many large HE craters formed c. AD 1320, including Champagne Pool.	7 wells, 500–1100 m deep, now all grouted shut. Drilling done in 1950s. Present-day monitoring and scientific investigations.	DOC Scenic Reserve. Forest harvesting and roading, tourist impacts since 1890s (minimal).
Wairakei	2000 y?	Champagne Pool, Geyser Valley	Many flowing alkaline springs and geysers.	Geophysical; chemical, botanical surveys; drilling.	Large subsidence bowl, cessation of all flowing hot springs and geysers, formation of hot ground.
Whakaari	All < 1000 y	Volcanic crater vents, fumaroles	Similar to today?	Chemical, geophysical, botanical surveys.	Sulphur mining, factory and housing buildings, wharf.
Whakamaru (see Ongaroto)					
Whale Island (see Moutohora)					
Whangairorohea	< 2000 y	Perched warm lake, extensive silicified sediments	Unknown.	Chemistry	2 hot springs drowned by filling of Lake Ohakuri in January 1961. Area now pine plantation.
White Island (see Whakaari)					

TABLE A1.3d

Field name	Exploitation	Extraction (Tonnes/day)	References*
Tongariro	Nil	Nil	Walsh 1997.
Ketetahi	None	Nil	Moore & Brock 1981; Mongillo & Clelland 1984; Walsh 1997.
Te Mari			
Emerald Lakes		Nil	
Waihi (see Tokaanu)			
Waikite Valley	Springs piped into bathing pools.	600	Sheppard & Robinson 1980; Wood 1994.
Baths Gully			
Te Waro Scarp			
Puakohurea			
Waimangu (and Rotomahana)	No exploitation, passive tourism.	Nil	Glover 1976; Keam 1981; Keywood 1991; McLeod 1992; Simmons et al. 1994.
Waiotapu	No extractive exploitation, solely tourism and bathing uses. Erosion of Champagne Pool margins, damage to vegetation.	Nil	Lloyd 1959; Hedenquist & Henley 1985; Hedenquist & Browne 1989; Bibby et al. 1994; Giggenbach et al. 1994.
Wairakei	Extraction of water and steam for electricity generation (c. 178 MWe), tourism, heat used in prawn farm.	160 000	Allis 1990; Allis 2000. www.nzgeothermal.org.nz (viewed April 2007).
Whakaari	Sulphur mining until c. 1930s; now tourism. Privately owned (Buttle family) administered by DOC as Scenic Reserve.	Nil	Houghton & Nairn 1989.
Whakamaru (see Ongaroto)			
Whale Island (see Moutohora)			
Whangairorohea	Used for bathing by local people.	Nil	Only 'discovered' to science in 1980s.
White Island (see Whakaari)			

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* References in bibliography lodged in Tongariro/Taupo and Rotorua Conservancies.

Appendix 2

INDIVIDUAL GEOTHERMAL FEATURES INVENTORY

This comprises a large spreadsheet split into a number of tables to enable reproduction in this report. To reconstruct the spreadsheet, the tables need to be viewed as follows:

A2.1a	A2.1b
A2.2a	A2.2b
A2.3a	A2.3b
A2.4a	A2.4b
A2.5a	A2.5b
A2.6a	A2.6b
A2.7a	A2.7b
A2.8a	A2.8b
A2.9a	A2.9b
A2.10a	A2.10b

A = active at present in geothermal field; Hn = historically active but now inactive or lost due to natural causes; Hh = historically active but now inactive due to human causes; P = prehistorically active; and N = never present.

O = outstanding example in its natural state; G = good example in its natural state; M = modified; and D = severely degraded.

I = internationally important, if it is the only one of its kind or the best in New Zealand; R = regionally important, if it is one of the best examples in the TVZ; L = locally important, if it is one of the best examples in its geothermal field.

HE = hydrothermal eruption.

TABLE A2.1a

Field name	Type of feature	Size	Feature name/number	Status (A, Hn, Hh, P, N)	Quality (O, G, M, D)	Represent-ation (I, R, L)	Hydrological character, gaseous character, flow and ebulation
Atiamuri	Deep fluid flowing spring	Large	Whangapoa East	A	M	R	Weak flow, weak bubbling
	Deep fluid flowing spring	Large	Whangapoa West	A	M	R	Weak flow, weak bubbling
	Deep fluid flowing spring	Small	Matapan Road Spring	A	G	L	Moderate flow, calm
	Extinct Spring	Large	Berg's Crater	P	D		Nil flow, calm
Broadlands (Ohaaki)	Deep fluid flowing spring	Large	Ohaaki Pool	Hh	O (D)	I, but now L	Strong, weak
	Deep fluid flowing spring	Small	Unnamed	Hh	D	L	Nil, calm
	Deep fluid flowing spring	Small	Unnamed	Hh	D	L	Nil, calm
Crater Lake (Ruapehu)	Steam and gas	Large	Crater Lake	A	O	I	Non-flowing, calm
	Steam and gas	Moderate	Silica Rapids	A	G	R	Flowing, calm
Golden Springs	Deep fluid flowing spring	Large	Golden Spring West	A	M	L	Strong flow, strong gas ebullition
	Deep fluid flowing spring	Large	Golden Spring Middle	A	M	L	Strong flow, weak ebullition
	Deep fluid flowing spring	Large	Golden Spring East	A	M	L	Strong flow, weak ebullition
Horohoro	Deep fluid flowing spring	Large	Waipupumahana	A	M	L	Weak flow, sporadic weak gas
	Deep fluid flowing spring	Small	Unnamed (Southern gully)	A	G		Weak flow, calm
	HE crater	Large	Unnamed roadside farmland	P	G	L	Non-flowing, calm
	HE crater	Large	Unnamed roadside farmland	P	G	L	Non-flowing, calm
	Deep fluid flowing spring	Large	Unnamed (roadside)	P	M	L	Non-flowing, calm
Humphrey's Bay	Gas venting	Large	Humphrey's Bay	A	G	R	Weak, gentle bubbling
Kawerau	Acid lake		Lake Rotoitipaku	Hh	O (D)	L	Non-flowing, calm
	Alkaline lake		Lake Umupokapoka	Hh	O (D)	L	Non-flowing, calm
	Hot barren ground		Unnamed	A	G	R	Non-flowing, calm
	Deep fluid flowing springs		Unnamed	A	M	L	Weak flows, weak bubbling
	Solfatara		Unnamed	A	G	R	Non-flowing, steaming
Managakino (excl. Whakamaru or Ongaroto	Deep fluid flowing springs	Weak	Unnamed	A	G	L	Weak flows, gentle bubbling

TABLE A2.1b

Field name	Chemical character	Physical character	Sinter deposition	Comments
Atiamuri	Chloride, neutral-alkaline	Hot clear flowing spring	Minor, amorphous silica, algal aprons	Several other springs submerged in Lake Atiamuri.
	Chloride, neutral-alkaline	Hot clear flowing spring	Minor, amorphous silica, algal aprons	Whangapoa springs DOC land since 2003.
	Chloride, neutral-alkaline	Hot clear flowing spring	Nil	Boiling mudpool and warm sinter spring found in 2003 on Bergs farm.
	Rainwater	HE crater, extinct spring	Minor, amorphous silica, silicified tephras	Infilled with debris but Env Waikato intend to fence it off.
Broadlands (Ohaaki)	Alkaline chloride	Hot turbid flowing spring	Massive and abundant, extensive terraces, aprons	All Ohaaki springs and the only geyser were destroyed by commissioning of power station in 1989. Ohaaki Pool vent infilled with concrete and water now supplied by pipeline.
	Dry	Dried up, once flowing spring	Minor	
	Dry	Dried up, once flowing spring	Minor	
Crater Lake (Ruapehu)	Acid sulphate, pH < 2	Warm, fumarolic strong, grey turbid	Nil	Intermittently flows and heats; volcanic crater lake with activity modified by meteorological conditions, fumarolic and volcanic activity.
	Bicarbonate alkaline	Cold mineralised springs, clear	Silica depositing	
Golden Springs	Neutral bicarbonate	Warm, slight turbidity	Nil	2 large flowing springs in RDC public reserve. Locally used for bathing. Also clear spring in streambed. Abundant algae and iron content.
	Neutral bicarbonate	Warm, slight turbidity	Nil	
	Neutral bicarbonate	Warm, clear	Nil	
Horohoro	Neutral chloride	Hot, clear	Minor, amorphous silica, apron and terrace	Terrace growth stopped with channel cut through wall before 1948.
	Neutral chloride	Hot, clear	Nil	In swampy gully, no sinters present.
	Dry	Cold, dry	Nil	Seasonal swampy marsh, eruption breccias, sinters absent.
	Dry	Cold, dry	Nil	Several large craters postdate c. 26 500 y BP.
	Dry	Cold, dry	Minor, amorphous silica, margins and walls	Sinter growth ceased when spring dried up in prehistorical time.
Humphrey's Bay	Bicarbonate alkaline	20°C, pH 6.5, clear	No silica, abundant iron oxides/ hydroxides	Widespread CO_2 bubbling into lake, iron deposits.
Kawerau	Acid sulphate	Infilled with wood wastes, rubbish dump area	Nil but previously silica residues	Lakes have been used for dumping of pulp mill wastes since 1970s and land now reclaimed, lakes almost completely gone. Springs along river and stream banks greatly reduced in flows since well production of 1970s.
	Acid sulphate	Infilled with wood wastes, rubbish dump area	Nil but previously silica residues	
	Steam, CO_2	Hillslopes of steaming ground	Nil	
	Alkaline chloride	Springs along banks of river and stream	Weak crusts and rims of amorphous silica	
	Steam, CO_2	Steaming barren sulphurous ground	Nil	
Managakino (excl. Whakamaru or Ongaroto	Alkaline chloride	Clear hot upflows	Unknown	Submerged under Lake Maraetai at Mangakino, no longer visible.

TABLE A2.2a

Field name	**Type of feature**	**Size**	**Feature name/number**	**Status (A, Hn, Hh, P, N)**	**Quality (O, G, M, D)**	**Represent-ation (I, R, L)**	**Hydrological character, gaseous character, flow and ebulation**
Mokai	Deep fluid flowing springs		Waipapa Stream springs	A	G	R	Strong, calm
	Fumarole		Unnamed (upper Mokauteure Stream)	A	O	N	Nil, strong c. 1 m
	Acid mud pools		Unnamed (upper Mokauteure Stream)	A	M	L	Nil, weak c. 0.5 m
	Mud cones ('volcanoes')		Unnamed (upper Mokauteure Stream)	A	G	L	Nil, weak c. 0.5 m
	Turbid acid lakelets		Unnamed (upper Mokauteure Stream)	A	M	L	Weak, calm
	Acid spring		Ohineariki (upper Okama Stream)	A	M	R	Weak, calm
	HE craters		Unnamed (beside Tirohanga Road)	A	M	N	Nil, strong c. 1 m
Moutohora (Whale Island)	Steam heated ground	Large	Sulphur Valley	A	G	R	Moderate flows, moderate < 0.5 m high
	Steam fumaroles	Large	Unnamed	A	G	R	Strong steam flows
	Steam heated ground waters	Large	Unnamed	A	G	R	Strong stream flows
Ngatamariki	Deep fluid flowing spring		Calcite Spring (Pavlova)	Hn	G	L	No outflows since 2003, calm
	Deep fluid flowing spring		Unnamed—HE 1	A	G	L	Weak flow, calm
	Deep fluid flowing spring		Unnamed—HE 2	A	G	L	Strong flow, moderate < 0.2 m
	Deep fluid flowing spring		Unnamed—HE 3	A	G	L	Moderate flow, weak bubbling < 0.1 m
	Deep fluid flowing spring		Lake	Hn	M	R	Moderate flow, weak bubbling < 0.1 m
	Deep fluid flowing spring		New South Spring	Hn	G	L	Weak flow, calm
	Deep fluid flowing spring		Northwest Spring	A	G	L	No outflows, calm
	Deep fluid flowing spring		South Spring	A	G	L	Moderate flow, weak bubbling < 0.1 m
	Deep fluid flowing spring		North Terrace spring	A	G	R	Moderate flow, weak bubbling < 0.3 m
	Deep fluid flowing spring		North Terrace New spring	A	G	L	Moderate flow, weak bubbling < 0.3 m
	Deep fluid flowing spring		Unnamed—Waikato River spring 1	A	M	L	Strong flow, calm
	Deep fluid flowing spring		Unnamed—Waikato River spring 2	A	M	L	Strong flow, weak bubbling < 0.1 m

TABLE A2.2b

Field name	Chemical character	Physical character	Sinter deposition	Comments
Mokai	Alkaline chloride	Hot, clear	Weak crusts and rims of amorphous silica	Springs along middle reaches of Waipapa Stream; ferns, etc.
	Acid sulphate	Muddy turbid	Nil	Powerful > 10 MW in crater against east side of ridge.
	Acid sulphate	Muddy turbid	Nil	Turbid steam and gas-heated groundwaters surrounded by farmland, unfenced, cattle walk through them.
	Acid sulphate	Muddy turbid	Nil	No odours, clear spring supplying bathing pool. Used as rubbish dumps, erupted across pasture in c. 1992.
	Acid sulphate	Muddy turbid	Nil	
	Acid sulphate	Warm clear	Nil	
	Acid sulphate	Muddy turbid	Nil	
Moutohora (Whale Island)	Acid sulphate	Clear boiling, 45–98°C	Silica residues	Steaming ground and small fumaroles in area of Sulphur Valley.
	Acid condensates	Clear, up to 101°C steam vents	Silica residues	Steam vents depositing sulphur.
	Acid sulphates	Clear, up to 98°C, pH 2, c. 5 L/s flow	Silica residues	Collected outflow of c. 5 L/s.
Ngatamariki	Alkaline chloride	Clear, 45°C, pH 7.5, warm	Calcite/amorphous silica aprons, rims	Ceased hot outflows in late 2002.
	Acid sulphate chloride	Grey turbid warm, 30°C, pH 6	Weak silica crust at water level	Formed c. 2001, ceased flowing 2003.
	Neutral sulphate chloride	Grey turbid hot, 75°C, pH 7.5	Nil	Formed 2003, flow and bubbling strengthened by early 2005.
	Acid sulphate chloride	Grey turbid hot, > 70°C, pH 6	Nil	Newly formed late 2003, pool c. 8 m dia., SW corner of old lake.
	Alkaline chloride	Clear and grey turbid flows, hot alkaline	Nil	Lake formed by HE in c. 1948, infilled by flood in c. 1995.
	Neutral chloride	Grey turbid warm, pH 6.8	Nil	Flow decreased over 1995–2004 and cooled.
	Neutral chloride	Clear, warm 50°C, pH 7	Weak waterline silica rim	Hot overflow until c. 1980, since then has cooled and level fallen.
	Neutral chloride	Clear, hot 80°C, pH 7.8	Weak waterline silica rim	Windblown pines lying over spring.
	Alkaline chloride	Clear, hot 98°C, pH 7.6	Amorphous silica cascades, rims, crusts	On large silica terrace, once stronger prehistoric flows?
	Alkaline chloride	Clear, hot 98°C, pH 7.6	Amorphous silica rim and crusts	Spring formed c. 1995 and has become clear and sinter depositing.
	Neutral chloride	Clear, warm 60°C, pH 7.5	Silica and iron oxide hydroxide sinters	Spring submerged by filling Lake Ohakuri in January 1961.
	Acid sulphate chloride	Clear, hot, pH 6.5	Nil	Spring submerged by filling Lake Ohakuri in January 1961.

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