EVOLUTION OF GEOTHERMAL-GROUNDWATER CIRCULATION SYSTEMS IN THE QUATERNARY TAUPO VOLCANIC ZONE: EXAMPLE OF THE UPPER WAIKATO RIVER CATCHMENT, NEW ZEALAND

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Geothermal systems, Upper Waikato River catchment, Taupo Volcanic zone, geothermal field evolution.

ABSTRACT

Geothermal-groundwater circulation systems in the Upper Waikato River (UWR) catchment of the Taupo Volcanic Zone (TVZ) have developed in the Quaternary in close association with volcanic activity, sedimentation and topography.

The age and evolution of some UWR catchment geothermal features (i.e., active fields and fossil fields) and the Tokaanu geothermal system, were assessed with: geological reconstructions in four epochs (i.e., pre-TVZ Hauraki Rift; 'old TVZ'; 'young TVZ 1'; and 'young TVZ 2') considering the formation of calderas, tectonic depressions and pre-historic lakes; groundwater elevation; and geothermal spring chemistry. Hierarchical Cluster Analysis was used to classify the 'evolutionary' status of active fields (i.e., unevolved, evolved and highly evolved) and a chloride mixing model that calculated the percentage of deep geothermal fluid in spring flow (P_m) with two end-members of deep geothermal fluid and cold groundwater.

No fields were classed as unevolved in the catchment; Tokaanu was the closest example of such a field as water quality in unevolved springs was probably very similar to deep geothermal fluid, i.e., median P_m in these springs was approximately 93%. Evolved geothermal fields (Waikite, Waiotapu and Rotokawa) possibly formed in the young TVZ 2 and highly-evolved fields (i.e., Atiamuri, Ngatamariki, Orakei Korako, Te Kopia, and Reporoa) possibly developed in the young TVZ 2 and young TVZ 1 epochs. Fossil fields probably date from the young TVZ 2 epoch.

Most fields indicated that evolution of geothermal systems followed progressive mixing, with time, of cold groundwater with geothermal-reservoir fluid. This approach may have applications as a geochronometer for UWR catchment geothermal systems after further research that could aim to provide more understanding of the evolution of fluids, permeability, and groundwater flow in each class of active field, and fossil systems.

1. INTRODUCTION

Energy generation and tourism are two important industries that are associated with geothermal resources in the Upper Waikato River (UWR) catchment (Figure 1). Electrical energy generation from geothermal energy in the UWR catchment is nationally-significant with geothermal-electric power stations in catchment (installed capacity 853 MW) providing approximately 97% of New Zealand's geothermal power generation capacity. In addition, many tourism activities have a geothermal focus.

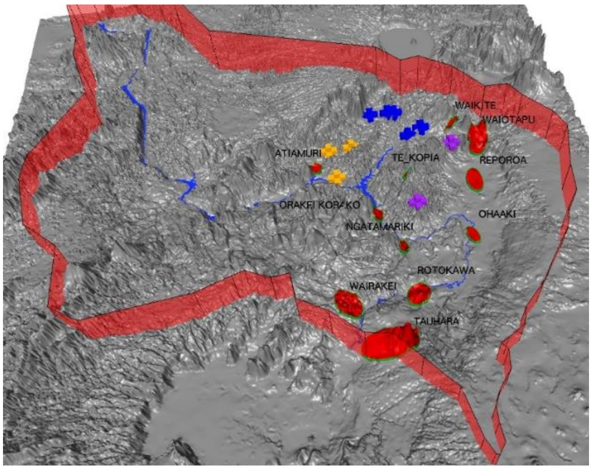

Figure 1: The Upper Waikato River catchment (bounded by the red line) with the current channel of the Waikato River (blue) and the areas of high-temperature geothermal fields (red ellipses), after White et al. (2015), and fossil geothermal systems represented by crosses, i.e., Ohakuri area (yellow), Ngakuru area (blue) and east-Paeroa Range area (purple).

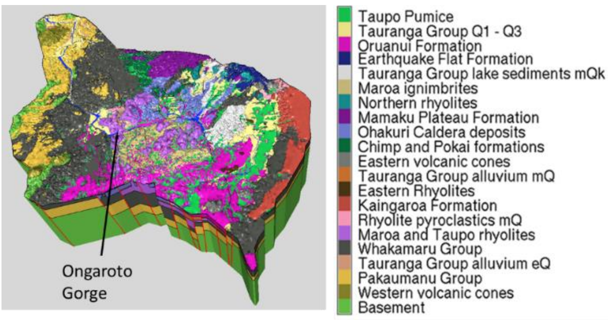

Figure 2: Three-dimensional geological model of the UWR catchment (after White et al., 2016).

The geothermal system in the UWR catchment has been the subject of a large body of research, much of it focussed on the distribution and properties of high-temperature geothermal systems. Important themes from this research include: geology (e.g., Figure 2), particularly the difficult problem of understanding the history of volcanism in the Taupo Volcanic Zone (TVZ); geophysics, which aims to assess the sub-surface distribution of fields; geochemistry, to assess heat sources and the effects of geothermal use; reservoir engineering, to calculate hydraulic properties of geothermal reservoirs; and groundwater, to identify the catchments of fields and the hydraulic links between fields and their receiving environments.

Clearly, geology and groundwater are crucial to the location and properties of geothermal fields. Volcanic and tectonic activity in the TVZ has provided energy to geothermal systems; groundwater, sourced from rainfall, transports heat to, and from, geothermal fields (Kissling and Weir, 2005; White and Reeves, 2017). Groundwater elevation is a significant control on field position because groundwater hydraulic head drives groundwater recharge to the fields and groundwater outflows, such as geothermal springs, are commonly located in topographic lows and break-slope locations (White and Reeves, 2017).

The importance of UWR catchment topography is demonstrated by the long axes of bounding ellipses to surface geothermal features (Figure 1). These axes are located at, or near, local topographic lows where groundwater is likely to be flowing to the surface; they are also mostly aligned in the broad direction of topographic gradient suggesting that groundwater flow, at depth, reflects general piezometric gradients. For example, the locations of geothermal-groundwater circulation systems (i.e., Waikite, Waiotapu, Te Kopia, Ngatamariki, Orakei Korako and Reporoa,) that surround the Paeroa Range fault block are probably influenced by the groundwater flow from the Range (White et al., 2015).

Geothermal systems evolve over long time scales. For example, measured chloride concentrations in the Kerepehi Fault system springs on the Hauraki Plains (which possibly formed in association with Miocene volcanism; Edbrooke, 2001) were approximately 20 mg/L (Reyes et al., 2010). At the time of formation, these springs may have had chloride concentrations representative of young geothermal fields (e.g., the Tokaanu field with a spring chloride concentration of approximately 3000 mg/L; Reyes et al., 2010). Such a transition, from high-chloride to low chloride chemistry, demonstrates field evolution as indicated by spring outflow that shifts over time from geothermal-reservoir-dominated to cold-groundwater-dominated.

A somewhat accelerated example of this progression was demonstrated by chloride concentrations in Wairakei Geyser Valley springs which declined during the testing and early-production phases of the Wairakei geothermal field (Figure 3; White and Hunt, 2005).

Other factors that are relevant to the evolution of geothermal fields may include heat-source movement, subsidence and faulting which may result in the waxing and waning of geothermal heat flux. Variability in the groundwater system over time (e.g., recharge, boundary conditions and groundwater flow) may also result in the long-term evolution of geothermal fields.

This paper considers the age and evolution of geothermal-groundwater circulation systems in the Quaternary UWR catchment. These systems include current geothermal fields and areas of extinct hydrothermal activity (i.e., fossil geothermal systems as represented by silica sinter, hydrothermal eruption deposits, hydrothermally-altered tephras and lake sediments) found at the margins of the Ngakuru Graben and the Taupo-Reporoa Depression (TRD). Three models are used to assess age and evolution: geology, groundwater elevation and spring chemistry.

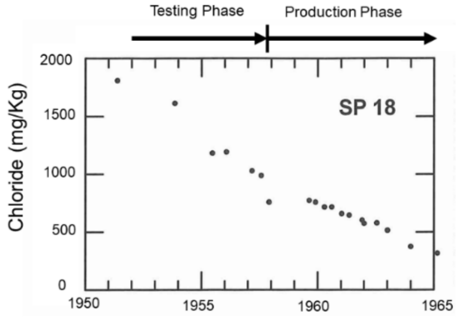

Figure 3: Chloride concentrations in spring SP18, Wairakei Geyser Valley, during the testing and early-production phases of Wairakei geothermal field (White and Hunt, 2005).

2. METHOD

Geological reconstructions, based on a 3D model of current geology (which describes 21 hydrogeological layers, nine faults and three calderas in the catchment; White et al., 2016), were used to discuss the formation of geology associated with geothermal fields. These reconstructions included a pre-TVZ Hauraki Rift as a southeast extension of the Hauraki Graben through the UWR catchment that was possibly linked with volcanic activity at Maungatautari, Pureora and Titiraupenga (early Quaternary age; Leonard et al., 2010) and with a volcanic centre in the Tokoroa area proposed by Stratford and Stern (2008).

TVZ geology development in the UWR catchment followed the epochs of Wilson and Rowland (2016) and the geological map of Leonard et al. (2010): 'old TVZ' when the large-volume Mangakino eruptions produced volcanic deposits that covered most of the catchment and left a caldera that was a location of sedimentation in the pre-TVZ Hauraki Rift; young TVZ 1 where Whakamaru eruptions also deposited a large volume of volcanic material over the UWR catchment and produced a caldera which possibly occupied (mostly) the pre-TVZ Hauraki Rift. Sedimentation also occurred in this caldera; and young TVZ 2 which included formation of calderas (Ohakuri and Reporoa) and structural depressions, e.g., TRD and Ngakuru Graben. Sediments were deposited by pre-historic lakes (e.g., Lake Huka in the TRD and Lake Ngakuru/Guthrie), Manville and Wilson (2004).

This paper assumed that pre-historic lakes in the young TVZ 2 epoch developed behind an impoundment of the Waikato River located at Ongaroto gorge (Wilson and Rowland, 2016), Figure 2. A lake elevation of 318 m above sea was assumed, corresponding to the maximum elevation of lacustrine sediments in Lake Huka (Manville, 2001). Other impoundments may have created these lakes, e.g., sedimentation in the Ngakuru Graben may have developed in the Lake Rotorua catchment (Marx et al., 2009) and an ignimbrite dam at Orakei Korako may have assisted with the creation of Lake Huka (Manville, 2001).

Groundwater elevation (G_e) in each epoch was taken as a function of topographic elevation and boundary conditions i.e., locations of open-water bodies such as the Waikato River and pre-historic lakes; small streams were not represented by the models. Topographic elevation was itself modelled from the geological reconstructions and the potential locations of open-water bodies were set as constant-head boundaries.

Hierarchical Cluster Analysis (HCA; Daughney and Reeves, 2005) was used to group selected water chemistry indicators (i.e., temperature, chloride, pH, B, Si, Fe, As and Cu) measured in 417 geothermal features (i.e., natural geothermal springs, streams, geysers and augmented flows) in the UWR catchment, and Tokaanu, in the period 2013 to 2016 (Power et al., 2018). The Tokaanu field has a large number of high-chloride springs and therefore was included in this analysis. HCA was undertaken on scaled data, in two steps. First, the nearest-neighbour linkage rule was applied to identify and remove outliers, which would have biased the clustering. Then, HCA was conducted on the reduced dataset using Euclidean distance and Ward's linkage rule.

Chloride concentrations in 312 natural geothermal springs, located in the UWR catchment and Tokaanu, were assembled from Power et al. (2018) and from GNS Science's historical geothermal chemistry data set. Several geothermal springs were excluded from the data set, i.e., Wairakei geothermal field springs which were impacted by geothermal development (e.g., Figure 3) and the Ohaaki Ngawha spring which was artificially augmented by deep geothermal fluid.

A mixing model based on spring chloride concentrations calculated the percentage of deep geothermal fluid in spring flow (P_m). P_m was calculated using sample chloride concentration in each spring (C_s) and a two-component model that had 'end-members' of deep geothermal fluid (C_p) and shallow groundwater fluid (C_k) with assigned chloride concentrations of 3200 mg/L (i.e., the maximum concentration in Tokaanu geothermal field springs that rise in middle Quaternary andesite lava; Lee et al., 2011) and 4 mg/L (i.e., the rounded average concentration in a shallow groundwater monitoring measured in a well located at Kuratau between 1999 and 2017), respectively, i.e.:

$$P_m = ((C_s - C_k) * 100) / (C_p - C_k)$$

The age and evolution of geothermal fields, and fossil fields, were assessed with a synthesis of the above models. Firstly, potential ages (i.e., epochs, as defined above) of fields were identified from their palaeogeographical association with volcanism in the geological reconstructions. Then, UWR catchment fields were assigned to epochs using the HCA groupings and the mixing model; fossil field ages were assessed by considering groundwater elevation and locations of pre-historic lakes. The current 'evolutionary' status of each field *in toto* was classed as: unevolved (median HCA groups 7 and 8), evolved (median HCA groups 4, 5 and 6), highly-evolved (median HCA groups 1, 2 and 3); with fossil fields as an additional status class.

3. RESULTS

3.1 Geology and topography

The pre-TVZ UWR catchment landscape was possibly dominated by the Hauraki Rift and the extension of the Coromandel/Kaimai Range into the TVZ (Figure 4A). A volcanic centre may have been located near Tokoroa at this time (Stratford and Stern, 2008). The northern UWR catchment boundary possibly coincided with this extension. The paleao-Waikato River channel was possibly bounded by the pre-TVZ Hauraki Rift in the UWR catchment and discharged to the Hauraki Gulf; this outflow location was maintained until the Oruanui eruptions, when the river was rerouted towards Hamilton (Manville and Wilson, 2004).

Large-scale, multi-event, Mangakino and Whakamaru eruptions deposited ignimbrites over most of the catchment; associated calderas, and pre-historic lakes, occupied the vestigial Hauraki Rift (Figures 4B and 4C). Volcanism and tectonic activity in the young TVZ epoch led to formation of calderas and basins and to pre-historic lakes (Figure 4D). In this epoch, marginal movement of the northern UWR catchment boundary has possibly occurred. This movement was possibly due to subsidence and faulting in the three major southwest-northeast striking structures (i.e., Ngakuru Graben, Paeroa Range and TRD) that cross the boundary (e.g., as observed in the Ngakuru Graben; Villamor and Berryman, 2001; Blick and Otway, 1995) and to impoundment of Lake Rotorua which may have caused drainage from the Ngakuru Graben to flow into the Lake Rotorua catchment (Marx et al., 2009).

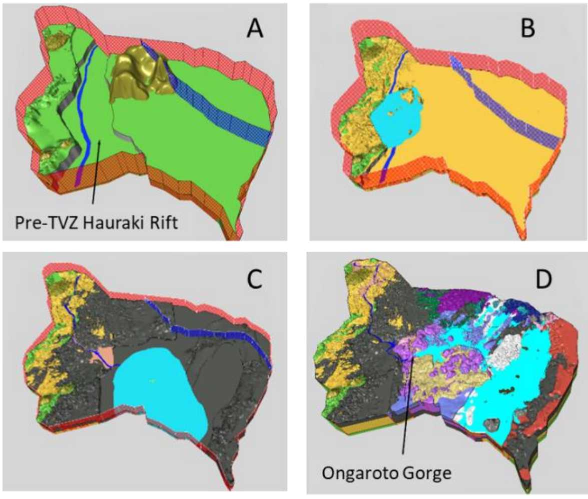

Figure 4: Geological evolution of the TVZ in the UWR catchment described in four epochs: A) pre-TVZ; B) 'old TVZ'; C) young TVZ 1; and D) young TVZ 2; refer to Figure 2 for the legend. Hydrological features include: the Waikato River (royal blue), the northern UWR catchment boundary (blue fence) and possible pre-historic lakes (teal).

3.2 Spring chemistry

Eight water chemistry groups were separated by HCA (Figure 5). The median HCA group number and median P_m were largest in the Tokaanu field (Figure 6). In other geothermal fields, median P_m was less than 30%, with several less than 10% (i.e., Waikite and Te Kopia), showing the dominance of cold groundwater in spring outflow.

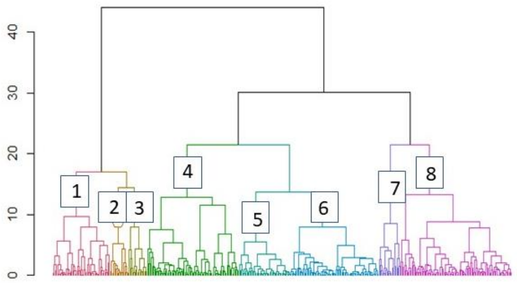

Figure 5: Dendrogram of UWR geothermal features spring chemistry, highlighting clustering at eight separation thresholds. Each terminus represents a single feature.

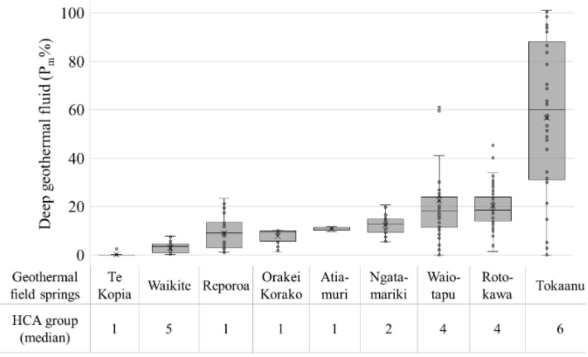

Figure 6. Quartile distribution of P_m in geothermal springs, by field. The fields are sorted by median P_m (marked with horizontal lines). Median HCA of the fields are also noted.

3.3 Field evolution

Median HCA group number and median P_m showed a general trend from geothermal-reservoir dominated (Tokaanu) to cold-groundwater dominated (e.g., Te Kopia and Reporoa), Figure 6 and Figure 7, respectively. Waikite springs were an exception to this trend; spring flow had low P_m yet the median HCA group number was relatively large.

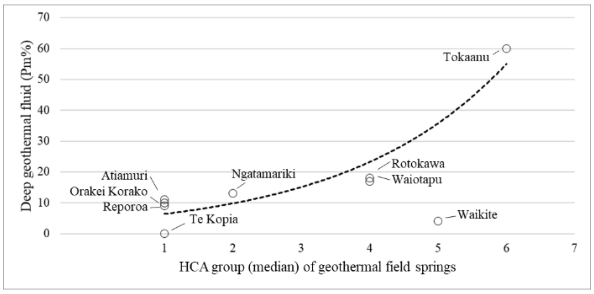

Figure 7. Median P_m and median HCA group number by geothermal field springs. The trend line (dashed) is defined by the median P_m of all fields but Waikite ($y = 4.1\ e^{0.43x}$).

UWR catchment fields were classified as evolved (Waikite, Waiotapu and Rotokawa) and highly-evolved (Atiamuri, Ngatamariki, Orakei Korako, Te Kopia, and Reporoa); none were classed as unevolved in the UWR catchment (Table 1).

Table 1. Age and evolutionary status of geothermal fields in the UWR catchment.

Field name	Age (epoch)	Median HCA	Evolutionary Status
Atiamuri	young TVZ 1	1	Highly-evolved
Ngatamariki	young TVZ 1	2	Highly-evolved
Orakei Korako	young TVZ 1	1	Highly-evolved
Te Kopia	young TVZ 2	1	Highly-evolved
Reporoa	young TVZ 2	1	Highly-evolved
Waikite	young TVZ 2	5	Evolved
Waiotapu	young TVZ 2	4	Evolved
Rotokawa	young TVZ 2	4	Evolved
Ohakuri area	young TVZ 2	NA	Fossil
Ngakuru area	young TVZ 2	NA	Fossil
East-Paeroa Range area	young TVZ 2	NA	Fossil

The fields (i.e., Atiamuri, Ngatamariki and Orakei Korako) that possibly formed in the young TVZ 1 epoch (i.e., Atiamuri, Ngatamariki and Orakei Korako) with the Whakamaru eruptions, were highly-evolved.

Young TVZ 2 fields were classed as highly-evolved and evolved; median P_m was largest for the evolved Waiotapu and Rotokawa systems (Figure 6). Fossil fields were also included in this group. Two fossil fields (Ohakuri area and Ngakuru area) were probably geothermal discharge features located in very close proximity to the shores of pre-historic lakes. Similarly, the two East-Paeroa Range fossil fields, while not located on the shores of Lake Huka, possibly commenced when the groundwater table in the area was at least 60 m higher than present, prior to the draining of Lake Huka.

P_m of individual springs was widely variable within fields (Figure 6). Spring HCA group, was also variable within fields. For example, the Waiotapu field (median HCA 4) includes Champagne Pool (HCA group 6). Therefore, fluids within individual fields may have a variety of sources and pathways within the reservoir, consistent with an interpretation of variable depths of spring sources in the Wairakei geothermal field (White and Hunt, 2005).

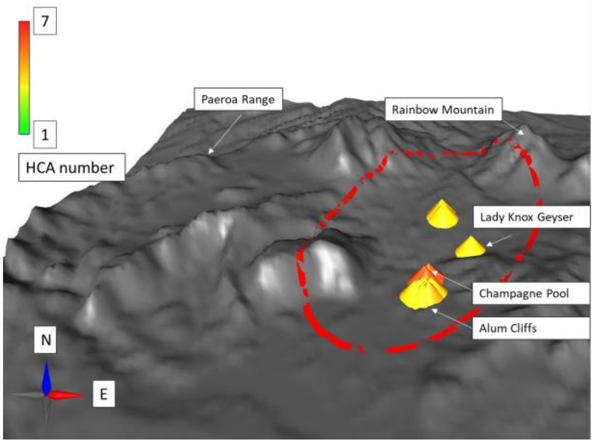

Figure 8. Waiotapu geothermal field area (red ellipse) with locations of springs (and HCA grouping): Champagne Pool (6), Alum cliffs springs (4) and Lady Know Geyser spring (4).

4. DISCUSSION

The assessment of geothermal-groundwater circulation system evolution may have relevance to a wider analysis of geothermal resources. Applications may include: the use of field evolutionary status (i.e., unevolved, evolved, and highly-evolved to fossil fields) as a geochronometer after consideration of age-related data; assessment of time-dependant features of geothermal systems such as permeability; and predictions of the environmental effects of geothermal resource use. This Discussion considers future research to further the understanding of each field status class including the evolution of fluid chemistry (reservoir and cold groundwater), formation permeability and two-phase three-dimensional groundwater flow (considering groundwater recharge from rainfall) in geothermal fields.

Water quality in outflow from **unevolved fields** is, by definition, the closest to the water quality in the geothermal reservoir. Therefore, these fields provide research opportunities to assess the chemical and physical character of geothermal reservoirs. However, unevolved fields are not represented in the UWR catchment. Tokaanu provides the closest example of a such a field, i.e., median HCA = 6 (Figure 6) with many springs (16) in HCA group 7. These springs could be described as unevolved because water quality is very close to reservoir fluid, i.e., median P_m in these springs is approximately 93%. Note that Tokaanu geothermal field springs flow from a formation that has an age which is comparable to the surface geology at numerous UWR geothermal systems. Therefore, unevolved spring chemistry does not necessarily indicate that Tokaanu field is younger than these systems.

Significant mixing of deep geothermal fluid and cold groundwater has occurred in **evolved fields.** Therefore, future research could assess the mechanism of geothermal fluid replacement by cold groundwater. Two-phase three-dimensional flow modelling will be a key technique to assess why geothermal flows reduce over time and the consequent effects on reservoir characteristics post formation. The Wairakei geothermal field provides an example that would be suitable for study because of the wealth of information available for this field and measurements of the effects of reservoir use (e.g., Figure 3).

Highly-evolved fields are possibly long-lived, e.g., Hauraki Plains fields, such as the Kerepehi Fault system springs, may have been flowing since the Miocene (see above). These systems could therefore be used to assess geochronometers for fluid-rock systems over large time scales including long-term changes in field permeability. Useful examples for research could include the Atiamuri system, i.e., a young TVZ system that includes fossil fields; and the much-older Hauraki Plains fields such as the Kerepehi Fault system.

Useful research on **fossil fields** could include 'forensic' investigations into the causes of field formation and flow cessation. Fossil fields identified in this paper probably do not represent the end-member of geothermal field evolution, as defined in this paper. This is because cessation of activity in these fields was possibly associated with changes in boundary conditions as lakes drained.

5. CONCLUSIONS

The age and evolution of geothermal-groundwater systems in the Upper Waikato River (UWR) catchment of the Taupo Volcanic Zone (TVZ) was assessed with geological reconstructions of the TVZ, models of groundwater elevation and models of spring chemistry.

Geological reconstructions represented pre-TVZ geology with a Hauraki Rift extension that contained the palaeo-Waikato River channel. Early in the Quaternary, Mangakino eruptions formed extensive ignimbrite deposits and the Mangakino caldera. The 'young TVZ' phase of TVZ formation (Wilson and Rowland, 2016) was divided into 'young TVZ 1' epoch, which saw large-scale Whakamaru ignimbrite eruptions and creation of the Whakamaru caldera, and 'young TVZ 2' epoch which included multiple eruptions and the formation of calderas (i.e., Reporoa and Ohakuri) and basins (i.e., the Taupo-Reporoa Depression and Ngakuru Graben).

UWR catchment geothermal fields were assigned to these epochs from a paleaogeographic assessment of volcanic features identified by the geological reconstructions and the current evolutionary status of geothermal spring chemistry. This status (i.e., unevolved, evolved, and highly-evolved) was determined by Hierarchical Cluster Analysis (HCA). Fossil fields were assigned to epochs considering groundwater elevation and palaeogeographical associations with pre-historic lakes.

Activity in three UWR catchment geothermal fields (i.e., Atiamuri, Ngatamariki and Orakei Korako) probably commenced in the young TVZ 1 epoch with the Whakamaru eruptions. Activity in other fields (i.e., Waikite, Waiotapu, Te Kopia, Reporoa, Rotokawa and Reporoa), and fossil fields (i.e., Ohakuri, Ngakuru and East-Paeroa Range) probably started in the Young TVZ 2 epoch.

Generally, spring flow in UWR catchment geothermal fields is dominated by cold groundwater because the median percentage of deep geothermal fluid in spring flow (P_m) was less than 30%, with several less than 10% (i.e., Waikite and Te Kopia). The HCA analysis and the mixing model identify general trends in spring chemistry from geothermal-reservoir dominated (Tokaanu) to cold-groundwater dominated (e.g., Te Kopia and Reporoa).

These trends possibly indicate that the evolution of fields follows progressive mixing, with time, of cold groundwater with geothermal-reservoir fluid. This evolutionary trend of geothermal systems may have relevance to a wider analysis of geothermal resources, e.g., as a geochronometer for geothermal fields. Therefore, it was suggested that future research could aim to better understand each evolutionary class, particularly with regard to fluid chemistry (reservoir and cold groundwater), formation permeability and groundwater flow.

6. ACKNOWLEDGMENT

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