A COMPARATIVE WATER GEOCHEMISTRY STUDY OF FIVE GEOTHERMAL FIELDS IN THE TAUPO VOLCANIC ZONE: ATIAMURI, MOKAI, NGATAMARIKI, WAIKITE, AND WAIOTAPU

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ABSTRACT

Our study involved a comparison of hot spring geochemistry data collected between 1905 and 2009 from five geothermal fields in the Taupo Volcanic Zone (TVZ), New Zealand. Atiamuri, Mokai, Ngatamariki, Waikite, and Waiotapu were chosen as the geothermal systems for this study for their east-west and north-south coverage of the central TVZ, their comparative data availability, and for representing development and protected systems. One neutral-chloride hot spring that best represented the deep reservoir fluid was chosen for each geothermal system. Water-type and geoindicator ternary diagrams were utilised for observing changes in each hot spring overtime. Chloride (Cl^-), silica (SiO_2), sodium (Na), potassium (K), magnesium (Mg), and boron (B) were the main parameters used for interpreting reservoir conditions and associated near-surface influences. Semi-qualitative concentration trend maps were constructed for comparing geochemistry trends between the five fields. The geothermal systems of Mokai and Ngatamariki as well as Atiamuri and Waikite which represented our East-West distribution of systems showed minimal similarities in geochemistry trends. Ngatamariki and Waiotapu were compared as the spatial relationship between these two fields is consistent with the major structural trend of central TVZ. They show definite trend similarities, especially for sodium concentrations between 1978 – 1984. Specific reasons or events causing similarities to occur between Ngatamariki and Waiotapu are not known. It has long been unclear if Waikite and Waiotapu are hydrologically connected. Geochemistry trends identified in our study for these two systems suggest they have dissimilar water chemistry, which may indicate separate geochemical controls. Caldera boundaries and lithological conditions surrounding the caldera-bounded Mokai and Atiamuri systems are identified as important factors for isolating fluids from these systems and minimising external influences on observed geochemical parameters. Our water chemistry study offers insights into comparing geochemistry trend changes at a regional scale by observing different geothermal systems with distinctive conditions.

1. INTRODUCTION

Most electricity-generating geothermal fields in New Zealand that recorded high temperatures of >240°C (Wilmarth and Stimac, 2005) and with natural heat discharges of >30 MWth (Hochstein, 1990) lie within the Taupō Volcanic Zone (TVZ), a volcanically active northeast trending marginal basin associated with the Taupō-Hikurangi arc-trench (Cole, 1990). Water chemistry is often collected and analysed from surface geothermal features when trying to understand water provenance, reservoir processes, and changes in a geothermal system. The earliest recorded geothermal water samples from the TVZ were collected in the early 20th century, with sampling and monitoring becoming more extensive and regular after the commissioning of the Wairakei power station in 1959, followed by the development of other geothermal fields.

Many studies have been conducted to understand the geochemical characters of geothermal fields in the TVZ including Waiotapu (Giggenbach et al., 1994; Hedenquist and Browne, 1989), Waikite (Glover et al., 1992), Mokai (Henley and Middendorf, 1985; Hulston et al., 1981), Waimangu (Sheppard, 1986), Ngatamariki (Chambefort et al., 2016; O'Brien, 2010). However, studies comparing the geochemistry of different TVZ fields remain limited. Our study aims to compare geochemical changes over time in five geothermal fields from the central TVZ region in the search for regional geochemistry trends.

2. SYSTEMS, SAMPLES, AND METHODS

2.1 Analysed systems and key springs

Five geothermal systems were chosen for our study. These fields are Atiamuri, Mokai, Ngatamariki, Waikite, and Waiotapu. **(Table 1)**, and represent different geothermal system classes (Luketina, 2010). The five fields have a good coverage of the central TVZ area, with Atiamuri and Mokai at the west and Waikite, Waiotapu, and Ngatamariki at the eastern boundary; both sets of fields have a relative northeast-southwest alignment, consistent to the main regional structural trend (Cole and Spinks, 2009). Best-representative hot springs for each system are chosen based on their highest chloride concentrations, as high chloride levels are attributed to upflow zones (Nicholson, 1993) in low terrain geothermal systems such as the TVZ, and for mature water chemistry. Waikite is the only system where the chosen spring, Te Manaroa Spring, does not have the highest chloride concentrations; Waikite Scarp Spring has a higher measured chloride concentration but lacks data continuity.

2.1 Analytical methods

The data used for this study was received from Waikato Regional Council (2009). There have been inconsistencies in naming hot springs by different authors and researchers through time; geographical coordinates and spring descriptions were used in identifying features, and only one name is used for each feature **(Table 1)**. The data from the springs were arranged based on the year of sampling. Two types of ternary diagrams were constructed using Grapher™ (Golden Software, LLC) for each geothermal field; "water type diagrams" showing relative Cl-SO_4-HCO_3 percentages were constructed for analysing the geothermal water

Table 1 – The five geothermal systems, the chosen key spring, and classifications based on Luketina (2010). LDS = Limited Development System, DS = Development System, PS = Protected System.

Geothermal System	Key Spring	System Class
Atiamuri	Whangapoua South Spring	LDS
Mokai	North Mokai Spring	DS
Ngatamariki	Main Pool	DS
Waikite	Champagne Pool	PS
Waiotapu	Te Manaroa Spring	PS

classification of samples, and "geondicator diagrams" showing relative Na-K-Mg percentages were used to assess the reliability of the water samples. "Concentration vs. time diagrams" were created by plotting he concentration of geochemical parameters) against time in years, using the scatter plot chart design option on Microsoft Excel. Polygons were constructed for comparing regional trends between the five analysed fields, with polygon boundaries used simply for ease of visual comparison. This base map was created in QGIS using Natural Earth Data provided by the software.

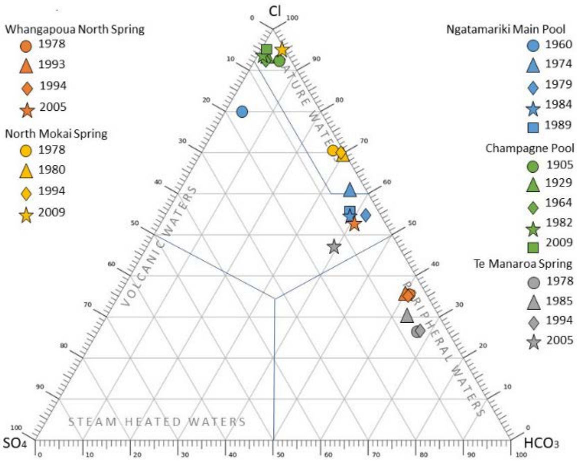

Figure 1 - Water type trilinear diagram showing relative Cl-SO_4-HCO_3 percentages over time for water samples from five representative springs.

3. RESULTS

3.1 Water type

Water samples taken from Champagne Pool between 1905 – 2009 and North Mokai Spring between 1978 – 2009 consistently showed mature water chemistry (**Figure 1**). The Cl percentage in North Mokai Spring showed a significant increase of over 24% between 1994 and 2009, making its water type chemistry more similar to that observed from the Champagne Pool. The water sample from Ngatamariki Main Pool initially showed a transitional volcanic-mature chemistry in 1960, with almost equal proportions of Cl and HCO_3. Both the Whangapoua North Spring and Te Manaroa Spring show a transitional peripheral-mature chemistry in 1978, before showing decreasing Cl percentage and plotting as peripheral waters in later years up to 2009.

3.2 Concentration vs. time study

Te Manaroa Spring at Atiamuri did not show any major concentration changes for the six analysed geochemical parameters (**Figure 2**). The greatest change is observed for sodium concentrations between 1994 – 2009, showing a decrease from 462 ppm to 400 ppm and 360 ppm. Five of the six studied parameters in North Mokai Spring, in exception to magnesium are observed to show very minor increases in concentrations between 1978 – 1993, before showing some change between 1994 and 2009. Magnesium concentrations show a decreasing trend within the same time period, although the change is observed to be minor, with >1.5 ppm difference between the measured maximum and minimum concentrations. Similarly, Ngatamariki Main Pool also show a weak increase in the concentrations of all parameters except magnesium between 1960 – 1987. Magnesium concentrations in this feature shows a >1 ppm decrease in concentration between 1960 and 1974, before stabilising until 1987. The representative feature for Waikite, the Te Manaroa Spring, does not show any major changes in the concentration of all parameters between 1978 and 2005.

Water samples from Champagne Pool, Waiotapu is observed to show variations in its parameter concentrations between 1905 and 2009, while chloride concentrations steadily decreased during the same period. However, samples from Champagne Pool still show short-term changes in the concentration of all parameters between 1978 and 1984. The changes observed during this time period are: (1) Chloride decreased from 1905 to 1986, before stabilising and slightly increasing between 1986 – 2009. (2) Silica, sodium and potassium concentrations show minor changes between 1926 and 1978. From 1978 to 1984, concentrations on these parameters experienced significant decreases, before stabilising between 1984 – 2009. (3) Magnesium concentrations increased from 1905 to 1928, before decreasing before 1978 and experienced minor changes until 2009. (4) Boron increased in concentration between 1926 and 1978, followed by a major decrease in 1982 and ultimately stabilised to 2009.

3.3 Relative concentration trends

A north-south segregation for chloride trends is observed for the analysed geothermal fields (**Figure 3a**). Mokai and Ngatamariki in the southern part of the study zone show major increasing trends (>100 ppm) in chloride concentration over time, despite the two fields being situated >20 km from one another and without known hydrological links. Two of the three northern geothermal fields, Atiamuri and Waikite, experienced variations of <50 ppm in chloride concentrations, which are minor relative to the changes observed in Mokai and Ngatamariki. Waiotapu, situated at the northeast boundary of the study area is the only field that has a decreasing chloride trend over time. A comparison between chloride trends of Mokai and Atiamuri, and between Ngatamariki with Waikite and Waiotapu show that there is no northeast-southwest correlation between the fields for chloride.

Silica concentrations did not show major changes in four of the five fields (from west to east): Mokai, Atiamuri, Ngatamariki and Waikite (**Figure 3b**). Waiotapu is the only field with variable silica trends, with increasing silica trends

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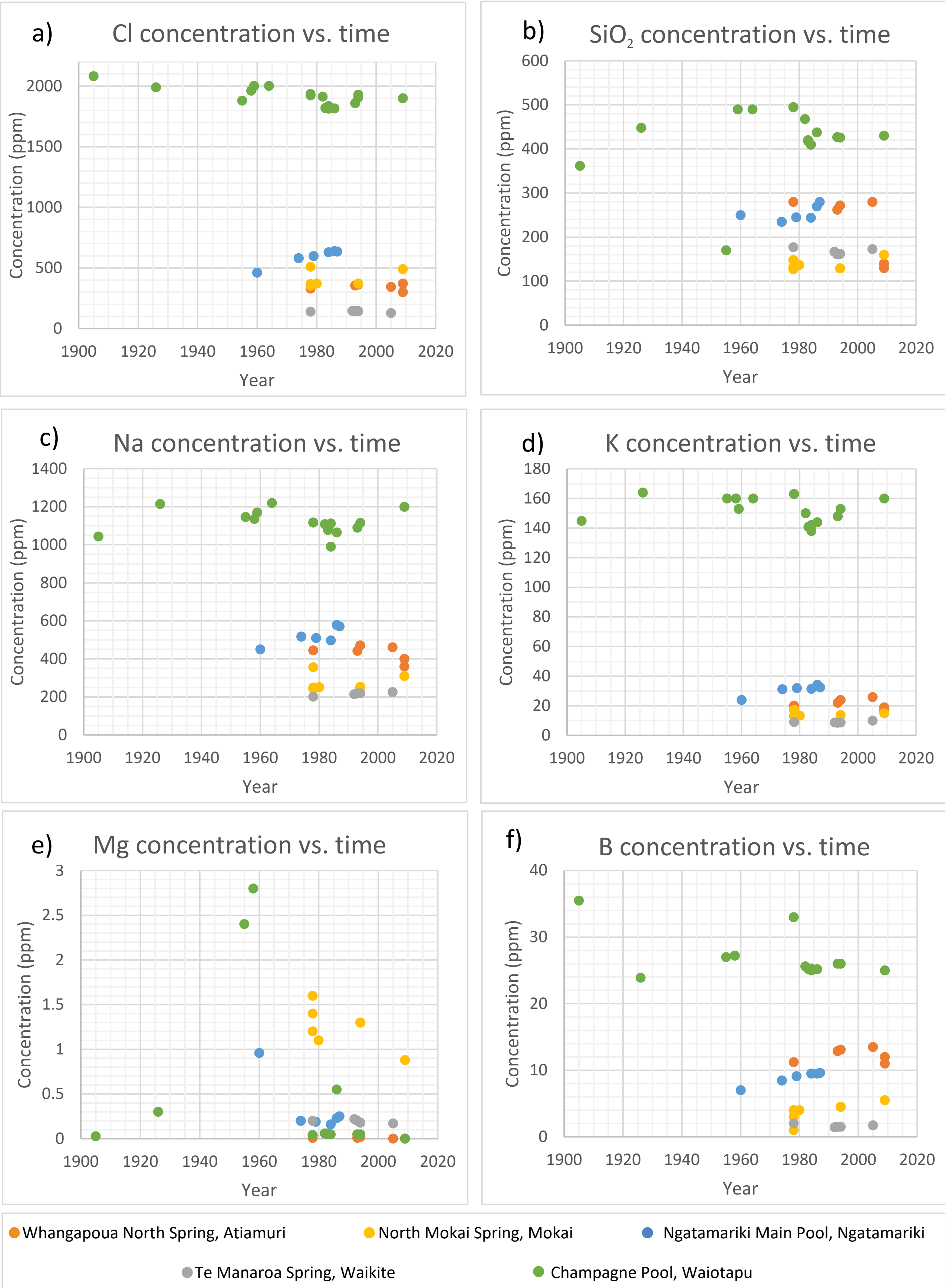

Figure 2 - Concentration time series diagrams for (a) chloride, (b) silica, (c) sodium, (d) potassium, (e) magnesium, and (f) boron for the five representative springs from analysed geothermal fields. Champagne Pool from Waiotapu is observed to show the highest average concentrations relative to the other hot springs and also the most continuous sample record.

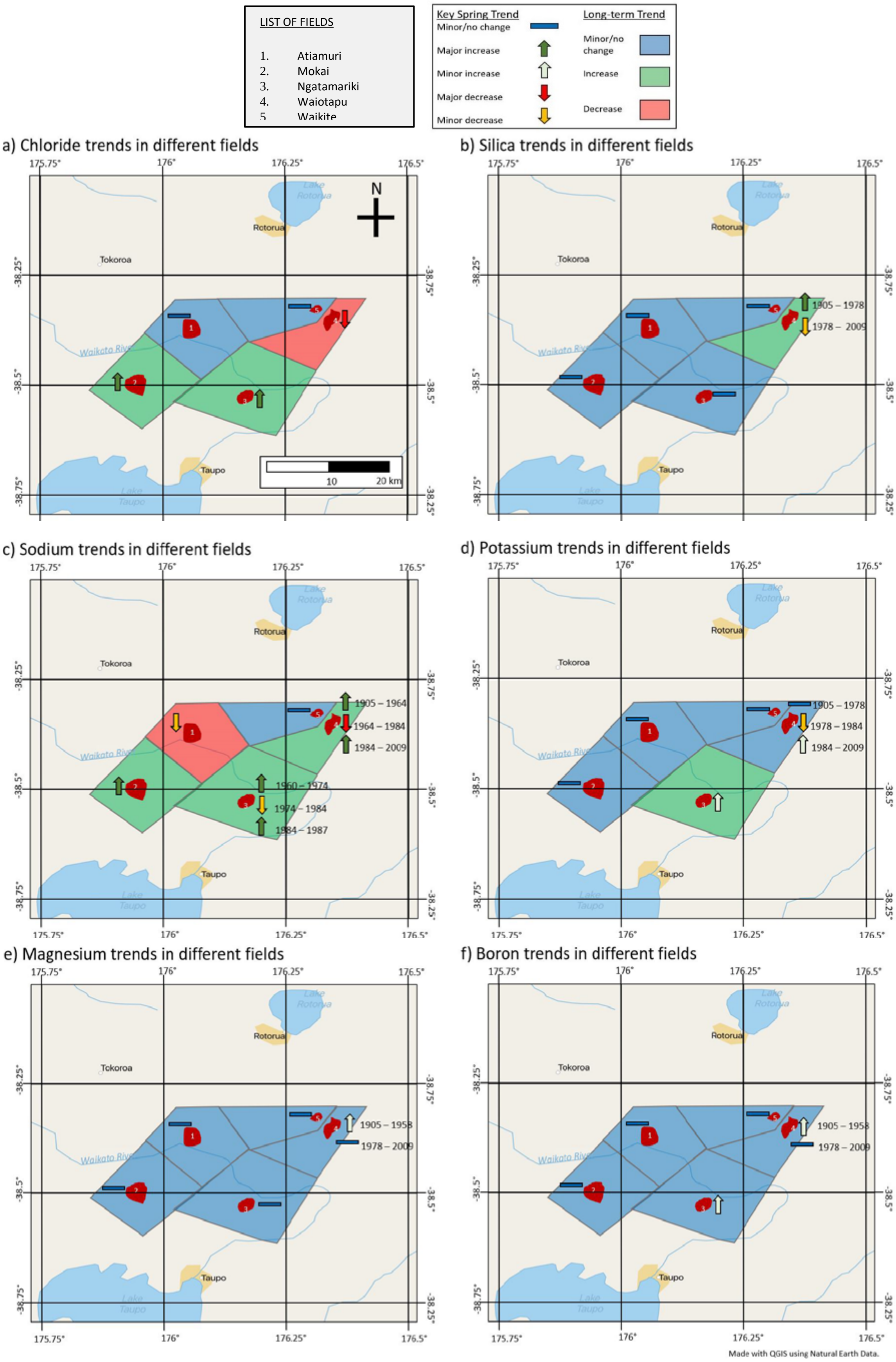

Figure 3 – Observed key spring and long-term trends observed for a) chloride, b) silica, c) sodium, d) potassium, e) magnesium, and f) boron. Polygons are constructed for ease of visual observation, with the real field boundaries shown in red.

between 1905 – 1978, before experiencing a slight decrease from 1978 – 2009. Despite its proximity to Waiotapu, silica concentrations in Waikite range did not show any similarity with trends observed in Waiotapu, instead only show minor changes. Atiamuri and Mokai from the western part of a field, are two fields which have a northeast-southwest relationship and share a common silica trend. One observation at the eastern part of the region shows that Ngatamariki shares a common silica trend with Waikite, but not with Waiotapu. There is no apparent northeast-southwest correlation in silica concentrations between Ngatamariki and Waiotapu.

Sodium concentration trends were observed to greatly vary between the five studied fields (**Figure 3c**), with Waikite being the only field without any major concentration changes. In the west of the study area, a common sodium trend in a NE-SW orientation was not observed. Atiamuri experienced decreasing sodium concentrations, whereas Mokai experienced an increase in concentration. Waiotapu and Ngatamariki to its southeast show the same alternating sodium trends, where the observed silica trends show an initial increase, before alternating to a decrease in value, and ultimately increasing again. Despite the similarity in sodium pattern between the two fields, the alterations occurred during different years. The sodium decrease observed from Waiotapu was also greater in magnitude than the decrease in Ngatamariki. However, the main trends for both Waiotapu and Ngatamariki show increasing sodium values, similar to the trend observed for Mokai.

Atiamuri, Mokai and Waikite experienced minor changes in potassium trends from 1978 to 2009, showing a NE-SW similarity between the two western fields (**Figure 3d**). Trends in Waiotapu show minor changes between 1905 and 1978, before experiencing alternating trends. From 1978 to 1984, there was a minor decrease in potassium values observed, before the trend increased in concentrations again between 1984 and 2009. The decrease in potassium in Waiotapu (1978) started in a different year to a decrease in sodium from the same field (1964). However, for both parameters an increase occurred during the same interval, between 1984 – 2009, suggesting that sodium and potassium trends in Waiotapu may be associated with one another. The potassium values in Ngatamariki show a very minor increase between 1960 to 1987 of <10 ppm (Figure 3.9d). Despite changes in the potassium trends of Waiotapu and Ngatamariki being minor, the trends still show that the eastern fields in the study area are more dynamic than the western fields.

All five analysed fields show minor changes in their magnesium concentrations over time (**Figure 3e**). Magnesium values in Atiamuri, Mokai, Ngatamariki and Waikite only experienced changes of <1 ppm. The concentrations in Waiotapu had more variations compared to other fields especially after 1978, however the measured concentration changes show minor changes (<3 ppm). Boron concentrations (Figure 3f) are also observed to be absent of any major variations over time (**Figure 3.6**). Ngatamariki shows an increase in boron concentrations and Waiotapu experienced an increase in boron from 1905 – 1958. However, the rise in boron values are not major (<10 ppm), hence the two geothermal fields have not shown significant changes over time.

4. DISCUSSION

4.1 East-West Distribution

The two east-west relationships between different geothermal fields observed are between (1) Atiamuri and Waikite; and (2) Mokai and Ngatamariki. Atiamuri and Waikite very minor changes for five parameters. The only exception is a general decrease in sodium concentrations only observed in Atiamuri. The two fields are separated by a distance of ~23 km, which is relatively significant within the TVZ; another geothermal system, Te Kopia, is situated between the two fields. Horizontal flows travelling as far as 15 km from the source system have only been observed in high-terrain systems such as in Chile (Healy and Hochstein, 1973), and not expected to occur in the flat-terrain systems of the TVZ. This makes it unlikely that similarly unchanged trends between Atiamuri and Waikite are due to common controlling factors.

In a regional tectonic perspective, both Waikite and Atiamuri are situated within the dextrally slipping Kapenga segment of the TVZ. This zone has a mean structural trend of 36° NNE ± 16°, resulting in extensional fractures which could accommodate the most horizontal permeability to predominantly trend north-northwest (Acocella et al., 2003). The trend does not conform to the relative orientation of Waikite from Atiamuri, which is situated 78°E of the latter field. This spatial relationship between the two fields makes it improbable that structural trends influence the geochemistry of the fields, consistent with the findings.

Mokai and Ngatamariki both show overall unchanged concentrations of silica, boron and magnesium over time. Unchanged silica and boron values are interpreted to represent stable reservoir conditions with no major changes to the main upflow. Stable magnesium concentrations may show largely unchanged interactions between neutral chloride waters with ground water bodies. Despite sodium showing an overall increase in Ngatamariki, its concentration experienced fluctuations that were not observed in Mokai, making the trends very different between the two fields. Potassium is the only parameter that does not show a common field trend and regional trend for both fields. Differing sodium and potassium trends are interpreted to show different fluid-mineral equilibria conditions in both fields (Nicholson, 1993), which may be caused by different fluid controls in the two reservoirs. The two fields show increasing chloride and sodium values over time, an event not observed on Atiamuri and Waikite. Magnetotelluric resistivity survey and exploration drilling in Ngatamariki (Boseley et al., 2010) show the presence of more permeable conditions to the west of the field, which are in the same direction as the known outflow and as the relative position of Mokai from Ngatamariki. However, the two fields are located 23.5 km from one another, minimising the possibility of related geochemistry.

The structural trends as discussed by Acocella et al. (2003) indicate north-northeast spreading structural trends, with a preference for extensional fractures nucleating in north-south orientations. This structural trend is different from the relative spatial distribution of Mokai and Ngatamariki, making it unlikely that similar trends observed on an east-west orientation to be controlled by the same factors. The association between the hydrology of Mokai and Atiamuri with associated calderas will be further discussed in **Section 4.4**.

4.2 Ngatamariki-Waiotapu Relationship

Observation of short-term geochemistry trends shows that only the fluctuating sodium trends show similarities between Ngatamariki and Waiotapu, although these changes occurred in different years. Despite a relatively limited data continuity, Ngatamariki shows an increase in sodium concentration between 1960 – 1974 , while a similar trend is observed in Waiotapu between 1905 – 1964. These trends were followed by decreasing concentration trends for both fields, although the change observed in Ngatamariki is more minor. Despite the decreasing sodium trends starting at different years, concentrations in both fields stopped decreasing at the same year in 1984. Although data post-1984 is limited for the Ngatamariki Main Pool, it shows an increase in sodium concentrations, similar to that observed in Waiotapu. Boron concentrations also experienced minor variations during different years in both fields.

Ngatamariki did not have any fluid extraction and power generation taking place in 1984, and Waiotapu has remained in its natural state until recent times (Legmann, 2014). The only actively producing field prior to 1984 was Wairakei, and no evidence is present that production at Wairakei affects both Ngatamariki and Waiotapu. Chloride has provenance from the geothermal reservoir, and both sodium and potassium are key parameters related to reservoir equilibrium, so it is unlikely for a weather-related event to be the cause of the fluctuations. No record of hydrothermal eruptions in the TVZ between 1978 and 1984 are found from studies of hydrothermal eruptions and hydrothermal breccias in Waiotapu and producing fields of the TVZ (Bixley and Browne, 1988; Browne and Lawless, 2001; Hedenquist and Henley, 1985), but it is possible that an unrecorded hydrothermal eruption proximal to Waiotapu and/or Ngatamariki could have affected the spring chemistry. The spatial orientation of central Waiotapu from South Orakonui in Ngatamariki is approximately ~38°NE, with Reporoa situated 3.7 km to the east of a straight line between the two fields. This observation is consistent with the structural trend for the Taupo rift segment of the TVZ which is 41°NE ± 9°, and is consistent with a study by Acocella et al. (2003), but more studies are required to better understand the relationship between the fields. It is not known whether similar geochemistry changes during the same time period are observed in geothermal systems proximally located to Waiotapu and Ngatamariki (e.g. Waimangu, Reporoa, Te Kopia, Ohaaki), as these fields are outside the scope of this study.

4.3 Waikite-Waiotapu Relationship

It has been suggested by Giggenbach et al. (1994) that Waikite has its own individual heat source, but still maintains a hydrological connection to Waiotapu through the Paeroa Fault (Glover et al., 1992; Kaya et al., 2014). Mahon (1965) observed that chloride-boron (Cl/B) ratios from hot springs in Waikite, Waiotapu, Te Kopia, and Orakeikorako to be very similar, suggesting a similar water source, or highlighting that Cl/B ratios of waters in rift-type systems associated with rhyolitic magmatism (Reyes and Trompetter, 2012) are relatively homogenous. A linked low resistivity area between Waiotapu and Waikite was also observed by Bibby et al. (1994) during an electrical resistivity survey of those fields. The connected conductive region may be caused by hydrothermal clay alteration taking place among the three fields, which may suggest hot fluids moving in between the fields. The hypothesis that Waikite waters are related to Waiotapu is further supported by a geological study on the Waiotapu-Waikite-Reporoa and Waimangu systems carried out by Wood (1994), and suggesting that the Waiotapu Ignimbrite and pumiceous tuff layers may be permeable enough to accommodate the migration of outflow waters through the Paeroa Fault from Waiotapu to Waikite. However, this implication requires geochemistry trends in Waikite to reflect geochemistry changes of Waiotapu to a certain extent.

The analysed geochemistry data from Waikite and Waiotapu provided results showing that trends in both fields behaved very differently. The trends of the six main parameters in Waikite experienced smaller concentration variations to those observed in Waiotapu, while also not showing variations in concentrations which occurred in Waiotapu between 1978 and 1884. This observation is supported by a Sheppard and Robinson's (1981) Cl/B analysis in Waikite, Waiotapu and Reporoa, which shows that Cl/B ratios from Waikite remained relatively stable, indicating minimal interaction with external waters. The absence of positive correlations between the general chloride, silica, sodium, and potassium trends in Waiotapu and Waikite are inconsistent with the hypotheses set by Giggenbach et al. (1994).

Magnesium concentrations below 0.3 ppm as observed in Waikite are very low for a geothermal field and is usually associated with low dilution (Nicholson, 1993). The stability of the main geochemical parameters over time is interpreted to be associated with impermeable lithology surrounding the reservoir. Previous geology, geochemistry and geophysics studies in Waikite (Glover et al., 1992; Wood, 1994) indicated the confinement of deep Waikite reservoir fluids within a rhyolite aquifer. A typical unfractured rhyolite from the TVZ has been tested to have low permeability between -23 m^2 to -16 m^2 (Rowland and Simmons, 2012) and preferentially acts as an aquitard, suggesting that fracture permeability may act as the main conduit for fluid flow in Waikite. Such unfractured rhyolites would be sufficiently impermeable to isolate reservoir fluids from other water bodies, minimising the possibility and effects of dilution.

4.4 Intra-caldera systems

The relatively stable geochemical parameters in Mokai and Atiamuri are possibly influenced to the position of the two fields relative to calderas; Mokai lies within the Whakamaru caldera (Henley and Middendorf, 1985), while Atiamuri is positioned at the northern margin of the Maroa caldera (Wood, 1995). Ring-faults that act as caldera boundaries often act as permeability controls at depth as observed in the Taupo Caldera, Cãnas Dulces in Costa Rica (Molina and Martí, 2016), and at Los Humeros in Mexico (Ferriz, 1982). Due to their structural setting and lithology, intra-caldera regions are typically associated with higher permeability conditions relative to proximal areas outside a caldera, creating isolated permeability zones. It is possible that similar to the calderas mentioned, fluid flow in Mokai and Atiamuri is confined to intra-caldera faults the associated calderas, minimising interaction between local geothermal waters foreign fluids and influences, keeping chemical parameters relatively unchanged over time. In Mokai, this is further supported by a stable isotope study conducted by Hulston et al. (1984) suggesting that chloride waters in the field only interact with water bodies proximal to the field.

Waiotapu is situated directly to the north of the Reporoa caldera, but lies outside of its structural boundary, which may contribute to a lesser degree of isolation of geothermal waters compared to the western fields. Previous conceptual models and studies of the hydrology and geochemistry also show interaction of waters in Waiotapu and Reporoa, suggesting that waters in the two fields are not as isolated as in Mokai and Atiamuri (Giggenbach et al., 1994; Healy and Hochstein, 1973; Kaya et al., 2014), which may allow for geochemical trends to become affected by external effects.

5. CONCLUSIONS

From the geochemistry analysis of cations and anions in Atiamuri, Mokai, Ngatamariki, Waikite and Waiotapu, there is a lack of clear observations suggesting the presence of convincingly similar trends for most of the fields. Atiamuri and Waiotapu show different behavioural trends of the studied parameters, despite existing suggestions that both fields are hydrologically connected. Continuous sampling of the hot springs in the Waikite Scarp are recommended to be conducted to create a comparison for the Te Manaroa Spring, as the limited data available in this study suggests that the Waikite Scarp may be more representative of the reservoir. Further studies on the structural and hydrological controls exerted by the Paeroa Fault to Waikite are also key to understanding the factors influencing permeability in the field. Fields with east-west spatial relationships show some similarity in geochemical trends, however, it is very likely that the factors affecting the chemistry to be independent in these fields is due to either one, or a combination of the following factors: great distances between the fields, isolation due to lithological barriers or the existence of calderas as permeability barriers, and an east-west spatial relationship of geothermal fields being inconsistent with the regional structural trends of the TVZ.

From the analysis, it appears that caldera boundaries may be a dominant control as to why the geochemistry trends of the analysed fields are largely different, as three of the five geothermal fields are intra-caldera systems. The fields with north-northeast relationships, such as Ngatamariki and Waiotapu, show the most apparent trend similarities – prominently for sodium concentrations. No definitive cause for the similarities have been identified, especially as other geothermal fields are situated within proximity to Ngatamariki and Waiotapu. However, the possibility remains open that the two fields are influenced by a common natural event, such as a hydrothermal eruption.

It is recommended for water sample collection from other geothermal fields in the TVZ be analysed and compared in the future, as well as more regular monitoring of already monitored surface features. Past studies such as one by Sheppard and Klyen (1992) on Te Kopia recorded a large number of features, but the lack of continuous sampling made the data unusable for studies comparing trends over long time periods. Existing water sampling programmes such as the *Regional Geochemistry Monitoring Programme* or *REGEMP* (Waikato Regional Council, 2009) should be regularly continued in the future, while projects with different scopes such as the microbiology-focused *one thousand springs* project (Stott et al., 2012) could be extended to include geothermal geochemistry and create a greater analysis coverage. Such continuous studies would result in a more robust understanding of regional-scale geochemistry trends of the TVZ.

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