# PETROLOGY AND HYDROTHERMAL ALTERATION OF THE
# SPA ANDESITE FROM THE WAIRAKEI-TAUHARA GEOTHERMAL SYSTEM,
# TAUPO VOLCANIC ZONE, NEW ZEALAND

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## ABSTRACT

Andesites are minor rock types in the Taupo Volcanic Zone (TVZ) and most occur near the Tongariro Volcanic Centre (TVC), White Island, Putuaki and Rolles Peak near Rotokawa. However, several subsurface andesites have also been intersected by wells drilled at the Ngatamariki, Rotokawa, Wairakei, Waiotapu, Kawerau and Tauhara geothermal fields. The Spa Andesite at Tauhara, at least 201 meters thick, comprises interbedded lavas and breccias between 390 and 591 m depth. It was intersected only in well THM18 in the Spa Bowl area. Some of rocks are intensely altered. This study characterizes the Spa Andesite and compares it with other andesites within the TVZ. Twelve cores were chosen to cover the vertical extent of the andesite as well as differences in its hydrothermal alteration. The samples were examined by petrography, X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF) and fluid inclusion geothermometry.

The Spa Andesite cores have silica contents ranging from basalt to dacite (52.2 to 63.4 wt.%). They have the characteristics of orogenic andesites, as described by Gill (1981), with Ba/La, Th/La, and La/Nb ratios ranging from 15-80, 2-7, and 2-5 respectively. The Spa Andesite has a composition, particularly its iron content, similar to other andesites in the central TVZ (Rotokawa, Ngatamariki, and Rolles Peak).

The hydrothermal alteration of the Spa Andesite is dominated by quartz, calcite and chlorite with subordinate wairakite, two unknown zeolites, titanite, and pyrite. The clays indicate a slight temperature reversal as a chlorite + illite zone retrogrades towards an interlayered chlorite $_{(0.9)}$-smectite + illite assemblage near the base of the andesite. The degree of clay crystallinity also decreases with depth. Fluid inclusion homogenization temperatures ($T_h$) are generally consistent with those indicated by the secondary minerals, including clays, in the temperature ranges of 235-250$^o$C and 220-235$^o$C at 435m and 587m depths respectively. The altering fluid was of near neutral pH with an apparent salinity of 1.4 % wt.

## 1. INTRODUCTION

The Taupo Volcanic Zone (TVZ) is recognized as host to most geothermal systems of New Zealand and extensive volcanism in central North Island. It resulted from the subduction of the Pacific Plate beneath the Indian Plate which creates crustal extension in the rifting-arc that allows heat sources to ascend. Andesite volcanism is subordinate to that of rhyolite in the TVZ. Cole (1981) reported that volumetrically, andesite comprises only about 2.5% of the volcanic rocks.

The Spa Andesite was intersected by one well (THM18) in the Tauhara geothermal field (Figure 1). It is the only andesite intersected within the area. It is here 201 metres thick and consists of interbedded lavas and breccias. The Spa Andesite is the youngest known subsurface andesite in the field and is stratigraphically situated on top of the Waiora Formation and directly below the Huka Falls Formation (HFF). A detailed description of these stratigraphic units is given by Bignall et al. (2010).
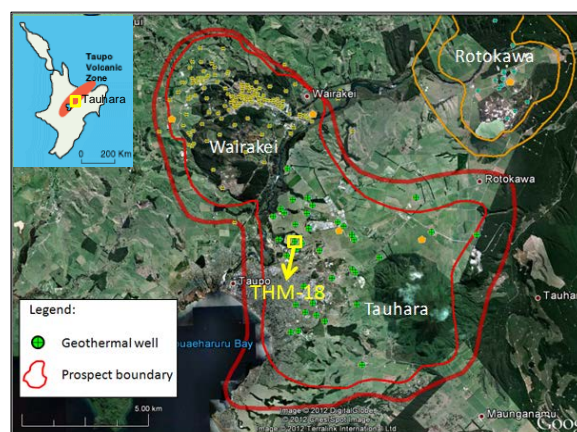


**Figure 1: The location of the Wairakei-Tauhara system in the TVZ and well THM18 in the Spa Bowl area. The system is outlined by the resistivity boundary.**

Twelve drill cores from well THM18 from selected depths were examined. Samples were chosen based on the megascopic characteristics of their structure, texture and hydrothermal alteration intensity.

This paper reports the characteristics of the Spa Andesite and compares them with other andesites in the TVZ. It also interprets, from the hydrothermal alteration, the changes that affected this part of the reservoir.

## 2. GEOLOGY OF THE FIELD

The Tauhara Geothermal Field is located northeast of Lake Taupo on the western flank of Mt. Tauhara. It is part of the Wairakei-Tauhara geothermal system.

## 2.1 Subsurface Geology

The subsurface geology of the Tauhara field is similar to that of the Wairakei field on the western side of the Waikato River. Results from drilling new deep wells inside the Wairakei-Tauhara geothermal system were reported by Rosenberg (2009) and updated by Bignall (2010). Some new formations (Figure 2) were encountered and the structures were modeled based on the drilling results. More than 30 wells have been drilled in Tauhara over the last 50 years (Rosenberg, 2009).

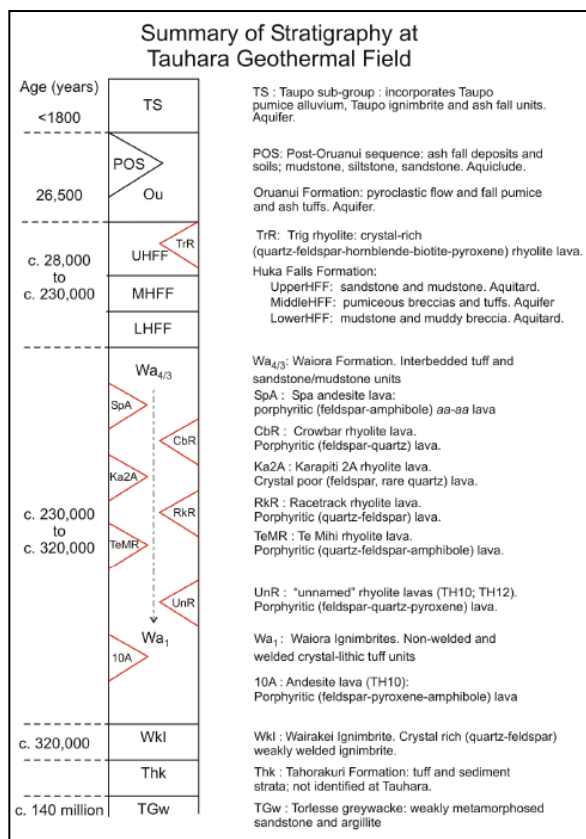Figure 2 summarizes the stratigraphy of the Tauhara geothermal field.



**Figure 2: Stratigraphy of the Tauhara Field and ages of major geological units drilled (GNS Science, 2010).**

Greywacke and argillites of Jurassic to Cretaceous age form the basement of the Wairakei-Tauhara system. They do not outcrop within 30 km of Taupo and basement was only intersected by well TH17 beneath Tauhara at -1484 mRSL in the northeast part of the field.

Andesite units occur in the Wairakei-Tauhara system, such as Waiora Valley Andesite, which overlies the Wairakei Ignimbrite in the western borefield and in the Te Mihi area, and a deep andesite complex (>700 m thick) at Tauhara South (TH10). The Spa Andesite is 201m thick in THM18.

## 2.2 Borehole geology of well THM18 and the Spa Andesite

THM-18 is located in central Tauhara . It was drilled by Contact Energy Ltd. for geotechnical purposes to a depth of 717 m. It was fully cored with 61mm HQ and 83 mm PQ size core barrels. The well was drilled through the Huka

Falls Formation (HFF) down to the Waiora Formation. Due to special regulatory conditions, THM18 was abandoned immediately after completion and therefore no long-term temperature data is available for this well.

Spa Andesite is underlain by Waiora Formation and overlain by HFF and comprises andesite lavas and breccias (Figure 3). It is the first andesite lava encountered in central Tauhara and may be the youngest in New Zealand geothermal fields (the Waiora Valley Andesite was intersected below the Waiora Formation and the Rotokawa Andesite is stratigraphically older). The lateral extent of the Spa Andesite is not yet known.
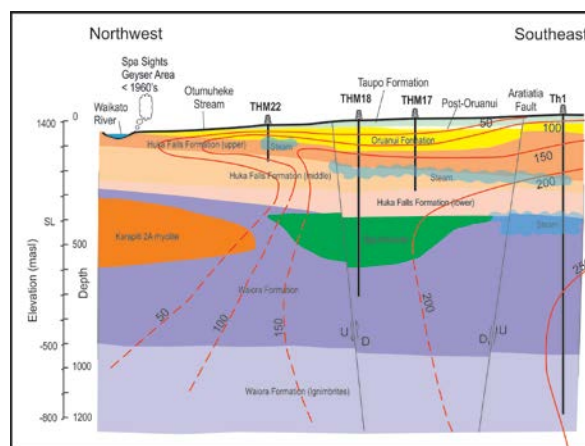


**Figure 3: Geological cross section beneath THM-18 which intersected Spa Andesite (modified from GNS Science, 2010).**

# 3. PETROLOGY OF THE SPA ANDESITE

## 3.1 Lithology and Mineralogy

The Spa Andesite is composed of lavas and breccias (Figure 4). Lavas predominate, interlayered with breccias that are mostly monomict but also polymict in places, consisting of pumice, lava, vitric sandstone and siltstone fragments.

The lavas have typical porphyritic texture. Most show a trachytic (flow structure) and are vesicular. There are veins and vesicles in some samples that are filled with secondary minerals. Major veins were sampled in two cores from depths of 487.5-487.6m and 554.4-554.5m (samples 3 and 5) respectively.

The phenocrysts consist of plagioclase, pyroxene (augite and hypersthene) and opaques with accessory biotite. The proportion of phenocrysts ranges from about 25 to 40% and plagioclase is the predominant mineral. The phenocryst sizes vary between 0.2 and 2mm. The crystals are subhedral to euhedral. In places, the phenocrysts (plagioclase, pyroxene and opaques) form clusters. They are surrounded by a groundmass which consists of plagioclase and pyroxene laths, small opaques and volcanic glass. The groundmass, particularly the plagioclase microlites, commonly shows a sub-parallel orientation or flow texture.

The breccias consist of clasts of monomict lavas with porphyry andesite as their only component. Most phenocrysts are plagioclase and altered pyroxene. The fragments are supported by the matrix, which is composed of smaller grains of andesite, glass and/or filled with

secondary minerals such as quartz and calcite. All of the breccias sampled are more intensely altered than the lavas. The matrix has altered most and shows that these rocks initially had good matrix permeability that allowed hydrothermal fluids to flow through them.

Vugs and vesicles host hydrothermal minerals. Hence, they allowed interconnectivity for hydrothermal fluids to flow. Secondary permeability is also evident from veins up to 6-8 mm wide that dip at 45-70 degrees relative to the core axis.
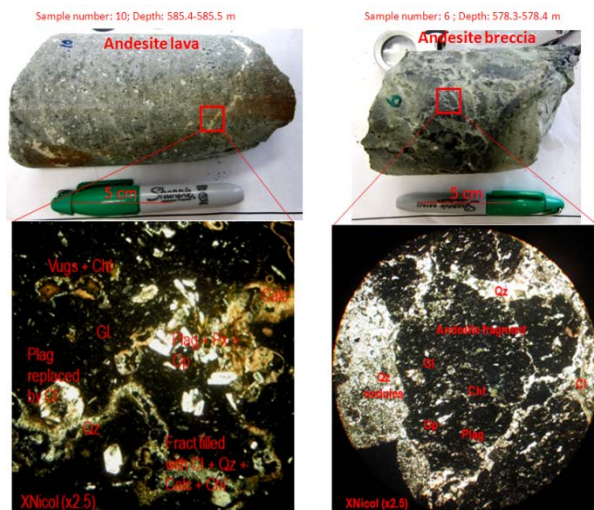


**Figure 4: Examples of andesite lava and breccia in cores from well THM18. Note that the breccia shows more intense alteration than the lava suggesting that matrix permeability plays an important role in water-rock interactions.**

## 4. CHEMICAL COMPOSITION OF THE SPA ANDESITE

Selected portions of 8 cores megascopically free from veins were crushed for analysis by X-Ray Fluorescence (XRF). Petrography later showed that most samples had already been affected by hydrothermal alteration.

The silica content of the Spa Andesite ranges from 52.19 to 63.44 wt. %. Most samples plot at the end member compositions of andesite with high-silica contents (Figure 5). The highest silica (sample 4; 545.9-546 m) and lowest silica (sample 7; 578.5-578.7 m), samples correspond to dacite and basalt respectively. The presence of secondary quartz in them and intense degree of alteration (e.g. samples 2 and 7) suggest that the primary composition was potentially affected by hydrothermal alteration.

Most samples plot within the calc-alkaline series and have medium-K contents (Figure 5), despite the possible effects of alteration. The rocks also display low $TiO_2$ contents (0.75-1.17% wt.) which are typical of orogenic andesites. The $TiO_2$ contents of most orogenic andesites ranges from 0.8-1.0% wt. (Gill, 1981).

Trace elements can provide information both about the source and the differentiation history of magma (Gill, 1981). Ba/La, Th/La, and La/Nb ratios for orogenic andesites range from 15-80, 2-7, and 2-5 respectively. The majority of the Spa Andesite samples fall within these values for Ba/La, Th/La, and La/Nb of 9.8-30.4, 2.0-8.5, and 2.1-4.3 respectively. Samples 2 and 7 have low Ba/La (13.5 and 9.8) ratios suggesting that they were affected by hydrothermal alteration which depleted them in barium; as both are intensely altered.

**Table 1: Composition of Spa Andesite, eight samples of vein free cores were selected for XRF analysis.**

Normalized major elements (% wt.)

| Sample | Depth (m) | SiO$_2$ | TiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MnO | MgO | CaO | Na$_2$O | K$_2$O | P$_2$O$_5$ | LOI | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 435.3 - 435.4 | 53.95 | 0.96 | 21.57 | 7.69 | 0.16 | 2.02 | 5.96 | 4.58 | 0.96 | 0.25 | 1.92 | 100.03 |
| 3 | 487.5 - 487.6 | 62.64 | 0.85 | 17.41 | 6.00 | 0.12 | 1.41 | 4.97 | 3.22 | 1.52 | 0.21 | 1.68 | 100.03 |
| 4 | 545.9 - 546.0 | 63.44 | 0.73 | 15.84 | 5.43 | 0.12 | 1.50 | 5.20 | 2.90 | 2.23 | 0.19 | 2.47 | 100.06 |
| 5 | 554.4 - 554.5 | 62.22 | 0.85 | 16.92 | 6.79 | 0.18 | 0.70 | 5.17 | 3.11 | 2.45 | 0.22 | 1.40 | 100.02 |
| 7 | 578.5 - 578.7 | 52.19 | 1.14 | 21.50 | 11.16 | 0.26 | 1.78 | 4.91 | 3.56 | 0.89 | 0.20 | 2.47 | 100.06 |
| 8 | 582.6 - 582.7 | 61.05 | 0.79 | 15.70 | 7.35 | 0.17 | 1.98 | 6.04 | 2.22 | 1.23 | 0.18 | 3.41 | 100.11 |
| 9 | 582.9 - 583.0 | 61.19 | 0.78 | 15.58 | 7.12 | 0.14 | 1.91 | 6.10 | 2.21 | 1.49 | 0.18 | 3.41 | 100.11 |
| 11 | 585.9 - 586.0 | 60.83 | 0.81 | 15.75 | 7.16 | 0.14 | 1.99 | 5.89 | 2.33 | 1.88 | 0.17 | 3.14 | 100.09 |

Trace Elements (ppm)

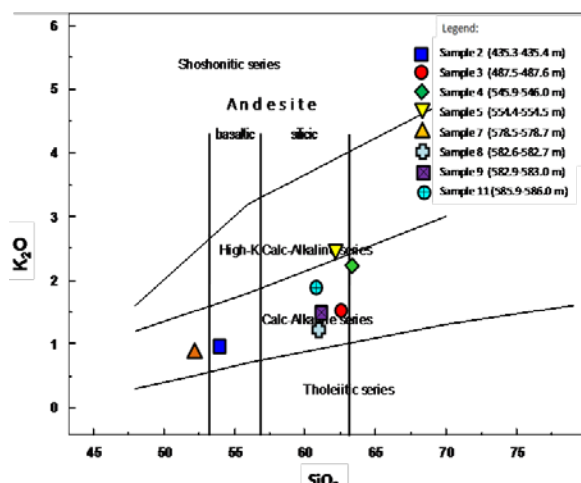| Sample | Depth (m) | V | Cr | Ni | Cu | Zn | Rb | Sr | Y | Zr | Nb | Ba | La | Ce | Pb | Th | Ba/La | La/Th | La/Nb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 435.3 - 435.4 | 106 | 6 | 0 | 2 | 159 | 54 | 368 | 32 | 234 | 10 | 350 | 26 | 45 | 8 | 8 | 13 | 3 | 3 |
| 3 | 487.5 - 487.6 | 98 | 3 | 1 | 2 | 92 | 84 | 319 | 26 | 189 | 7 | 740 | 27 | 44 | 10 | 11 | 27 | 2 | 4 |
| 4 | 545.9 - 546.0 | 81 | 3 | 0 | 2 | 74 | 107 | 280 | 23 | 180 | 9 | 467 | 20 | 41 | 13 | 6 | 23 | 3 | 2 |
| 5 | 554.4 - 554.5 | 98 | 2 | 0 | 3 | 94 | 74 | 276 | 23 | 179 | 8 | 484 | 21 | 37 | 14 | 8 | 23 | 3 | 3 |
| 7 | 578.5 - 578.7 | 156 | 3 | 0 | 4 | 107 | 33 | 356 | 31 | 222 | 9 | 216 | 22 | 45 | 9 | 11 | 10 | 2 | 2 |
| 8 | 582.6 - 582.7 | 125 | 4 | 0 | 2 | 85 | 53 | 320 | 22 | 156 | 6 | 407 | 26 | 35 | 13 | 8 | 16 | 3 | 4 |
| 9 | 582.9 - 583.0 | 121 | 1 | 0 | 3 | 81 | 62 | 326 | 24 | 158 | 8 | 516 | 17 | 22 | 10 | 2 | 30 | 9 | 2 |
| 11 | 585.9 - 586.0 | 122 | 4 | 0 | 3 | 82 | 64 | 328 | 22 | 157 | 8 | 494 | 20 | 41 | 9 | 0 | 25 |  | 3 |

**Figure 5: Classification of Spa Andesites (modified from Gill, 1980 and Pecerillo and Taylor, 1976).**

## 5. HYDROTHERMAL ALTERATION

### 5.1 Distributions of secondary minerals

A summary log of the distribution of hydrothermal minerals downwell is given in Figure 6.
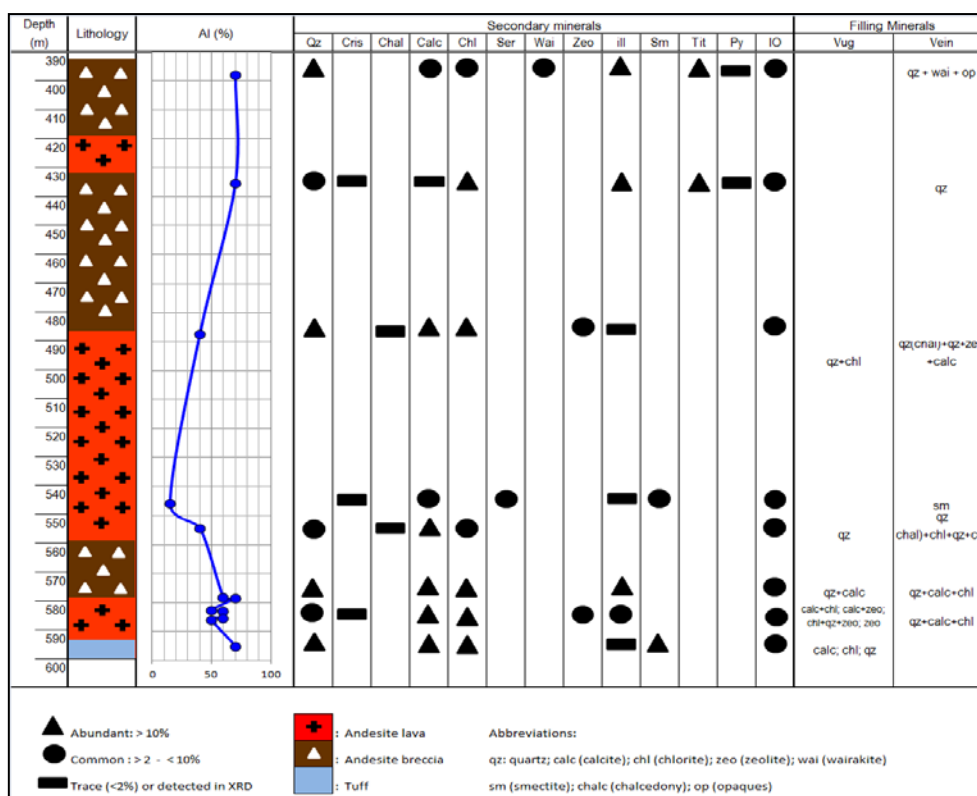
*Silicate Minerals*

Hydrothermal silicate minerals present include quartz, chalcedony, chlorite, wairakite, two unknown zeolites, sericite and titanite.

Quartz is common and occurs throughout the samples mainly in veins or vugs. It replaces volcanic glass in places. Chalcedony occurs as fine grained quartz on the periphery of veins such as in samples 3 and 5 from 487.5-487.6 and 554.4-554.5m depth respectively. Cristobalite is present in samples 2, 4, 8, 9, 10 and 11, from 435.3-435.4m; 545.9-546m and from 582.6 to 586m. Where quartz fills cavities, it is closely associated with calcite and chlorite but it was usually the earliest mineral deposited.

Chlorite is ubiquitous and occurs as a replacement mineral as well as filling cavities. It readily replaced pyroxene, particularly orthopyroxene. Chlorite may also replace plagioclase, but not so intensely as that of pyroxene. It also directly deposited into vugs, vesicles and veins, and is closely associated with calcite and quartz. Normally chlorite has a typical flaky green or blue-grey color and intense pleochroism. Its birefringence is medium to high. However in samples 8 to 11, from depths 582.6-582.7 to 585.9-586 m, it has an anomalous blue color which is generally characteristic of Mg-rich chlorites.

Wairakite occurs only in sample 1, from 397.9-398 m, where it fills veins together with quartz and was the last mineral deposited.



*Note: AI- Alteration Intensity

**Figure 6: Distribution of hydrothermal minerals downwell in Spa Andesite.**

Its most distinct characteristic is its cross-hatch twinning. It is a high temperature mineral that usually deposits above 220°C (Reyes, 1990).

Two other zeolites occur in samples 3 and 8 from 487.5-487.6 and 582.6-582.7m depths respectively. One has a needle, radially fibrous form and is usually entombed within calcite in a vein. The other is platy and is also radial that deposited into a vug. Both are present in only accessory amounts.

Sericite occurs in sample 4 (554.4-554.5m) only, as aggregates replacing plagioclase.

Titanite is distributed in the upper part of the andesite at depths of 397.9-398.0 and 435.3-435.4m. It is disseminated throughout these rocks. Although titanite is an accessory mineral, it is quite abundant in some samples

### Non-Silicate Minerals

The non-silicate minerals are calcite, pyrite and iron oxides. Calcite is common and occurs throughout the samples. It replaces plagioclase and the groundmass and was also deposited into veins and vugs. In places, it forms aggregates of carbonates and even sheet-like platy crystals in a vein. It is closely associated with quartz and/or chlorite in veins and vugs.

Pyrite is abundant in samples 1 and 2. It is fine grained and disseminated throughout the rocks.

The iron oxides are brown translucent phases that appear like rusty pigments in the groundmass and along the margins between fragments and matrix. They also rim the outer part of a vein or vesicle.

### 5.2 Clay Mineralogy

The clay minerals in the Spa Andesite are interlayered smectite-illite, illite, chlorite, corrensite and interlayered chlorite$_{(0.9)}$-smectite.

The sequence, with increasing depth, of the clay assemblages from 397.9m to 595.2m is:

*Chlorite + Illite → Smectite-illite → Chlorite → Corrensite + Illite → Chlorite$_{(0.9)}$-Smectite + Illite*

There is an apparent temperature reversal from chlorite + illite towards chlorite$_{(0.9)}$-smectite + illite where the transition from chlorite + illite to chlorite$_{(0.9)}$-smectite is marked by the occurrence of corrensite. Between them, the clay mineralogy there indicates a significant temperature reversal, as interlayered smectite-illite is present at 545.9-546m depth.

In summary, the vertical zonation of the clay assemblages from top to bottom (397.9-595.2m) are: chlorite + illite deposited in the temperature range of 220-300°C followed by a significant temperature reversal recorded by smectite-illite which has a usual temperature of formation of about 160-180°C; corrensite+illite formed after chlorite as a transition zone; and finally chlorite$_{(0.9)}$-smectite + illite formed towards the base of the andesite.

### 5.3 Fluid Inclusion Geothermometry

Three crystals (1 of calcite and 2 of quartz) were picked for fluid inclusion study. These samples were chosen due to their clarity and richness in inclusions. The homogenisation temperatures of two-phase liquid inclusions were measured for samples 2, 6 and 7 from 435.3-435.4m   578.3-578.4m and   578.5-578.7m depths respectively. The histograms (figure 7) show the distribution of the homogenization temperatures ($T_h$) of those samples.
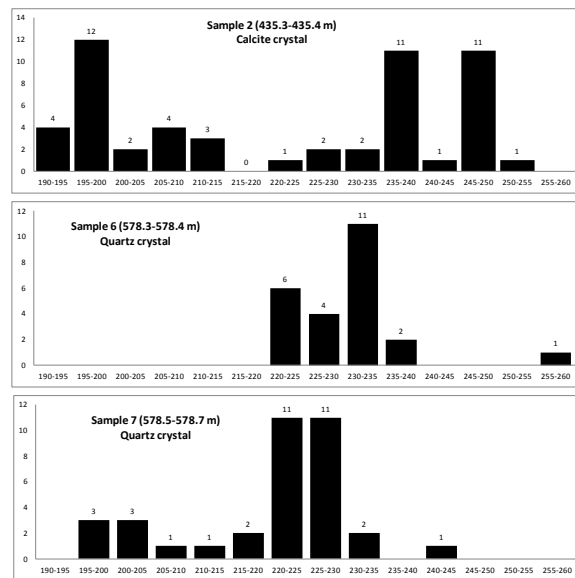


**Figure 7: Histograms of $T_h$ (°C) values of inclusions in samples 2, 6 and 7.**

Figure 7 shows two modes for sample 2 (435.3-435.4m) that suggest two generations of inclusions trapped fluids. One ranges from 190-215°C and peaks at 195-200°C. The other ranges from 220-255°C with two peaks, at 235-240°C and 245-250°C. The first group of inclusions appears elongate in shape and maybe necked. Hence, the Th values of the latter group are probably closer to the current conditions. These crystals derive from the chlorite-illite zone that indicates a temperature above 220°C.

Samples 6 and 7 originate from almost the same depths (578.3-578.7 m). They have $T_h$ distributions that range from 220-240°C and 195-235°C respectively. Sample 6 has peaks at 230-235°C and sample 7 at 220-230°C. These temperature ranges are consistent with the chlorite and corrensite zones that exist here. The 255-260°C and 240-245°C values may be spurious.

The ice melting temperatures ($T_m$) were measured by first cooling the inclusions down to about -30 to -50°C. Large liquid-rich inclusions were selected. Two samples were measured. Calcite from sample 2 (435.3-435.4m) give a $T_m$ of +1.5°C. The other, quartz from sample 7 (578.5-578.7m), give a $T_m$ of -0.8°C.

The apparent salinity was estimated by using Bodnar's (1993) formula. This indicated an apparent salinity for sample 7 (578.5-578.7m) of about 1.4%wt. NaCl.

## 6. DISCUSSION

### 6.1 Comparison of Spa Andesite with other andesites in the TVZ

Figure 8 displays bivariant plots of silica versus some major elements of some TVZ andesites. Samples 2 (435.3-435.4m) and 7 (578.5-578.7m) were excluded due to their intense alteration Overall, the samples exhibit normal trends with higher silica correlating with increasing $K_2O$ but decreasing CaO. $Al_2O_3$ also shows a negative correlation with $SiO_2$ except for some olivine and hornblende andesites of the TVC and White Island. Iron has a negative trend with increasing silica. The bivariant plot has two distinct characters. One group comprises samples from more central TVZ (Rotokawa, Ngatamariki, Tauhara, and Rolles Peak). The other group originates from both the northeast and southeast ends of the TVZ (White Island and the TVC).

### 6.2 Current estimated borehole conditions.

The predominant secondary minerals are quartz, calcite and chlorite with subordinate wairakite, two other zeolites, titanite and pyrite. Quartz, calcite and chlorite form over a wide temperature range. However, wairakite and titanite in samples 1 (397.9-398m) and 2 (435.3-435.4m) suggest a temperature range of 220-300$^o$C and this agrees with the temperature range indicated by the presence of illite.

The clay assemblages include chlorite + illite, smectite-illite, chlorite, corrensite + illite, chlorite$_{(0.9)}$-smectite + illite. Their distribution indicates a temperature reversal from chlorite + illite to chlorite$_{(0.9)}$-smectite. Between them, interlayered smectite-illite occurs and this represents a lower temperature.

Fluid inclusion homogenisation temperatures show a relatively close agreement with the secondary minerals. Homogenisation temperature ($T_h$) measurements from sample 2 (435.3-435.4m) range between 235 and 250$^o$C whereas, samples 6 (587.3-587.4m) and 7 (587.5-587.7m) exhibit Th ranges from 230-235$^o$C and 220-230$^o$C respectively. Based on the mineralogy and fluid inclusion study, the thermal fluid that was involved in the hydrothermal alteration of the Spa Andesite was of near neutral pH and had an apparent salinity about 1.4 % wt. NaCl.

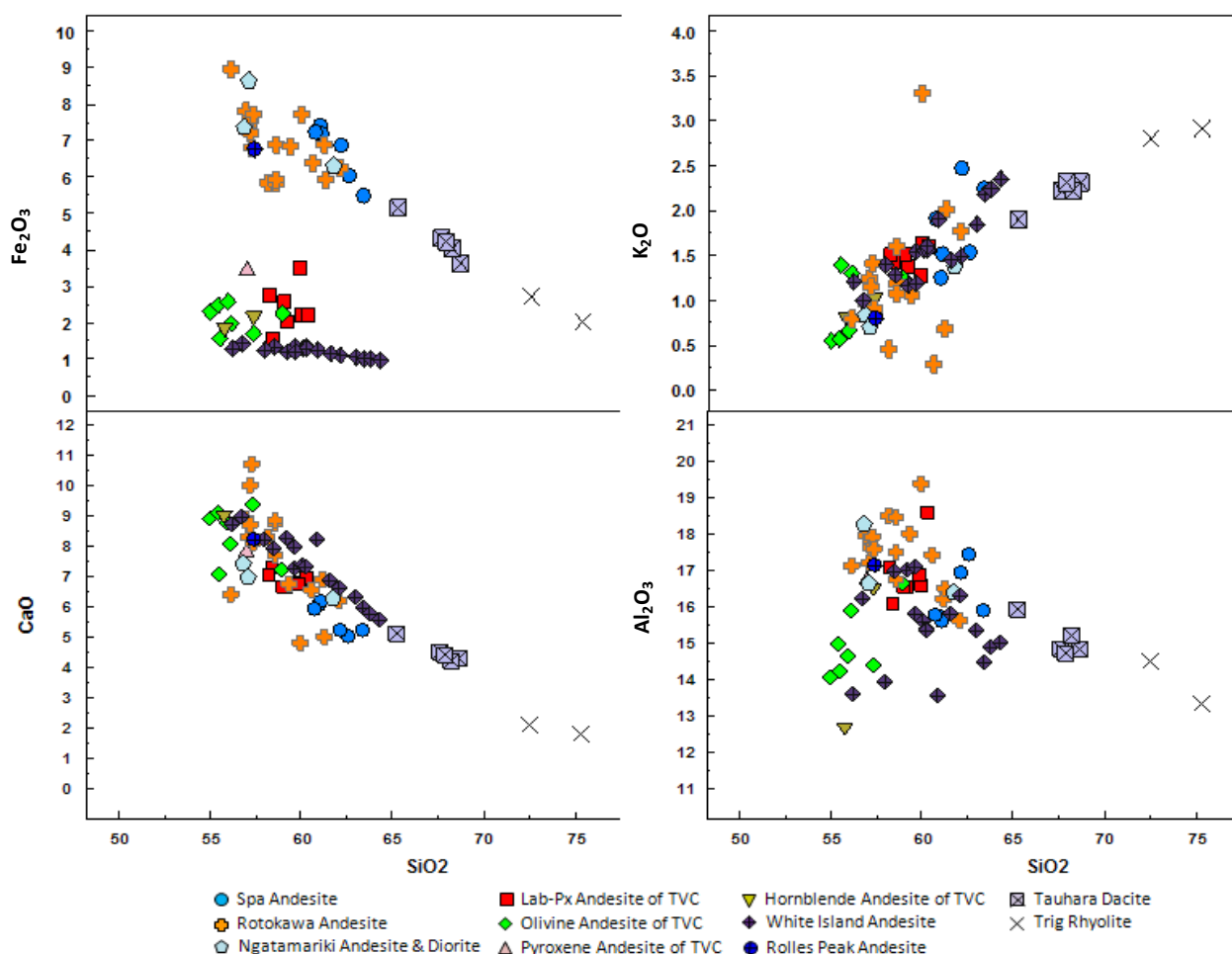A summary of estimated borehole temperatures is shown on Figure 9.



**Figure 8: Bivariant plots of andesites and other volcanic rocks from TVZ. The samples are from Rotokawa and Ngatamariki ( Browne, 1992); The Tongariro Volcanic Centre (TVC), consisting of labradorite-pyroxene andesite, olivine andesite, pyroxene and hornblende andesite (Cole, 1978); White Island (Graham & Cole, 1991); Rolles Peak, Tauhara and Trig Rhyolite (Graham & Worthington, 1998).**
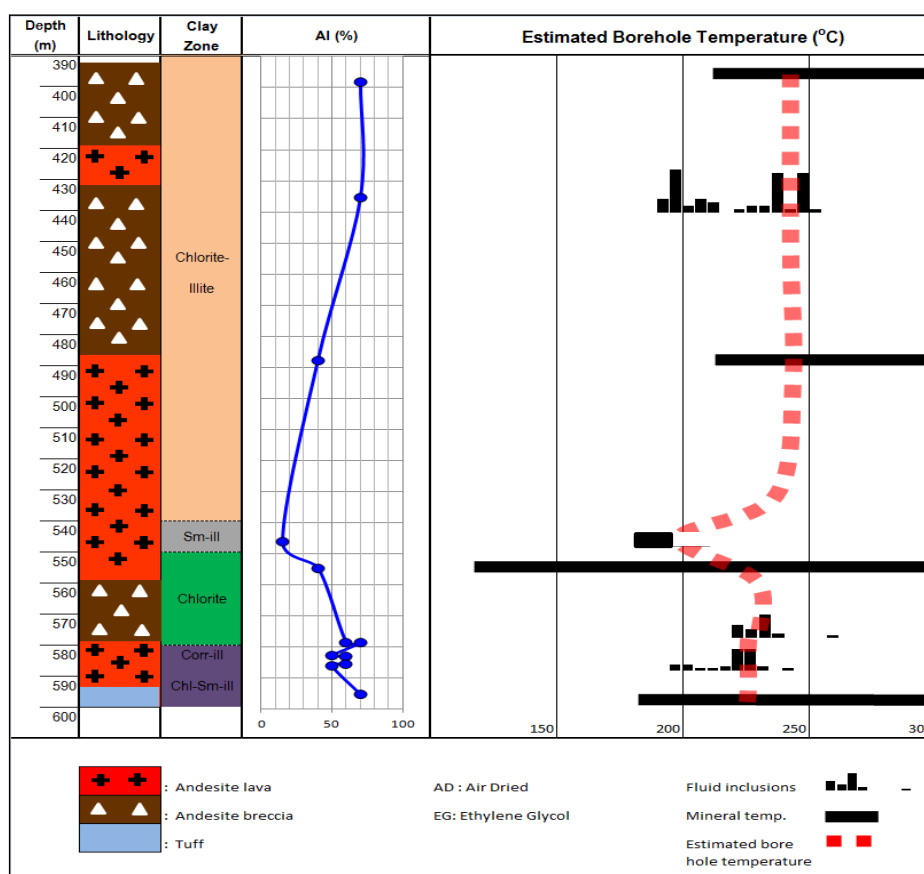
**Figure 9: Composite summary log of estimated borehole temperatures based on the hydrothermal alteration mineralogy and fluid inclusion geothermometry.**

## 7. CONCLUSIONS

- The Spa Andesites cores are classified as high silica andesite according to their $SiO_2$ contents (52.2-63.4 % wt.) with few exceptions in the range of basalt and dacite.
- They have the characteristics of orogenic andesites, as described by Gill (1981), with low $TiO_2$ (0.8-1.0% wt.) and trace element ratios e.g. Ba/La, Th/La, and La/Nb from 15-80, 2-7, and 2-5 respectively.
- A similarity in their chemical compositions, particularly in iron, suggests that the Spa Andesite is more closely related to the central TVZ andesites (Rotokawa, Ngatamariki, Rolles Peak) than to those of the TVC or White Island.
- The alteration intensity ranges from low to very high. Breccias are more intensely altered than lavas showing that matrix permeability plays an important role in water-rock interactions.
- The predominant alteration assemblage of the Spa Andesite is quartz, calcite, and chlorite with subordinate amounts of, wairakite, two other zeolites, titanite and pyrite.
- The clay mineral assemblages in the Spa Andesite, from top to bottom, include chlorite + illite, interlayered smectite-illite, chlorite, corrensite+illite, interlayered

- chlorite$_{(0.9)}$-smectite + illite. These assemblages indicate a slight temperature reversal towards the base of the andesite.
- The vertical temperature distribution within the Spa Andesite, based on its hydrothermal alteration and fluid inclusions, is as follows: from 390m to about 545m, the temperature ranged from 235-250°C; a significant temperature reversal of approximately 160-180°C occurs from 545m to about 554m depth; below that to 595m, the temperature of alteration ranged from 220 to 235°C.
- The secondary minerals show that the altering fluid was of near neutral pH and had an apparent salinity of about 1.4% wt. NaCl. This is similar to the reported composition of waters from the Tauhara geothermal field of 1200-1700 mg/kg Cl.

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