HYDROTHERMAL FELDSPARS IN THE BROADLANDS-OHAAKI GEOTHERMAL SYSTEM NEW ZEALND

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Summary – Petrographic, microprobe and XRD studies were made to characterise hydrothermal feldspars in twenty-two cores of Ohaaki rhyolite and Rautiwiri breccia from the Broadlands-Ohaaki geothermal system. Albite and adularia coexist in the deep central upflow zone (>600 m depth). Albite occurs alone in the deep and peripheral parts of the system in areas undergoing sodic metasomatism, whereas adularia occurs alone in the shallow upflow zone in areas undergoing potassic metasomatism. Their compositions are nearly pure and unaffected by temperature. Hydrothermal feldspars appear to replace precursor andesine crystals through a coupled dissolution-precipitation process at microscopic scale. The slight differences in structural ordering reflected in adularia XRD data and its absence from well scales suggests this feldspar precipitates at different rates under different conditions.

1.0 Introduction

The hydrothermal feldspars, adularia and albite, are common minerals in high temperature, near neutral pH alteration assemblages in igneous rocks in many geothermal reservoirs (Browne, 1978). Their presence is the basis for the reliable Na-K aqueous geothermometer (e.g. (Giggenbach, 1988). They are also used as indicators of permeability and boiling (Browne and Ellis, 1970; Browne 1970).

Here, we report results of our observations of adularia and albite in cores from the Broadlands-Ohaaki geothermal system, revisiting features which were first described 30 years ago (Browne and Ellis, 1970). This work was part of a larger investigation of the effects of mass transfer during hydrothermal alteration to be presented elsewhere.

2.0 Broadlands-Ohaaki Geothermal System

The Broadlands-Ohaaki geothermal system is located in the Taupo Volcanic Zone (Fig. 1) and has been the subject of numerous papers (Simmons and Browne, 2000 and references therein). Figure 2 shows the thermal structure and the location of the two main upflow zones on the east and west banks of the Waikato River. Mesozoic greywacke forms the basement rocks, and these are unconformably overlain by flat lying rhyolitic to dacitic lavas and pyroclastic rocks. Permeable units within the volcanic stratigraphy host the main geothermal reservoir. Northeast trending normal faults created secondary permeability in the Ohaaki sector, transmitting deep fluid to the surface via the Ohaaki Pool (Grindley and Browne, 1968), the only significant surface feature in the field. The deeply derived geothermal water is termed a chloride water, though the pre-exploitation reservoir fluid contained about 1000 mg/kg Cl and >25,000 mg/kg CO_2.

3.0 Hydrothermal Feldspars

Adularia and albite are the only hydrothermal feldspars and they comprise up to 10-20 percent of altered volcanic host rocks. They commonly coexist at > 600 m depth within the upflow zone, occurring together with quartz, illite and/or calcite (Fig. 2). K-feldspar is most abundant in permeable zones of the central upflow zone from 100 to >1000 m depth. Its presence and abundance are directly related to bore output, and it has been used as an indicator of high permeability zones in geothermal fields (Browne, 1970; Browne and Ellis, 1970).

Albite occurrences extend laterally to the deep margins (>800 m depth). Browne and Ellis (1970) suggest that its distribution is controlled by depth and temperature, and requires the presence of plagioclase in the unaltered rock.

Albite occurs as twinned, unzoned, cloudy crystals that replace or partly replace igneous plagioclase, often together with other minerals. The twins mimic those in the primary andesine and appear to be inherited. In the samples we studied, co-existing andesine and albite did not exist, so this hypothesis could not be substantiated. The cloudy appearance of albite has been attributed to mineral inclusions of iron oxide formed during alteration (Browne and Ellis, 1970), but there are also abundant fluid inclusions. High magnification SEM images of albite confirm the existence of voids rather than mineral inclusions, and these presumably represent the fluid inclusion cavities (Fig. 3). Microprobe analyses of several hundred

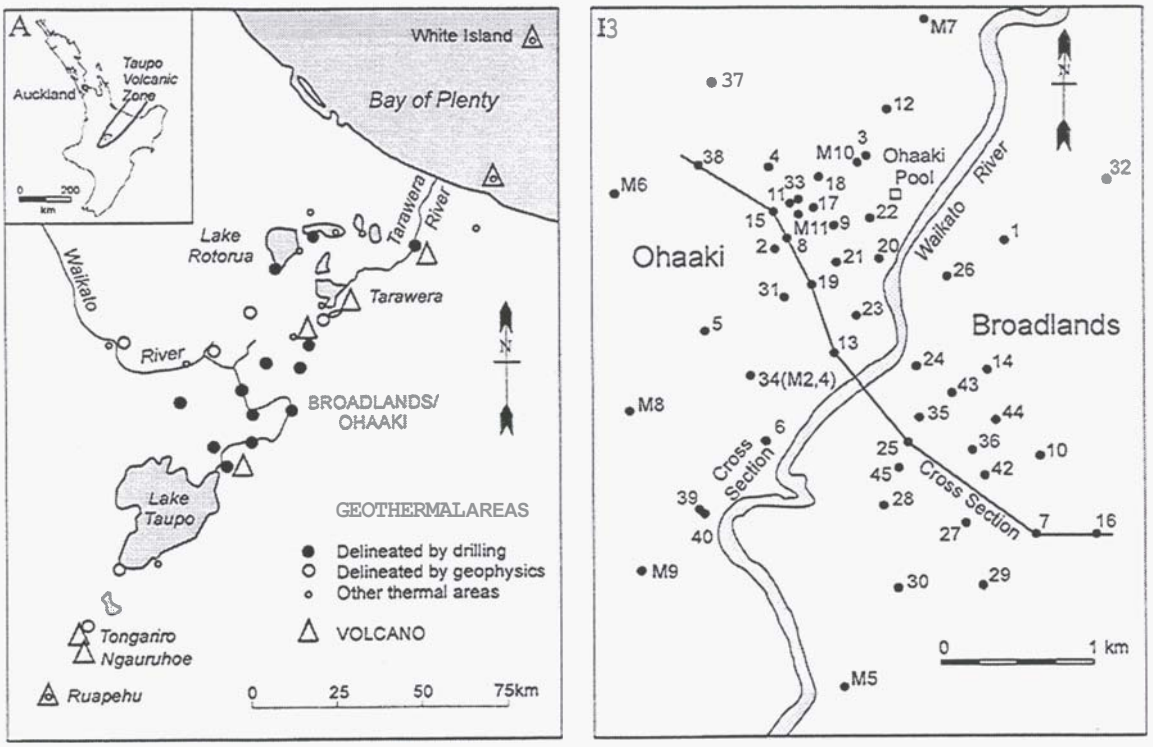

Figure 1. Location of Broadlands-Ohaaki (A) and the borefield (B).

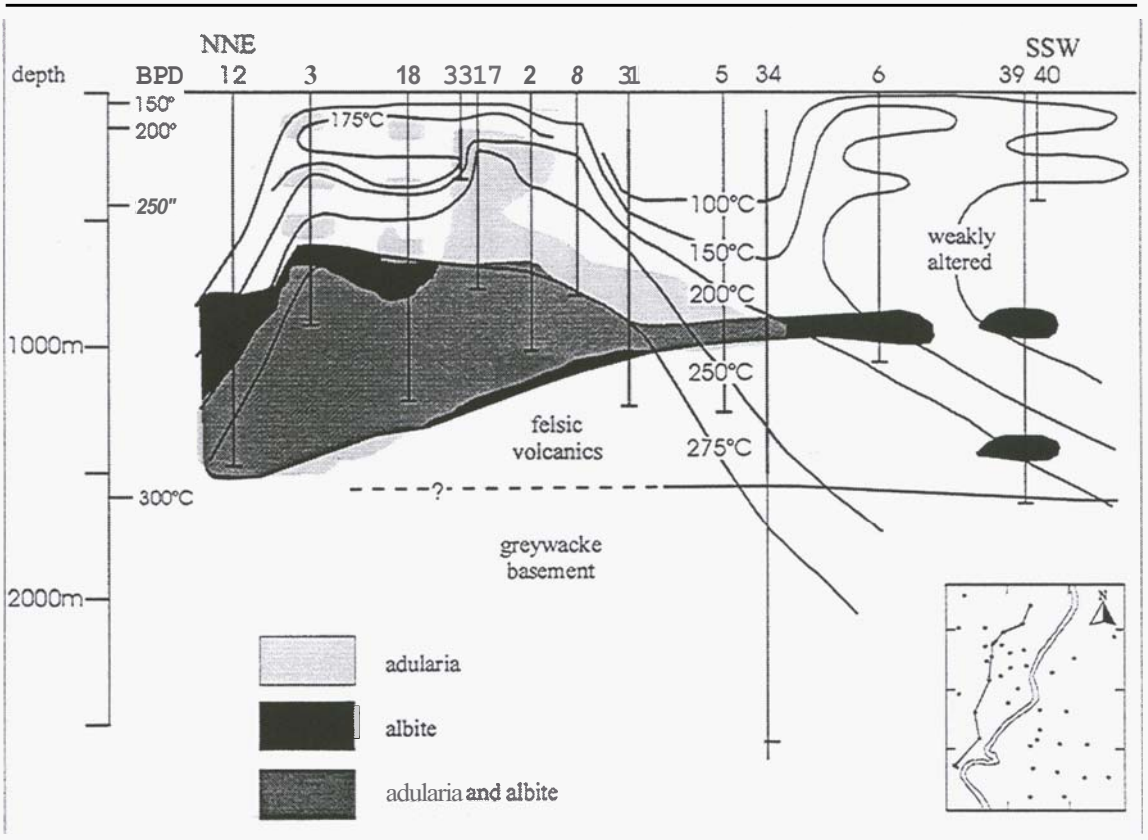

Figure 2. NW-SE cross section showing the distribution of albite and adularia in the Broadlands-Ohaaki geothermal system.

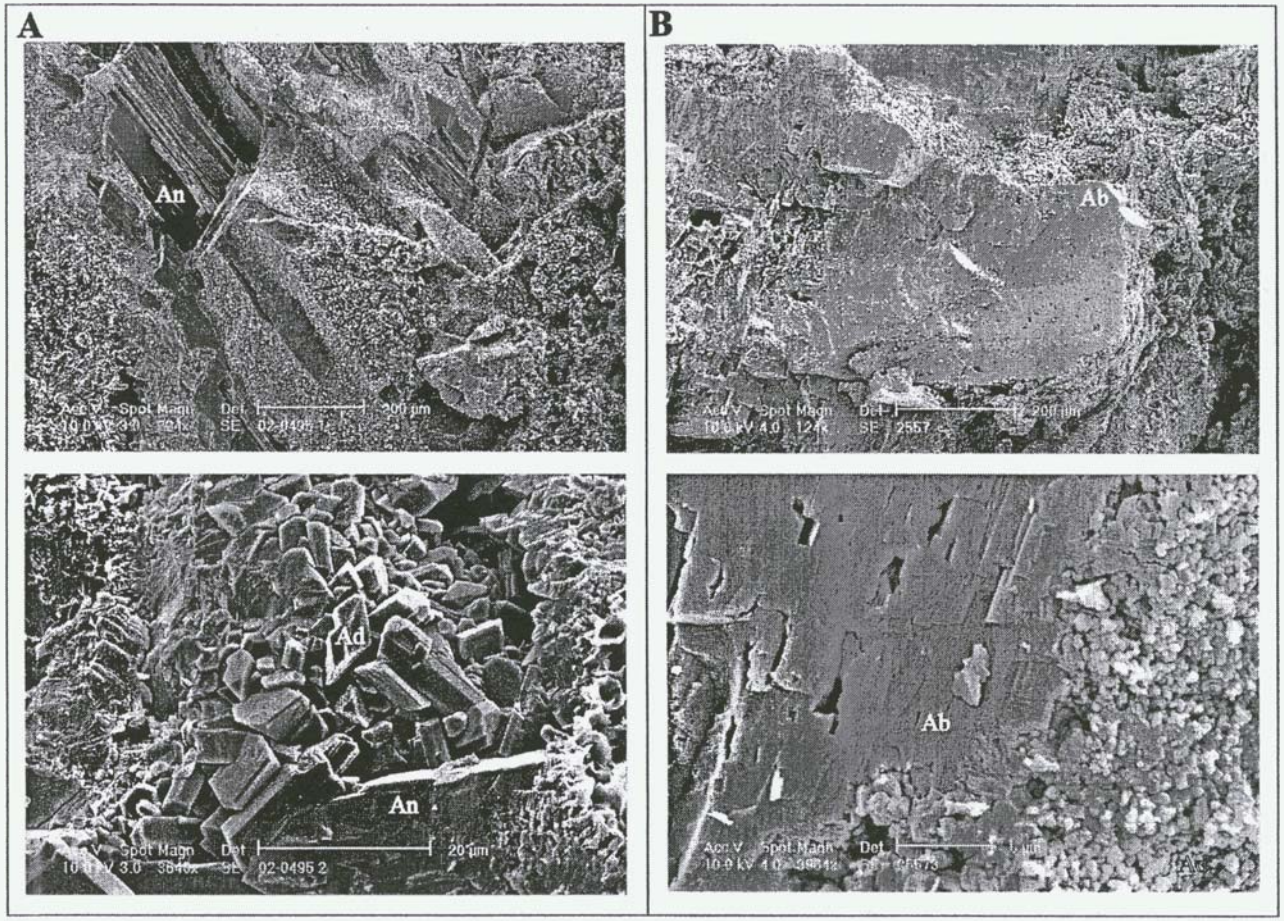

Figure 3. Scanning electron microscope images illustrating feldspar occurrences. A) Andesine (An) partly replaced by adularia (Ad; Br2, 495'). The upper image shows an andesine phenocryst mantled by a veneer of secondary minerals. The lower image is a close up of the same phenocryst, showing the corroded andesine surface being replaced by an aggregate of rhombic adularia crystals. B) Andesine completely replaced by albite (Ab; Br8, 2557'). The lower image is a close up of the same feldspar, showing the inclusions in albite.

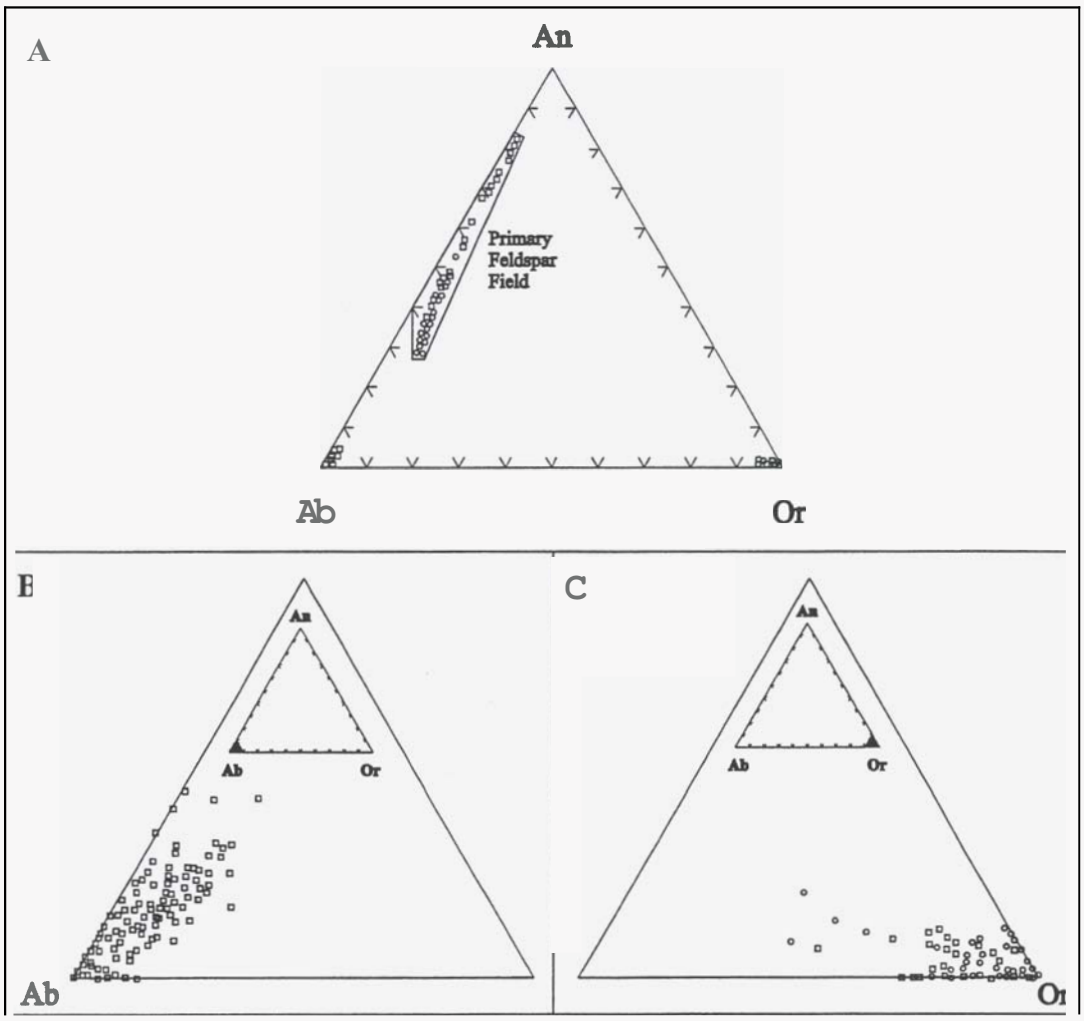

Figure 4. Feldspar compositions in the Ohaaki Rhyolite (circles) and the Rautiwiri breccia (squares) based on 606 microprobe analyses: A) igneous plagioclase (andesine to bytownite); B) albite; and C) adularia (represented as orthoclase). An=anorthite, Ab=albite, Or=orthoclase.

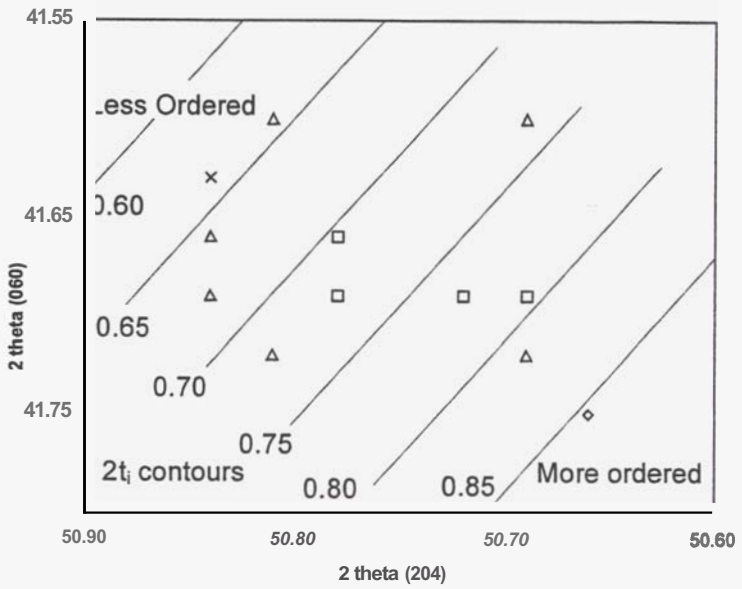

Figure 5. 2ti plot showing the relationship between adularia structure and its occurrence (after Kroll and Ribbe, 1987). Vein adularia (X) is the least ordered. Replacement adularia (◇) that has been partially altered to illite is the most ordered, while unaltered replacement adularia (□) shows intermediate ordering. Samples which may contain both replacement and vein adularia (A) show a range of ordering; these samples were not examined in thin section.

feldspars indicate that albite and adularia have similar amounts of iron oxide of 0-0.28 wt %, whereas andesine contains 0-0.42 wt % FeO. Of the 181 microprobe analyses of albite, no anomolously high concentrations of iron oxide were noted.

Browne and Ellis (1970) describe adularia has having three distinct morphological occurrences at Broadlands-Ohaaki:

- Replacement - replacing primary plagioclase in a similar manner to, and often in equilibrium with, albite as clear, structurally complex crystals.
- Groundmass - as minute diamond shaped crystals in the groundmass, especially in devitrified glass.
- Vein - as euhedral rhombic crystals lining cavities and fractures as a result of direct deposition fiom a fluid.

Unlike albite, the replacement adularia crystals are clear and have no albite twins, suggesting that "replacement" by adularia is faster than replacement by albite (E. Merino, Pers.Com.). Vein and some replacement adularia exhibits sector twinning. Groundmass adularia twinning was difficult to see due to its small grain size.

4.0 Composition and Structure

Approximately 650 microprobe analyses were made on polished thin sections fiom 22 localities in the Ohaaki rhyolite and Rautiwiri breccia, representative of a full range of temperatures (~150 to 275° C). The results show igneous plagioclase compositions range from andesine to bytownite, whereas hydrothermal albite (An_{0-5}, $Or_{0-2.5}$) and adularia (An_{0-2}, Ab_{0-6}, mostly Ab_{0-3}) are restricted to near end member compositions (Fig. 4). These variations appear to be unrelated to temperature. Microprobe traverses across grain boundaries separating igneous and hydrothermal feldspars indicate sharp compositional gradients over distances of a few micrometers or less. These suggest that hydrothermal feldspar precipitation requires complete dissolution of the precursor phase, rather than involving some sort of replacement by diffusive coupled cation exchange (Hedenquist and Browne, 1989).

We also assessed the compositions of the different adularia morphologies. Replacement adularia has the greatest variance, with up to 5 mol % albite and 2 mol % anorthite. Groundmass adularia shows a similar range of albite but less than 1 mol % anorthite substitution. Vein adularia by contrast contains no anorthite and less than 2 mol % albite.

Adularia is monoclinic based on its single sharp (131) reflection (Borg and Smith, 1969). Structural order is reflected in the Al/Si distribution in tetrahedral sites, and previous work suggests that this is related to crystallisation rate (Stewart and Wright, 1974; Kroll and Ribbe, 1987; Dong and Morrison, 1995). Ordering was assessed following the method of Kroll and Ribbe (1987), as determined fiom the positions of the (060) and (204) peaks (in the X-ray diffraction patterns) and the calculation of 2ti:

$$2t_i = \frac{2\theta(060) + 12.1814 - 1.040932\theta(204)}{0.6112 + 0.01592.2\theta(204)} \quad (1)$$

The provisional results of 14 samples (Fig. 5) show that structural states reflect adularia occurrence. Vein or fissure grown adularia is the least ordered (2ti=0.63), and it deposits in response to cooling and pH increase in response to CO_2 loss during boiling (Browne and Ellis, 1970). Replacement adularia is the most ordered (2ti=0.84), consistent with Cerny and Chapman, (1986) and Dong and Morrison (1995). Samples containing replacement adularia only, display intermediate ordering (2ti=0.69-0.78).

5.0 Discussion and Conclusions

The distribution of albite and adularia (Fig. 2) reflects recrystallisation of the volcanic host rock and mass transfer during hydrothermal alteration. Albite and adularia coexist within the deep central reservoir along with quartz, K-mica, chlorite, pyrite, calcite and pyrite. As indicated by the whole rock compositions, these minerals mainly form in response to recrystallisation (ie. metamorphism) and incorporation of H_2O, CO_2 and H_2S to form a propylitic mineral assemblage (Browne and Ellis, 1970; Giggenbach, 1984; Simmons and Browne, 2000). Outside this deep reservoir, feldspar formation is more strongly influenced by metasomatic effects (Browne and Ellis, 1970; Giggenbach, 1984; Simmons and Browne, 2000). Adularia is the main hydrothermal feldspar in the shallow upflow zone due to potassium metasomatism as controlled by cooling, CO_2 loss due to boiling and pH increase. This, and the common occurrence of vein adularia, makes the absence of adularia fiom pipe scales surprising but kinetics may impede its precipitation (Simmons and Browne, 2000). If this is true, then the range of structural ordering in adularia (as shown in Fig. 5) may truly reflect precipitation rate. By contrast, albite dominates in the deep peripheral environment due to sodium metasomatism, as controlled by heating of inflowing waters. For all of these environments, dissolution-precipitation reactions are the main means of feldspar replacement.

6.0 Acknowledgements

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