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Shallow magmatic degassing: Processes and PTX constraints for paleo-fluids associated with the Ngatamariki diorite intrusion, New Zealand

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ABSTRACT: A study of the alteration halo surrounding a diorite intrusion in the Ngatamariki geothermal system is being conducted to ascertain the nature of the reservoir fluids extant at the time of diorite emplacement. Preliminary results show that hot, highly saline (>30 wt % NaCl) fluids were in equilibrium with a low density, volatile-rich phase within, and immediately adjacent to the diorite, and that these fluids interacted with convecting meteoric fluids during formation of the extensive alteration halo. Temperatures in this system range from 250 °C in the alteration halo to > 500 °C in the diorite, and evidence points to the existence of repeated pressure transients across the brittle-plastic transition during subsolidus cooling of the intrusion.

1 INTRODUCTION

A diorite intrusion intersected by geothermal well Ngatamariki NM4 is the only in situ plutonic rock yet encountered in the TVZ. Alteration within and adjacent to the diorite is extensive and distinctive, and suggests that the intrusion served as a convective heat source for the hydrothermal system active at the time. Petrographic, stable isotope and fluid inclusion analyses of alteration associated with this intrusion provide clear insights into both the nature of the paleo-fluids and the reservoir processes adjacent to the pluton, and how shallow, degassing magma bodies evolve through time.

2 GEOLOGY & HYDROTHERMAL PETROLOGY OF NM4

The reservoir stratigraphy of the Ngatamariki field consists of a sequence of interbedded rhyolites, andesites and silicic pyroclastic rocks, and in this respect is similar to the adjacent Rotokawa field (Browne et al., 1992). A feature which sets the Ngatamariki field apart from other explored systems in the TVZ, however, is the presence of a diorite intrusion, intersected between 2640-2750 m in NM4 (Fig. 1). Although the diorite is relatively old (ca. 700 ka, Arehart et al., 1997) and does not serve as a present-day heat-source for the field, there is an extensive alteration halo associated with the intrusion, suggesting that it interacted strongly with hydrothermal fluids in the past.

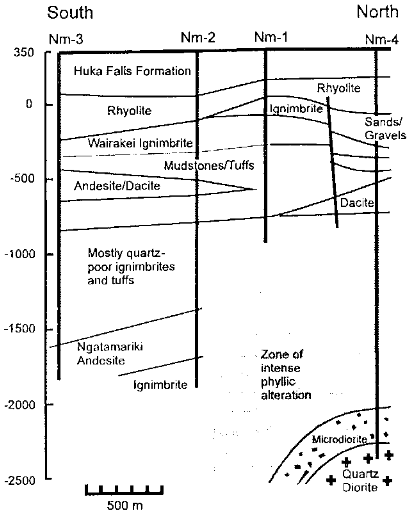

Fig. 1 Geologic cross section through the 4 exploration wells at Ngatamariki.

There is an abrupt increase in alteration rank and intensity beneath the Wairakei Ignimbrite (ie. below ca 750 m depth), suggesting that convection driven by this intrusion had probably ceased by the time this unit was deposited (ca. 330 ka bp). Between 750 and 1700 m depth, the alteration is characterised by an

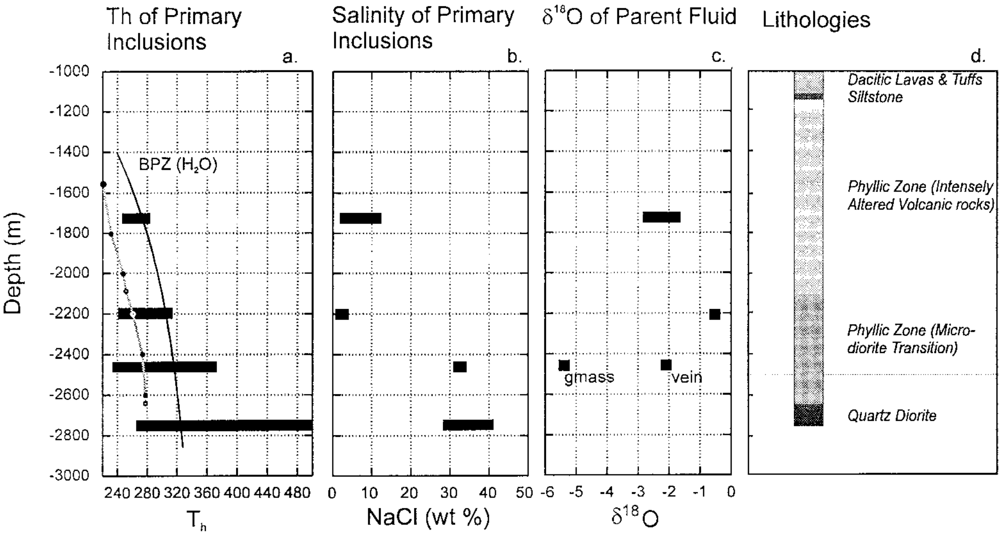

Fig. 2 Phyllic zone fluid inclusion and mineral stable isotope data in NM4. a.) Th ranges compared to present day measured temperatures and boiling point temperatures. b.) Salinities (wt % NaCl). c.) δ^{18}O(SMOW) for waters in equilibrium with analysed mineral phase. d.) Stratagraphic column.

illite-rich, mixed-layer illite-smectite clay, quartz and pyrite, with dissolution and silicification textures predominating. Veins of calcite and pyrite are found at 1000 m depth.

Between 1700 m and 2200 depth, the alteration is very intense, with nearly all primary textures destroyed. Groundmass alteration over this interval consists largely of coarse grained sericite and quartz, with lesser amounts of chlorite and pyrite. Late-stage illite is also present, often replacing sericite. Quartz-pyrite veining, including minor galena and sphalerite, is prevalent over this interval, although sericite-anhydrite veining is observed at 2208 m.

The exact boundary of the pluton is difficult to ascertain owing to the alteration intensity over the transition interval, but a contact between a coarse diorite and what is identified as microdiorite is observable at 2459 m, and the finer-grained variant appears to extend through to 2208 m depth. The coarse diorite at 2749 m consists of up to 60 % plagioclase (oligoclase), 25-30 % amphibole and 5 % magnetite, with interstitial quartz comprising the remaining 5-10 of the rock. A later, green fibrous amphibole grows from the earlier phase, and also occurs in late quartz veins and late interstitial quartz. Oligoclase is variably replaced by albite and epidote, and epidote is also found intergrown with late (ie. interstitial) quartz. Equilibrium temperatures in excess of 350 °C are indicated for the amphibole-bearing assemblage.

At least two hydrothermal alteration events are represented in the cores. Over much of the phyllic alteration interval, fine grained illite is observed overprinting the earlier, coarser-grained sericite. An early assemblage consisting of quartz + sericite + anhydrite + apatite is locally overprinted by quartz + wairakite + epidote + sphene + chlorite ± calcite. Calcite is observed locally replacing epidote, making this the latest stage alteration phase encountered. The earliest assemblage is similar to that commonly observed in phyllic alteration zones in porphyry copper deposits, whereas the latter is more typical of TVZ-type geothermal systems.

Correlation of the diorite to possibly coeval volcanic rocks higher in the sequence is difficult owing to the altered state of the overlying volcanic units. However, given the age constraints provided by Arehart et al. (1997) for the pluton and the Ngatamariki andesite, and the 330 ka age of the little-altered Wairakei Ignimbrite (Wilson et al., 1995), it would appear that the dacite found between 900-1090 m (Fig.1) is the most likely eruptive coeval to the diorite, which would imply the pluton intruded to within 2 km of the ground surface.

3 FLUID INCLUSION AND MINERAL STABLE ISOTOPE DATA

Preliminary results of fluid inclusion and mineral stable isotope analyses from three core intervals in the phyllic zone and one from the diorite proper are summarised in Fig. 2. Quartz is the most prevalent fluid inclusion host mineral, and occurs in veins, vug fillings and as recrystallised groundmass. Anhydrite from anhydrite/sericite veins in core from 2208 m have also provided rare, but usable inclusions.

There are at least three assemblages of fluid inclusions present in hydrothermal alteration products in the diorite and microdiorite. One assemblage contains high salinity, liquid-dominated inclusions (with halite daughter minerals). These are intimately associated with low salinity (ie. daughter-free) vapour dominated inclusions, and as such, are evidence of fluid immiscibility in the hydrothermal system. Secondary inclusions are relatively common in crystals containing the high salinity fluids, and whilst highly variable vapour-liquid ratios in these inclusions imply entrapment of boiling fluid, the salinities are markedly lower than in the primary inclusions. It is assumed that this assemblage of inclusions represents post-magmatic hydrothermal activity. A third population of inclusions is found in quartz that is demonstrably later than those described above. These inclusions are predominantly liquid-dominated, and are devoid of daughter minerals. This assemblage is presently interpreted to be related to the later hydrothermal over-print evident in the hydrothermal alteration phases described above.

There is a large range of homogenisation temperatures (T_h) recorded in the high salinity inclusions in the diorite and microdiorite (Fig 2a), with the higher end of the range clearly reflecting conditions extant within the cooling pluton. The lower end of the Th range is thought to represent, at least in part, cooling of the heat source, although pressure fluctuations in the hydrothermal environment also contribute to variations in the observed Th values.

Salinities of primary inclusion fluids are shown in Fig. 2b. Inclusion compositions in the diorite (2459 and 2749 m) range from 28 to 41 weight per cent NaCl. Whereas inclusions in vein quartz from 1725 m range from 2 to 12 wt. % NaCl, those in anhydrite from anhydrite-sericite veins from 2208 m have relatively low salinities (<2 wt % NaCl).

$\delta^{18}O$ signatures of the fluid are plotted in Fig. 2c. These values derive from fractionation factors for quartz-water (Clayton et al., 1972) and anhydrite-water (Lloyd, 1968) equilibria, and temperatures are constrained by the relevant T_h values. Calculated compositions for fracture-bound waters range between –0.5 to –2.8 (SMOW). Although these values are 2 to 3 per mil heavier than the present day thermal waters from the adjacent Ohaaki system (Hedenquist, 1990), they are considerably lighter than the +8 to +10 per mil values representative of andesitic water (eg. Giggenbach, 1992). Similarly, δD_{water} from matrix sericite in core from 2208 m suggests a composition, at –38±5 per mil (fractionation factor of Gilg & Sheppard, 1996), only marginally heavier than present-day Ohaaki fluids (-38 to –42; Hedenquist, 1990).

Mosaic quartz from the recrystallised groundmass from the microdiorite at 2459 m yields a derived water $\delta^{18}O$ composition significantly lighter (-5.5) than that for the adjacent vein (Fig. 2c). Given that this value is rather similar to present-day Ohaaki reservoir compositions, we interpret the mosaic quartz to represent recrystallisation from later, meteoric-dominated fluids. Overall, the mineral stable isotope data point to mixing between magmatic fluids and meteoric waters.

4 RESERVOIR PARAMETERS AND PROCESSES IN THE INTRUSIVE ENVIRONMENT

Fluid pressures in the subsolidus Ngatamariki diorite would have been bound by lithostatic loading on the high end, and hydrostatic loading on the low end. If we assumed, as mentioned previously, that the dacite eruptives intersected at 900 m (Fig. 1) were coeval to the diorite, the depth to the intrusion represented at 2749 m would have been ca. 1800 m. For an average rock density of 2.7 g/cm^3, this equates to ca. 480 bar lithostatic pressure. Hydrostatic reservoir pressures at this level would have been approximately 180 bars. However, the actual pressure conditions at any one location in the hydrothermal system in and adjacent to the diorite (ie. lithostatic, hydrostatic, or intermediate value) would have been governed by the rheological properties of the reservoir medium.

The entire observed range of fluid inclusion salinities from 2749 m (Fig. 2) is observable over relatively small distances (≈ few hundred microns) within single quartz crystals. Noting that there is an inverse relationship between Th and salinity amongst these inclusions, it seems that dilution of the brine by meteoric water can be effectively ruled out as a cause. Rather, the compositional variations are better explained by the occurrence of pressure transients in the hydrothermal environment.

It has long been recognised that pressure variations within the magma-ambient environment are a natural consequence of shallow (3-4 km) pluton emplacement, where in-situ crystallization leads to saturation of the magma with respect to H_2O and other volatile species, and a net increase in molar volume of the system (eg. Burnham, 1979). At constant volume, this leads to increased fluid pressures, and ultimately hydraulic fracturing of the rocks confining the H_2O-saturated carapace. Evidence of such fracturing at Ngatamariki is found in the large number of quartz veins and segregations throughout the diorite and enclosing microdiorite.

Pressure transients can markedly affect the composition of the magmatic fluid. For example, an aqueous fluid with a bulk salinity of ca. 10 wt % NaCl, at 450 °C, and confining pressure of ca. 330 bars consists of two immiscible phases, including a high density brine (salinity of 28 wt % NaCl) and a low density, volatile-rich vapour (ca. 0.2 wt. % NaCl). A pressure drop of just 30 bars can increase the salinity of the high-density brine from 28 to 40 wt % NaCl, whereas the salinity of the vapour decreases to < 0.1 wt % NaCl.

This process can explain not only the observed salinity variations on the sub-millimeter scale in the Ngatamariki diorite, but more importantly, it also represents a mechanism by which heat and mass was transferred across the pluton-reservoir interface. Owing to density and viscosity differences in the two fluid phases, and relative permeability effects under high vapour/liquid ratios, the low density, volatile rich phase is likely to be more mobile during these events and will be compositionally similar to that released from passively degassing volcanoes (eg. Shinohara, 1995). This vapour interacted with convecting, meteoric-dominated fluids and led to the formation of the observed phyllic alteration assemblage via reaction path processes analogous to those discussed by Christenson and Wood (1993).

The intermediate salinities observed in vein quartz from 1725 m are best explained by flushing of the higher salinity brine by convecting, meteoric-dominated hydrothermal fluid from its source in the diorite. Given that permeability within the diorite would have remained low until it had cooled to below ca. 350 °C (eg. Fournier, 1991, Hayba and Ingebritsen, 1997), it is unlikely that meteoric infiltration and dispersal of the brine occurred until late in the sequence of events. This view is supported by the limited distribution of similar high salinity fluids in the granitic heat-source of the present-day Kakkonda system (Kasai et al., 1996).

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