Pre-eruption thermal rejuvenation and stirring of a partly crystalline rhyolite pluton revealed by the Earthquake Flat Pyroclastics deposits, New Zealand

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Abstract: The Earthquake Flat Pyroclastics form a c. 10 km³ rhyolite deposit erupted at c. 50 ka from the margin of Okataina Volcanic Centre, immediately following the caldera-forming eruption of the Rotoiti Pyroclastics (c. 100 km³) from vents c. 20 km to the NE. Earthquake Flat Pyroclastics deposits display textural and compositional complexity on a crystal-scale consistent with rejuvenation of a near-crystalline pluton in the upper crust. Quartz and plagioclase crystals are resorbed, whereas hornblende and biotite are euhedral. Fe–Ti oxides indicate large variations in pre-eruption temperatures (702–805 °C). Differences of up to 70 °C within pumice lapilli show that crystals were chaotically juxtaposed during magma stirring and evacuation. Chemical zoning within hornblende crystals is consistent with rimward increases of c. 50 °C. These features are consistent with a convective self-stirring process. Previous isotope studies demonstrate a long (>100 ka) crystallization history for the magma. Resorption of crystals deep in the magma may have produced a Ca-, Fe- and Mg-enriched rhyolite melt that allowed the growth of reverse-zoned hornblende. Microdiorite lithic fragments in the Earthquake Flat Pyroclastics and Rotoiti deposits and a basaltic eruption that immediately preceded the Rotoiti eruption suggest that mafic underplating beneath Okataina Volcanic Centre provided a major thermal and volatile pulse to drive the caldera eruptions.

The accumulation of magma bodies and the causes of their eruption are central to understanding the future activity of volcanoes and hence their impact as natural hazards. Recent studies have highlighted the importance of new inputs of heat and volatiles to pre-existing crystal-rich magma bodies that had stagnated before rejuvenation and eruption. Examples span the spectrum of volcanism and magma volumes, from small andesite–dacitic volcanoes to rhyolite caldera supervolcanoes, in both arc and intra-continental settings (Hervig & Dunbar 1992; Murphy et al. 2000; Bachmann et al. 2002; Wark et al. 2007). Episodes of rejuvenation are also important in the construction of plutons (e.g. Wiebe et al. 2004). Some erupted products of magmas rejuvenated prior to eruption display obvious disequilibrium textural features such as heterogeneous mafic enclaves that record basalt intrusions that provided new inputs of heat and volatiles. In other examples, evidence for magma rejuvenation may be subtle, as indicated by quartz resorption and regrowth, and the compositionally complex zoning of plagioclase and mafic phenocrysts. The investigation of magmatic rejuvenation processes can therefore provide insights into the mechanisms of pluton growth and leakage to generate silicic eruptions.

The Taupo Volcanic Zone (Fig. 1) of New Zealand has erupted small to moderate volumes of rhyolite magma (1–10 km³) at a millennial-scale frequency, punctuated by larger (>100 km³) caldera-forming events at c. 20–100 ka intervals (e.g. Nairn 2002; Smith et al. 2005). Here we investigate the thermal record leading up to one such caldera-forming event. The Earthquake Flat Pyroclastics (Nairn 2002) form a crystal-rich rhyolite pyroclastic density current deposit (volume c. 10 km³) erupted at c. 50 ka (Charlier et al. 2003; Shane & Sandiford 2003) from the SW margin of Okataina Volcanic Centre (Fig. 1) in the Taupo Volcanic Zone. The Earthquake Flat Pyroclastics eruption immediately followed the rather similar but much larger (c. 100 km³) caldera-forming eruption of the rhyolitic Rotoiti Pyroclastics from vents c. 20–25 km to the NE (Nairn & Kohn 1973; Nairn 2002). The Earthquake Flat and Rotoiti deposits have been the subject of earlier petrographic, chemical and isotopic studies (Davis 1985; Schmitz 1995; Burt et al. 1998; Charlier et al. 2003; Schmitz & Smith 2004; Shane et al. 2005a). Most of these studies have concluded that the Earthquake Flat Pyroclastics magma body was coexisting with, but separate from, the Rotoiti magma. Zircon ages from Earthquake Flat Pyroclastics deposits demonstrate a prolonged magma storage history, requiring periodic rejuvenation and final reactivation from a largely crystalline pluton (Charlier et al. 2003). Although the Rotoiti rhyolite eruption was immediately preceded by a small basaltic subplinian eruption (Matahi Scoria; Pullar & Nairn 1972), implying a trigger via mafic intrusion, there has been little previous evidence for any mafic input to the Earthquake Flat Pyroclastics eruption. Here we use crystal chemistry to describe the final crystallization and thermal history of the Earthquake Flat Pyroclastics magma prior to eruption, examine its relationship to the Rotoiti magmas, and discuss implications for the pre-caldera magma dynamics.

Deposits, samples and methods

The Earthquake Flat Pyroclastics eruption occurred from six vents defining a 5 km long NW–SE-trending lineament (Fig. 1) overlying the inferred Okataina Volcanic Centre outer ring fracture (Nairn 2002). The eruption produced c. 10 km³ of pumiceous pyroclastic flows and interbedded fall and surge deposits that form thick (up to 150 m) low-angle pyroclastic fans around the vent area. Deep sections expose up to 14 flow units, typically 0.5–7 m thick and containing pumiceous ash, lapilli and blocks to 50 cm in size, with a minor accessory lithic rhyolite content (Davis 1985; Nairn 2002). The intercalated fall beds extend beyond the pyroclastic flow fans, to form the distal ‘Rifle Range Ash’ tephra. Rifle Range Ash directly overlies the analogous distal fall deposit (‘Rotoehu Tephra’) of the Rotoiti Pyroclastics, with a sharp conformable
contact that lacks weathering or soil formation (Nairn & Kohn 1973). The contact is consistent with sequential deposition of the two tephras, separated by a time interval as short as hours to weeks. The Rotoiti Pyroclastics, including a voluminous non-welded ignimbrite (Fig. 1), the widespread Rotoehu Tephra fall deposits, and the preceding Matahi Scoria basalt, are thought to have been erupted from vents on the northern part of the Haroharo Linear Vent Zone (Fig. 1), since buried by intracaldera lavas (Nairn 2002).

The Earthquake Flat Pyroclastics deposit is non-welded and vitric, showing little evidence of post-emplacement alteration other than meteoric hydration. Pumice clasts and bulk ash samples were collected from five main sites representing different stratigraphic levels and azimuths from the vent area. No thick proximal or medial sections expose the complete Earthquake Flat Pyroclastics deposit sequence, so that the precise stratigraphic level for samples collected from near the middle of these sections is unknown.

The Earthquake Flat Pyroclastics are chemically and mineralogically distinct from most of the Rotoiti Pyroclastics (Davis 1985; Schmitz & Smith 2004; Shane et al. 2005a). However, late-stage Rotoiti ejecta (the Re3 beds; Shane et al. 2005a) include a mingled magma component that contains ferromagnesian minerals (including biotite) similar to those in the Earthquake Flat Pyroclastics deposits. Thus, minerals from the Rotoiti Re3 beds were re-examined for comparison with Earthquake Flat Pyroclastics data.

Sample locations, analytical methods and full datasets are available online at http://www.geolsoc.org.uk/SUP18298.

**Petrography**

All Earthquake Flat Pyroclastics pumice clasts are crystal-rich and contain large quartz and plagioclase phenocrysts (Fig. 2). On a clast scale (<10 cm), we found crystal contents to be variable (c. 25–45% crystals). In a detailed modal study, Davis...
(1985) reported a somewhat narrower range (25–35% crystal content) in his sample suite, comprising plagioclase (c. 16–23%), quartz (4–11%), biotite (1–3%), hornblende (1–2%), Fe–Ti oxides (<1.5%) and orthopyroxene (<0.5%). The accessory minerals apatite and zircon occur as micro-inclusions within biotite and hornblende. We found that c. 3% of crystals occur as aggregates or multi-phase glomerocrysts up to 8 mm in size, composed of the above phases. Burt et al. (1998) observed similar glomerocrysts but noted they were mostly composed of ferromagnesian phases. We did not examine lithic components in any detail. Burt et al. (1998) described very rare glass-bearing microdiorite clasts with a plagioclase- and amphibole-dominated mineralogy, and suggested they could represent quenched mafic magma.

**Whole-rock and glass chemistry**

Earthquake Flat Pyroclastics pumice clasts are low- to medium-silica rhyolites and display a moderate compositional range in whole-rock anhydrous major element chemistry (i.e. SiO₂ 69.6–74.8 wt%, K₂O 2.14–3.25 wt%; Fig. 3). On variation diagrams, Fe₂O₃, Al₂O₃, TiO₂, MgO, CaO, Sr and Zr display linear inverse trends with SiO₂, whereas K₂O (Fig. 3) displays a positive linear trend. Other elements such as Rb (Fig. 3) and Ba lack linear trends. Earthquake Flat Pyroclastics pumices have moderate negative Eu anomalies; Eu/Eu* = 0.64–0.87 (and one outlier of 1.02), and are enriched in light rare earth elements (LREE); Ce/YbN = 3.65–4.62 (Fig. 3). Ranges in high field strength element (HFSE) ratios are relatively narrow (e.g. Ta/Hf = 0.18–0.24). We found no evidence for a separate high-
K–low-Zr magma reported by Davis (1985). Our re-analysis of two of the four pumice clasts that Davis (1985) classified as high-K–low-Zr samples lie within the total compositional cluster representing all samples. We found no correlation between compositional variation and sample stratigraphic position.

Microprobe analyses of matrix glass within the pumices, and glass shards in bulk ash samples, reveal a compositionally uniform high-silica rhyolite melt with variation within that of analytical error (i.e. SiO$_2$ 77.29 ± 0.21 wt%; K$_2$O 4.51 ± 0.10 wt%; Fig. 3). Thus, the whole-rock compositional variation must be controlled by variation in crystal content.

Mineral textures and chemistry

We focused our investigation on the compositional variability of hornblende in Earthquake Flat Pyroclastics and Rotoiti Pyroclastics deposits, but discuss each crystal phase in the former in order of abundance. Crystal phases in Rotoiti deposits have been described by Schmitz & Smith (2004) and Shane et al. (2005a).

**Earthquake Flat Pyroclastics plagioclase and quartz**

Plagioclase crystals are commonly large (>5 mm), subhedral to anhedral, tabular laths. A wide range of textural features are displayed including oscillatory zoning and sieve textures (Fig. 2). Some crystals have cores with melt channels and embayments (Fig. 2e and f), whereas others display zones of fine pits on their outer margins (Fig. 2d). Randomly analysed crystal cores reveal a compositional range of An$_{21}$–50 (Fig. 4). Analytical traverses across large crystals reveal compositional variations of up to c. An$_{15}$ within crystals. There are no consistent trends or patterns revealed in the traverses. However, 20–50 µm wide zones of significantly higher An were encountered in some crystals (Fig. 5).

Quartz occurs as large anhedral crystals up to 6 mm in size, with some relict bi-pyramidal forms evident. The crystals are often deeply incised by melt channels and embayments (Fig. 2a–c), and melt inclusions are common but many are devitrified.

**Earthquake Flat Pyroclastics hornblende**

Hornblende occurs as euhedral–subhedral tabular crystals up to 5 mm in size. They display strong brown–green pleochroism. There is no evidence of resorption or post-crystallization interaction with the melt (Fig. 2h). Microinclusions of Fe–Ti oxides, apatite and glass are common. Hornblendes are generally calcic (Ca$_9$ >1.5 atoms per formula unit (a.p.f.u.)), have alkali contents (Na + K$_2$O of <0.5 a.p.f.u., and following Leake et al. (1997) classify as magnesio-hornblendes (Mg/(Mg + Fe) >0.5) (Fig.4). The total hornblende population displays moderate compositional variation in Al$_2$O$_3$ (5.23–8.01 wt%), FeO (15.87–18.5 wt%), MgO (10.74–13.12 wt%) and Na$_2$O (0.99–1.64 wt%). In contrast, CaO is relatively uniform (9.08–10.54 wt%).

Most of the Al variation occurs in the tetrahedral site (Al$^4$)
The amount of \( M_{1-3} \) Al is minor, mostly \(<0.2\) a.p.f.u. There are positive linear correlations between both \( T \) Al and \( A \) (Na + K), and between \( T \) Al and Ti (M2 site) (Fig. 6). These atomic substitutions are consistent with edenite (\( 1^\text{Si} + A = T \) Al + A (Na + K)) and Ti-Tschermak (\( 1^\text{Si} + M_{1-3} \) Mn = \( T \) Al + \( M_{1-3} \) Ti) exchange, respectively. Such atomic exchanges in hornblende are considered to be temperature controlled (Bachmann & Dungan 2002). There is no indication of pressure-sensitive atomic substitutions such as Al-Tschermak exchange (\( 1^\text{Si} + M_{1-3} \) Mg = \( T \) Al + \( M_{1-3} \) Al) (Fig. 6).

Rim to core analytical traverses (Fig. 7) at 10–20 μm spot spacing reveal complex cyclic zoning patterns within some crystals. The compositional variability within a single crystal is comparable with that of the entire crystal population examined. Overall, the traverses show rimward trends of increasing \( \text{Al}_2\text{O}_3 \),
TiO₂ and alkalis (Fig. 7). Smaller cycles with <100 μm wavelengths are commonly superimposed on these trends. There are positive correlations between FeO, Al₂O₃, Na₂O and K₂O. These elements correlate negatively with MgO and SiO₂. Other crystals show very little compositional variation (Fig. 7). In addition, a few display pronounced elemental spikes in Al₂O₃, TiO₂ and (Na₂O + K₂O) rather than rimward trends (Fig. 7c).

Hornblende in Rotoiti late-stage ejecta

Previous studies have recognized a bimodal population of hornblende in Rotoiti deposits (Schmitz & Smith 2004; Shane et al. 2005a). Small acicular high-MgO (c. 14.5–15.5 wt%) hornblende occurs as a rare phase throughout the entire eruptive sequence, and is joined by a second population of large stubby (up to 5 mm in size), low-MgO (c. 10.5–13 wt%) hornblends in mingled pumice in the uppermost fallout units (Re3 beds) (Fig. 4). In compositional traverses of the low-MgO hornblends we found a wide range of compositions within crystals including Al₂O₃ (4.25–10.22 wt%), FeO (15.27–18.23 wt%), MgO (9.81–13.39 wt%) and Na₂O (0.90–2.23 wt%). These ranges are similar to and encompass those of the Earthquake Flat Pyroclastics hornblends (Fig. 4), and show the same elemental correlations. Most of the Al variation occurs in the tetrahedral site (‴Al) (range c. 0.6 a.p.f.u.). As with Earthquake Flat Pyroclastics, atomic substitutions in Rotoiti Pyroclastics low-MgO hornblends are consistent with edenite and Ti-Tschermak exchange (Fig. 6). Some smaller (<300 μm wide) Rotoiti hornblende crystals show rimward increases in Al₂O₃, TiO₂ and Na₂O + K₂O (Fig. 8). The largest crystals (c. 600 μm wide) show complex zoning in these elements, including high-Al₂O₃ zones (<100 μm wide) separated by abrupt transitions to low-Al₂O₃ zones.

Fig. 6. Plots of the atomic composition (apfu, atoms per formula unit) of hornblende in Earthquake Flat Pyroclastics and Rotoiti deposits (low-MgO crystals). Positive linear relationships are consistent with atomic substitutions discussed in the text.

Biotite occurs as large (up to 5 mm in size) flakes and books with common microinclusions of apatite, zircon and Fe–Ti oxides. The crystals do not show evidence of optical zoning or resorption (Fig. 2g). The biotite crystals display little compositional variation (FeO 18.68–21.08 wt%; MgO 10.33–11.86 wt%), both within and between crystals (Fig. 4).

Earthquake Flat Pyroclastics biotite

Fe–Ti oxides occur as free crystals, generally euhedral and up to 150 μm in size, and as micro-inclusions within or attached to other phenocrysts. The octahedral phase is spinel with a very narrow compositional range (Xₐsp = 27 ± 1, n = 111) (Fig. 4). Some minor elements display a wider range (MnO 0.65–1.13 wt%; Al₂O₃ 1.22–1.90 wt%). The rhombohedral phase is ilmenite (Xₐilm = 90 ± 1, n = 37) (Fig. 4). Some compositional variation is evident (TiO₂ 46.55–49.10 wt%; Fe₂O₃ 7.67–12.04 wt%; MnO 1.12–2.10 wt%).

Orthopyroxene occurs as a rare phase in the form of acicular euhedral to subhedral crystals up to 1.5 mm in length. Reconnaissance spot analyses reveal a moderate compositional range (En₄₇–₅₄, average 49 ± 2). The orthopyroxene crystals commonly contain Fe–Ti oxide micro-inclusions.

Earthquake Flat Pyroclastics intensive parameters

Estimates of temperature (T) and oxygen fugacity (fO₂) were obtained using the algorithm of Ghiorso & Sack (1991) for Fe–Ti oxide pairs considered to be in equilibrium using Mn–Mg distribution criteria (Bacon & Hirschmann 1988). Fe–Ti oxide pairs attached to the same host crystal were used to ensure that oxide crystallization occurred within the same part of the magma chamber. Thirty-one oxide equilibrium pairs produced T–fO₂ estimates in the range 702–805 °C and NNO = 0.26 to +0.32 (where NNO is log units above or below the Ni–NiO buffer) (Fig. 9). T–fO₂ values vary randomly in the eruption sequence; there is no relationship to geographical or stratigraphic locations of the samples. Wide ranges (i.e. values of T = 705–778°C and fO₂ = NNO = 0.1 to +0.19) were obtained from single pumice lapillus (Fig. 9a).
Pre-eruption magma temperatures were also obtained from amphibole and plagioclase using the algorithm of Holland & Blundy (1994). The edenite–richterite algorithm was used because it is considered to be less influenced by pressure (Bachmann & Dungan 2002). The estimation assumes that the two phases are in equilibrium, which is difficult to assess because both phases display some degree of variability. For plagioclase, we used an average composition of Ab$_{69}$ ± 4 based on the narrow unimodal population (Fig. 4). Atomic substitutions in hornblende suggest that Al variation is thermally controlled. Thus, we selected low- and high-Al$_2$O$_3$ analyses that correspond to rim and core areas in two zoned hornblendes (crystal 38050, Al$_2$O$_3$ 5.55 and 6.70 wt%; crystal 1-2, Al$_2$O$_3$ 5.32 and 7.21 wt%) to estimate temperatures. A pressure of c. 250 MPa was assumed (see below). Crystal 38050 produced temperatures of 732 °C (low-Al) and 769 °C (high-Al) and crystal 1-2 produced temperatures of 722 °C (low-Al) and 770 °C (high-Al). These temperatures are in good agreement with the range of values from Fe–Ti oxide equilibrium. Bachmann & Dungan (2002) reported that the edenite–richterite algorithm is sensitive to changes in Ab. They found that a decrease of Ab$_5$ could result in a temperature increase of 20 °C. For Earthquake Flat Pyroclastics deposits, the exact plagioclase equilibrium composition(s) correlating with the low- and high-Al hornblende is uncertain. However, the narrow compositional mode in plagioclase analyses indicates that Ab$_{68}$–70 are the dominant compositions, and thus the resulting temperature estimates may not vary greatly (i.e. by <15 °C) from those calculated.

Equilibrium pressures can be estimated by plotting the glass (melt) composition on the Quartz–Albite–Orthoclase (−H$_2$O) diagram. 

![Fig. 7. Examples of analytical traverses of Earthquake Flat Pyroclastics hornblende crystals. (a) Crystal 1-2 and (b) crystal 38050 display rimward increases in Al$_2$O$_3$, TiO$_2$ and alkalis. (c) Crystal 38049b displays prominent Al-rich spikes surrounding an Al-poor core. (d) Crystal 38049 displays little compositional variability.](image-url)
ternary of Tuttle & Bowen (1958) following the method of Cashman & Blundy (2000). An absolute pressure at the time of crystallization can be estimated for magmas that are saturated with silica and water. Without volatile abundance data, it is not known whether Earthquake Flat Pyroclastics magma was water-saturated. However, Johannes & Holtz (1990) have shown that in water-undersaturated experiments the cotectics are not greatly displaced from those of water-saturated melts. The average Earthquake Flat Pyroclastics melt (glass) composition plots close to the 200 MPa cotectic (Fig. 10); we use this value for the Earthquake Flat Pyroclastics magma.

Discussion

Earthquake Flat Pyroclastics magma zoning

The analysis of pumice clasts from different geographical sectors and stratigraphic levels within the Earthquake Flat Pyroclastics deposits reveals no consistent compositional or mineralogical trends either in space or time. This suggests that any pre-eruption zoning of the magma body was largely disrupted before or during eruption. Whole-rock (magma) major element analyses show some variation whereas glass (melt) composition plots close to the 200 MPa cotectic (Fig. 10); we use this value for the Earthquake Flat Pyroclastics magma.

Thermal and crystallization history of Earthquake Flat Pyroclastics magma

Several features suggest the Earthquake Flat Pyroclastics magma had a complex thermal history involving late-stage cooling and crystallization followed by rejuvenation by input of heat and volatiles shortly before eruption.

1. Large quartz crystals display relict bi-pyramidal forms consistent with early phenocryst formation in a slowly cooling melt. However, they are deeply embayed and resorbed by remelting. Similarly, large plagioclase crystals display a range of internal and marginal resorption textures.

2. Glomerocrysts composed of all the main phenocryst phases are common, indicating that parts of the magma body had completely crystallized prior to eruption.

3. Hornblende and biotite are mostly euhedral and lack resorption textures, indicating they represent a separate and late stage of the crystallization history. Their growth continued until eruption.

4. Al and Ti variation in hornblendes is consistent with temperature-controlled atomic substitutions. Increasing abundance of these elements rimward in many crystals indicates their late growth in a regime of increasing temperature (Figs 6 and 7).

5. Plagioclase–hornblende geothermometry indicates a temperature increase of c. 50 °C as these crystals grew.

6. Fe–Ti oxide equilibrium pairs provide temperature estimates from 702 °C to 805 °C (Fig. 9), indicating that considerable temperature variation existed in the pre-eruption magma body. This variation was not accompanied by variation in magma composition or mineralogy. Crystal pairs within a single pumice clast (≤5 cm in size) can provide temperature estimates that vary by up to 70 °C, indicating crystals from different temperature regions were juxtaposed. As Fe–Ti oxides can re-equilibrate within days to months (Devine et al. 2003), the thermal variation they record here was produced shortly before eruption.
Plagioclase composition can be controlled by temperature, pressure and water content (e.g. Housh & Luhr 1991), in addition to bulk composition. Ca-rich spikes in some plagioclase analytical traverses (Fig. 5) could result from one or more occurrences of heat pulse, recharge by Ca-rich magma, or volatile loss or gain.

Charlier et al. (2003) reported a wide spectrum of U–Th single crystal zircon ages (c. 70 to >350 ka) with a peak at 105 ka, interpreted as earlier crystallization events.

Most of the characteristics described above for the Earthquake Flat Pyroclastics magma are remarkably similar to those documented for the Fish Canyon Tuff by Bachmann et al. (2002). Those workers concluded that the Fish Canyon Tuff was erupted from a voluminous crystal mush zone in the upper crust, after rejuvenation by mafic underplating. The Fish Canyon Tuff magma body lacked bulk compositional gradients, but the deposits display diverse textural and chemical complexities on a crystal scale, indicating that crystals of differing histories had been juxtaposed by convective stirring shortly before eruption. As pointed out by Bachmann et al. (2002), the mineralogical features displayed by the Fish Canyon Tuff are consistent with models of convective ‘self-mixing’ (stirring) described by Couch et al. (2001), and do not require the mechanical mixing of two separate magmas. In the convective self-stirring model, a silicic magma body is heated at its base; for example, by underplating with freshly injected mafic melt. This produces a relatively thin basal layer of hot silicic melt, which is unstable and buoyant, and rises as discontinuous plumes into the overlying cooler part of the magma, carrying crystals that may record the thermal history. Cooler pockets of crystal mush would descend into the hot boundary magma zone where remelting of some crystal phases would occur (Fig. 11).

The self-stirring model seems applicable to the Earthquake Flat Pyroclastics magma body (Fig. 11), where higher temperature Fe–Ti oxide equilibrium pairs (c. 750–800 °C) would have originated in the basal hot boundary layer, along with the reverse-zoned hornblende crystals with Al-rich rims (c. 770 °C). Resorption of quartz and plagioclase crystals would have occurred where overlying pockets of crystal mush descended into the hot basal layer. In addition to convective stirring, further juxtaposition of different parts of the magma body could have occurred during syneruptive disruption as the magma chamber was evacuated, and during magma ascent in the conduit (Fig. 11).

The apparent paradox inherent in the late-stage growth of Al-rich hornblende, and euhedral biotite, during heating of a highly evolved melt that had already undergone considerable quartz and plagioclase crystallization has been discussed by Bachmann et al. (2002). In the Earthquake Flat Pyroclastics magma body, mafic components may have been carried in fluids from the inferred underplating mafic magma, even though direct mafic–rhyolite magma mixing was minimal. Alternatively, resorption of crystals in a deeper (perhaps non-erupted) part of the silicic magma body produced a rhyolitic melt enriched in Ca, Fe and Mg from which late-stage ferromagnesian phases could grow (Fig. 11).

In the Bishop Tuff, some quartz crystals display evidence of resorption followed by regrowth at higher temperature (Wark et al. 2007). This was considered to be due to the influx of CO2 from a mafic intrusion lowering the activity of H2O and allowing quartz to grow at a higher temperature following thermally induced resorption. In contrast, quartz grains in the Fish Canyon Tuff exhibit resorption with little evidence of late high-temperature regrowth (Bachmann et al. 2002; Wark & Bachmann 2005).

Fig. 9. Estimate of temperature and fO2 based on Fe–Ti oxide equilibrium pairs in Earthquake Flat Pyroclastics deposits (this study) and Rotoiti Pyroclastics (Shane et al. 2005a). NNO, units above or below the Ni–NiO buffer.

Fig. 10. The normative composition of Earthquake Flat Pyroclastics (EFP) matrix glass projected following Cashman & Blundy (2000) onto a quartz (Qtz)–albite (Ab)–orthoclase (Or) ternary diagram. +, Eutectics from Tuttle & Bowen (1958) at stated pressures (in MPa).
This could be explained by input of H$_2$O-dominant fluids acting to depress the solidus. We note that textural and crystal zoning features in Earthquake Flat Pyroclastics are similar to those of Fish Canyon Tuff, and thus imply an Earthquake Flat Pyroclastics mafic intrusion containing fluids dominated by H$_2$O rather than CO$_2$. The contemporaneous Rotoiti magma was water-saturated as shown by the presence of cummingtonite (Shane et al. 2005a), indicating the availability of water at Okataina Volcanic Centre immediately before the Earthquake Flat Pyroclastics eruptions.

**Mafic intrusion and tectonic implications**

The only direct evidence for the involvement of a mafic magma with the Earthquake Flat Pyroclastics (and Rotoiti) eruptions comes from rare glass-bearing microdiorite lithic fragments found in both deposits, and interpreted as quenched mafic magma (Burt et al. 1998). However, the Rotoiti Pyroclastics directly overlie the basaltic sub-Plinian Matahi Scoria (<0.5 km$^3$), demonstrating the presence of mafic magma at Okataina Volcanic Centre immediately before the Rotoiti and Earthquake Flat Pyroclastics eruptions. Neither of these rhyolite eruption deposits contains hybrid or mafic ejecta that would demonstrate mechanical mixing of basaltic and silicic magmas, but the absence of mafic enclaves in the rhyolitic eruptive rocks is consistent with the convective self-stirring process inferred for the Earthquake Flat Pyroclastics eruption.

The Matahi Scoria records the rise of a basaltic dyke to the surface, locally unhindered by encounter with a less dense rhyolite magma body. The exact vent location for Matahi Scoria is unknown but is considered (Pullar & Nairn 1972) to be near the northern end of the Haroharo Linear Vent Zone (Fig. 1), and now buried within Haroharo caldera. Further to the SW the basaltic intrusion may have ponded beneath the main Rotoiti magma body and triggered it into eruption (Shane et al. 2005a). Thermal rejuvenation of the Earthquake Flat Pyroclastics magma also implies mafic underplating, and thus basaltic intrusion may have extended (as a dyke swarm?) c. 20–30 km NE along the Haroharo Linear Vent Zone and into the Earthquake Flat Pyroclastics vent area (Fig. 1). The NW–SE trend of the Earthquake Flat Pyroclastics vents is orthogonal to the NE–SW trend of the inferred dyke swarm, but is subparallel to the adjacent

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**Fig. 11.** Schematic model of Earthquake Flat Pyroclastics magma following the concept of convective self-mixing (stirring) of Couch et al. (2001). Step 1: mafic (black) underplating of the silicic magma body (grey) produces a hot basal boundary layer where extensive resorption of felsic crystals produces enriched silicic melt from which reverse-zoned hornblende crystals with high-Al rims grow. Overlying crystal mush descending into the boundary layer transports felsic phases that are partially resorbed. Plumes rising from the heated boundary layer mechanically mix the crystal mush, juxtaposing crystals with different thermal histories. Step 2: eruption entrainment causes chaotic mixing of the magma, disrupting the thermal gradients and melt plumes.
Haroararo caldera boundary (Fig. 1). Together, the thermal, temporal and tectonic relationships suggest that the Earthquake Flat Pyroclastics magma body was primed by mafic underplating related to a regional dyke intrusion event, and triggered into eruption by lithostatic readjustments including external ring faulting that accompanied collapse of Haroararo caldera.

**Relationships between Earthquake Flat and Rotoiti magmas**

The most voluminous of the multiple rhyolite magmas erupted during the Rotoiti episode (T1 magma, Shane et al. 2005a) is characterized by a ferromagnesian mineral assemblage dominated by cummingtonite. The Rotoiti T1 and Earthquake Flat Pyroclastics magmas are clearly distinguished by their different chemical compositions (Figs 3 and 4), mineralogies and intensive parameters (Fig. 9). However, mingled pumices in the uppermost beds of Rotoiti Pyroclastics contain a crystal sub-population similar to that of Earthquake Flat Pyroclastics (Fig. 4). This crystal sub-population includes large quartz grains, and plagioclase, hornblende, biotite and Fe–Ti oxides compositionally similar to Earthquake Flat Pyroclastics phases; with T–fO2 values that plot on a similar trend (Fig. 9). The crystal sub-population and its accompanying K2O-rich melt (Fig. 3) define the Rotoiti T2 magma of Shane et al. (2005a). The lack of universal re-equilibrium of the Rotoiti T1 and T2 Fe–Ti oxides (Fig. 9) in the mingled pumices indicates that contact of the two magmas was transitory, and probably occurred in the conduit.

The similarity between crystal assemblages in Earthquake Flat Pyroclastics and late-stage Rotoiti Pyroclastics was first described by Schmitz (1995), who suggested that the Rotoiti eruption may have tapped the Earthquake Flat Pyroclastics magma body. This concept was subsequently dismissed on the basis of differences in whole-rock chemistry (Burt et al. 1998), and zircon single crystal age spectra (Charlier et al. 2003). However, this does not require the existence of a laterally continuous melt body across the Okataina Volcanic Centre at the time of the Rotoiti eruption. The Rotoiti deposits also contain glass-bearing granitoid lithic fragments that display differing age spectra, mineralogy and isotopic ratios from Earthquake Flat Pyroclastics and Rotoiti (hybrid T1 + T2) magma (Burt et al. 1998; Charlier et al. 2003).

Thus, we concur with Charlier et al. (2003) that multiple semi-molten bodies resided in the mid- to upper crust, and were disrupted and entrained in the Rotoiti caldera-forming event (Fig. 12). Earthquake Flat Pyroclastics-like melts may have occurred as isolated ponds residing in a highly crystallized mush zone. The similarities between Earthquake Flat Pyroclastics and Rotoiti T2 crystal populations and their compositions suggest that this mush zone may have been the crystallized residuum of a largely homogeneous magma body that had originally extended across the Okataina Volcanic Centre (Fig. 12).

Although we lack at present a comprehensive dataset of zoning in Rotoiti crystals, our hornblende data are consistent with heating rejuvenation of Rotoiti T2 magma, based on Al variation consistent with temperature-controlled atomic substitutions (Fig. 6). Analytical traverses show rimward increases in Al2O3, TiO2 and Na2O + K2O in some crystals, implying growth with increasing temperature, similar to that in Earthquake Flat Pyroclastics crystals. In addition, the largest Rotoiti T2 hornblende crystals show even greater and more complex variations (Fig. 8) revealing rapid changes in temperature, consistent with magma heating events.

**Implications for Okataina Volcanic Centre**

A boundary between lower-velocity (metasediments and silicic igneous rocks) and underlying high-velocity rocks (mafic cumulates and intrusions) occurs under the Taupo Volcanic Zone at c.

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**Fig. 12.** Conceptual diagram of magma zones beneath Okataina Volcanic Centre immediately before the Earthquake Flat Pyroclastics and Rotoiti eruptions, and caldera formation. Mid-crustal plutons represent rhyolite plumes that ponded and largely crystallized at depth, with periodic rejuvenation by new basaltic or rhyolite intrusion. This was the source region for melts represented by EFP, Rotoiti T2 ejecta and glassy granitoid lithics. The voluminous Rotoiti T1 melt was rapidly extracted from the deep crust and ponded at mid-crustal depth for a short time before eruption. Widespread mafic underplating provided a thermal and volatile input to drive the eruptions. Horizontal and vertical scales are equal.
15 km (Harrison & White 2004). Thus, the production and aggregation of silicic melts is likely to occur at shallower depths (e.g. Charlier et al. 2005). Partial melts may exist at present below c. 10 km, as indicated by magnetotelluric data (Ogawa et al. 1999). New silicic melts are thought to form as a result of mafic intrusion-induced crustal melting, and associated fractionation and assimilation processes (Graham et al. 1995; Charlier et al. 2005). Melts extracted from these depths would ascend until reaching neutral buoyancy (Fig. 12) (or erupt if tectonic conditions allowed direct passage to the surface). The Earthquake Flat Pyroclastics crystalization pressures of c. 200 MPa and temperatures extending down to <720 °C, point to a mid- or upper crustal environment (<8 km) for magma ponding prior to eruption. Many of the Earthquake Flat Pyroclastics zircons have ages >100 ka (Charlier et al. 2003), and thus represent relicts from previous magmatic cooling events. They provide evidence for a long-lived pluton that was periodically thermally rejuvenated and incrementally augmented by new melts, preventing its complete crystallization. The near-identical mineralogy and associated crystallization temperature and pressure (Figs 9 and 10) in Earthquake Flat Pyroclastics and Rotoiti T2 magmas suggest that this long-lived pluton may have been areally extensive, underlying much of the Okataina Volcanic Centre (Figs 1 and 12). Evidence for the existence of such plutons was first recognized from granitoid lithic fragments by Ewart & Cole (1967).

There is little evidence for surface volcanism at Okataina Volcanic Centre for a prolonged period of uncertain duration prior to the Rotoiti episode (Nairn 2002). The Rotoiti Pyroclastics overlie a well-developed regional paleosol. Distal tephra records show a pronounced increase in rhyolite fall events from Okataina Volcanic Centre after the Rotoiti eruption, and very few for the preceding c. 100 ka (Shane & Hoverd 2002; Shane et al. 2006). During this time no large pyroclastic eruptions occurred from Okataina Volcanic Centre; eruptive activity seems to have been restricted to extrusion of minor rhyolite lavas now preserved at only a few sites around the margins of Haroharo caldera (Nairn 2002). This pre-Rotoiti quiet period coincides with peak periods of zircon crystallization in the Earthquake Flat and Rotoiti magmas (and the associated glassy granitoids) (Charlier et al. 2003), and represents the period when these magmas were assembling in the mid-crust. Interaction with parts of the semi-continuous mush zone would provide a source for relict crystals and could explain the variety of crystal populations and melt types erupted in the many post-Rotoiti eruption episodes at Okataina Volcanic Centre (e.g. Shane et al. 2005b; Smith et al. 2005).

Evacuation of the large volume of Rotoiti magma and formation of Haroharo caldera significantly changed the extrusive and intrusive regime at Okataina Volcanic Centre. Post-caldera rhyolite activity (c. 50–35 ka) was more frequent, less voluminous and involved hotter lower-Si magmas (Shane et al. 2005b). It is likely that caldera formation enhanced magma transport from greater depths by providing vertical conduits, and by depleting the crystal mush zone that had previously hindered magma ascent through mid-crustal depths.

Conclusions

The Earthquake Flat Pyroclastics magma was a crystal-rich body residing at mid-crustal depths (c. 8 km) before reactivation by thermal and volatile inputs from mafic underplating that involved little or no direct mafic–silicic magma mixing. Compositional and textural complexities on a lapilli scale demonstrate a long history of periodic crystallization followed by late-stage remelting. Earlier formed felsic phenocrysts were remelted, and euhedral ferromagnesian phases grew in a regime of increasing temperature. These characteristics are similar to those reported for the Fish Canyon Tuff (Bachmann et al. 2002). They are best explained by convective self-stirring (Couch et al. 2001) that produced the mixing of crystals with diverse thermal histories. The late-stage growth of reverse-zoned ferromagnesian crystals during heating of an already highly evolved and crystallized magma required new inputs of water and Ca, Fe and Mg components. These inputs could have come directly from the inferred underplating mafic magma, and/or from extensive crystal resorption in the heated basal silicic magma to provide a rhyolite melt that percolated into the overlying crystal mush.

Other similar magma pockets occurred beneath Okataina Volcanic Centre prior to caldera formation at c. 50 ka. Mingled magmas and granitoid inclusions in Rotoiti ejecta provide evidence for the existence of a widespread mid-crustal zone of semi-continuous melts and crystal mush at this time. This zone had experienced a complex thermal history of cooling and reheating, as indicated by single-crystal zircon age spectra spanning >100 ka (Charlier et al. 2003), representing periodic mafic intrusion and amalgamation of new silicic melts that failed to reach the surface. This mid-crustal, partly crystalline ‘proto-pluton’ developed during a quiet eruptive period at Okataina Volcanic Centre lasting up to 100 ka before the Rotoiti eruption. Rejuvenation of the low-temperature crystal-rich magma bodies required a major thermal and volatile influx from mafic intrusion that rapidly led to the caldera-forming Rotoiti eruption at c. 50 ka.

Relict, zoned and resorbed crystals in the Earthquake Flat Pyroclastics deposits reveal a complex history of temperature fluctuations that many other plutons and pre-eruption magma bodies must also experience. Such crystal-rich bodies (e.g. Vinalhaven Granite, Wiebe et al. 2004; Fish Canyon, Bachmann et al. 2002) were probably never completely molten or completely crystalline. Instead, they represent a zone that was intermittently recharged by mass, volatiles and heat throughout its history. The Earthquake Flat Pyroclastics magma was erupted only when allowed by the particularly favourable tectonic conditions that were induced by adjacent caldera collapse.

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