

**Geochemical Evolution at
White Island, New Zealand**

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(ABSTRACT)

White Island, New Zealand, is an active andesitic volcano that is located near the southern end of the Tonga-Kermadec Volcanic Arc at the convergent plate boundary where the Pacific Plate is being subducted beneath the Indian-Australian Plate. The plate tectonic setting, volcanic features and the petrology of White Island are thought to be characteristic of the environment associated with formation of porphyry copper deposits. White Island has only been active for about 10 Ka and, as such, is thought to be an ideal location to study early magmatic processes associated with formation of porphyry copper deposits. In this study, the geochemistry of the silicate melt at White Island has been characterized through detailed studies of silicate melt inclusions, phenocrysts, and matrix glass contained in recent ejecta (1977-1991). Most melt inclusions contained only glass, however, daughter minerals present in multiphase melt inclusions in the 1991 sample indicate a different P-T history compared to the other samples.

Samples studied are vesicular porphyritic andesitic dacites containing phenocrysts of plagioclase, orthopyroxene, and clinopyroxene. A glassy matrix containing crystallites surrounds the phenocrysts. Both mineral and silicate melt inclusions occur in all three phenocryst phases. Inclusions of plagioclase occur in pyroxenes and inclusions of orthopyroxene and clinopyroxene occur in plagioclase. Compositions of minerals are independent of mode of occurrence - that is, plagioclase (and orthopyroxene and clinopyroxene) compositions are the same regardless of whether they occur as phenocrysts or as inclusions in another mineral. Moreover, compositions of mineral inclusions and phenocrysts show no systematic variation within individual samples or in samples representing different eruptive events, indicating that the magma chamber is chemically homogenous over the time-space scale being sampled.

Various major, trace element and volatile compositional features of economic and non-economic (or barren) porphyry copper systems were compared to the White Island data. The $Al_2O_3/(Na_2O+K_2O+CaO)$ ratio observed in economic porphyry copper deposits is always greater than or equal to 1.3, and glass in one phase melt inclusions, as well as glass in unhomogenized (1991) inclusions from White Island equal or exceed this value. The glass in the unhomogenized 1991 melt inclusions is corundum normative, with $Si/(Si+Ca+Mg+Fe_t) > 0.91$, and $K/(K+Ca+Mg+Fe_t) > 0.36$, all of which are characteristic of productive systems. Melt inclusions from White Island also show a positive Eu anomaly similar to that found in productive porphyry deposits, whereas non-productive systems show a negative Eu anomaly.

Copper concentrations (170-230 ppm) in melt inclusions from White Island are sufficiently high to generate an economic porphyry copper deposit based on theoretical models. High Cl/H₂O ratios (0.15) in melt inclusions furthermore indicate that copper will be efficiently partitioned from the melt into the magmatic aqueous phase. The inferred pressure in the magma chamber at depth (1 kbar) is ideal for extracting copper from the melt, and mineral phases (pyrrhotite, biotite or amphibole) which could scavenge copper before it could be partitioned into the magmatic vapor phase are absent. Concentrations of S in the melt are also low, which would prevent pyrrhotite from crystallizing.

The tectonic setting and geochemical characteristics of the magma body at White Island are similar to features observed in economic porphyry systems elsewhere. These data suggest that development of economic porphyry copper mineralization at White Island is likely.

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Introduction

Porphyry copper deposits are magmatic-hydrothermal ore deposits that form at convergent plate boundaries where magmas generated from a subducting slab migrate upwards to produce shallow silicic plutons (Sawkins, 1984). It is thought that most, if not all, of the magmatic systems associated with formation of porphyry copper mineralization were continuously or intermittently open to the surface through an overlying stratovolcano or other surface manifestation of the deeper magmatic-hydrothermal system. White Island, located off the North Island of New Zealand (Figure 1), is an active andesitic-dacitic volcano that occurs at a convergent plate boundary and thus represents an appropriate environment for formation of porphyry copper mineralization. Copper is currently being released into the atmosphere at White Island at an estimated rate of 300 kg/day during continuous degassing of the volcano (Rose et al., 1986; Tedesco and Toutain, 1991; Le Cloarec et al., 1992).

The presence of an active hydrothermal system at White Island is indicated by surface features including high temperature fumaroles and acid springs (Giggenbach, 1987; Giggenbach and Sheppard, 1989). Furthermore, Hedenquist et al. (1993) and Hedenquist and Lowenstern (1994) noted that the near-surface geochemical environment at White Island is similar to that associated with the formation of high-sulfidation Cu - Au mineralization elsewhere. More recently, Arribas et al. (1995) documented a clear genetic link between near-surface, high-sulfidation Cu-Au mineralization and deeper porphyry-type mineralization in the Lapanto-Far Southeast mineralized system in the Philippines. Based on these observations, it is logical to suggest that White Island might represent a modern ore-forming system in which shallow high-sulfidation Cu-Au mineralization overlies deeper porphyry copper-type mineralization.

Although there have been numerous geochemical and fluid inclusion studies of porphyry copper deposits, conditions during the early magmatic stage have been difficult to characterize because magmatic assemblages are commonly overprinted by later magmatic and hydrothermal events (Beane and Titley, 1981; Beane, 1982; Beane and Bodnar, 1995). White Island, however, is still in its infancy relative to the productive stage for porphyry copper mineralization and thus offers a unique opportunity to document the early history of a potential porphyry copper-forming magmatic system. In this study, phenocrysts, silicate melt inclusions, and matrix glass contained in ejecta from White Island were analyzed. Major, trace element, and volatile concentrations were determined to characterize the early magmatic system associated with a porphyry copper type deposit. Melt inclusions within ejecta are especially valuable for this purpose because they provide a sample of melt that was trapped in the magma chamber at some depth beneath White Island. As such, the melt inclusions record the volatile and metal concentrations of the silicic melt at depth, at a time before the major episodes of copper mineralization occurred.

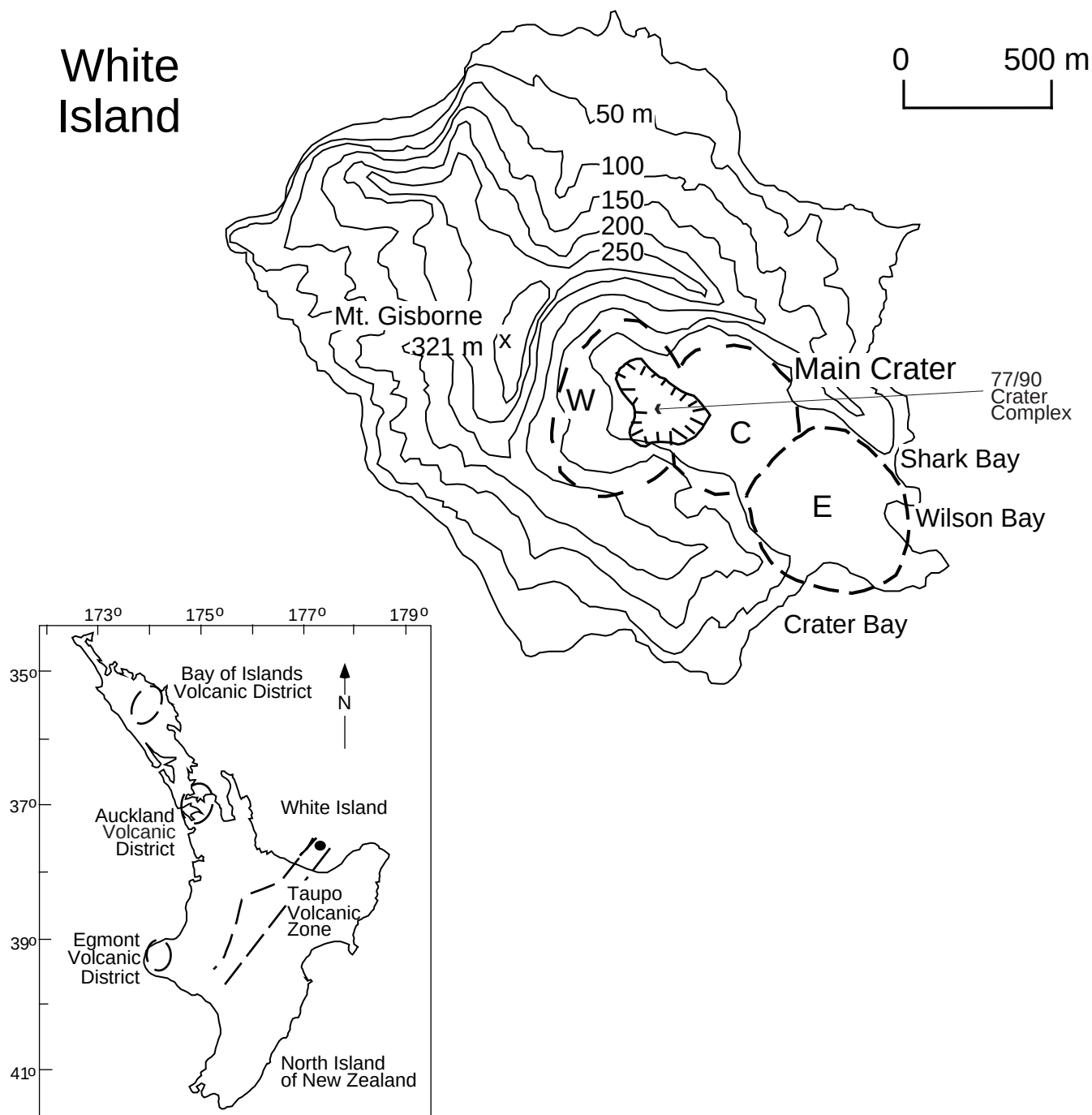


Figure 1. Location of White Island and topographical features. "W", "C", and "E" correspond to the western, central, and eastern subcraters respectively.

Geologic Setting

The North Island of New Zealand is located above an active plate boundary where the Pacific plate is being subducted beneath the eastern margin of the Australian plate (Isacks et al., 1968). This produces an active zone of intermediate to deep earthquakes and associated volcanism (Hamilton and Gale, 1968; Dickinson and Hatherton, 1967). The North Island has four compositionally distinct zones of volcanic activity, which are; the Bay of Islands, Auckland, Egmont and the Taupo Volcanic Zone (TVZ). The TVZ is 200 - 270 km west of the White Island Trench and extends 250 km from the central North Island north-east to White Island (Figure 1). Volcanoes in the TVZ are rhyolitic to basaltic in composition; White Island is andesitic-dacitic in composition (Cole and Nairn, 1975).

White Island is the summit of a large submarine volcanic massif that is 16 km by 18 km at its base, which rests on the sea floor at 300 to 400 m water depth. The volcano is a 700 m high composite volcano consisting of two overlapping cones, of which the western part is older and the central and eastern parts are younger (Black, 1970). The island reaches approximately 320 m above sea level and extends 2.4 km in the east-west direction and 2 km in the north-south direction. Erosion on wave cut cliffs and gullies on the outer part of the cone indicate that long periods of quiescence interrupted cone building episodes at White Island (Cole and Nairn, 1975).

One of the most notable characteristics of White Island is the breached main crater that collapsed in 1914 on the southeast side. The collapse occurred along a fault in the southwestern and western rim of the crater (Cole and Nairn, 1975). The main crater is 1.25 km long and 0.5 km wide and consists of three subcraters: eastern, central and western (Figure 1). Recent volcanic activity has occurred in the western subcrater and in the western part of the central subcrater (Houghton and Nairn, 1991).

Recent Volcanic Activity

Volcanic activity at White Island was first recorded by Europeans exploiting the area for sulfur in 1826. The historic activity, recorded as continuous fumarolic and solfataric emissions with brief episodes of tephra eruptions (Cole and Nairn, 1975), is similar to recent eruption patterns with crater-forming eruptions occurring in 1933, 1947, 1965-1966, 1968, 1971, 1976-1982, and 1986-1992 (Houghton and Nairn, 1991; Wood and Browne, 1996). Estimates from trace metal enrichment of marine sediments suggest that the volcano and its associated hydrothermal system have been active for the past 10,000 years. (Giggenbach and Glasby, 1977).

In mid-1973 a large (approximately 10^6 m^3) body of basaltic andesite magma began to rise to a shallow emplacement depth (0.5 km) at White Island and continued to rise until eruptive

activity started in 1976 (Clark and Cole, 1989). This magma and its associated hydrothermal system led to intense volcanic activity that continued over the next several years, consisting of alternating strombolian and phreatomagmatic eruptions. The volcano continuously erupted for about 16 years, allowing effective release of magmatic gases. Exsolved gases interacted with the surrounding hydrothermal system, acidifying the hydrothermal fluids. The acidified fluids saturated the crater floors and conduit system, weakening substructures and making them susceptible to alteration and collapse during earthquake activity (Houghton and Nairn, 1989a; 1991). The condition of the crater floors and conduit system, in turn, influenced the eruptive style at White Island. For example, continuous phreatomagmatic events erupting mainly ash occurred when conduit walls were stable. Discrete explosions, producing juvenile block aprons, occurred when conduit walls were weakened and/or clogged (Houghton and Nairn, 1989a; 1991).

A second sequence of eruptive activity at White Island began in February, 1986, with a discrete phreatomagmatic eruption. Volcanic activity during this eruption period consisted of continuous gas emissions, interrupted by frequent alternating strombolian and phreatomagmatic type eruptions. This activity continued until May 1992 (Wood and Browne, 1996).

Representative samples of ejecta from seven eruptions that occurred between 1977 and 1992 were used in this study. The samples were collected by Dr. C. Peter Wood of the Institute of Geological and Nuclear Sciences, Wairakei, New Zealand. After preliminary examination of all samples, those from the 1977, 1988, 1989, and 1991 eruptions were chosen for detailed study owing to their abundance of silicate melt inclusions.

Analytical Techniques

Samples were examined both in hand sample and in doubly polished thin sections using transmitted and reflected light microscopy. Plagioclase phenocrysts were etched with fluoboric acid and examined using differential interference microscopy (Anderson, 1983) to observe chemical zoning that might not be obvious during usual petrographic observations. Phenocrysts, silicate melt and mineral inclusions in phenocrysts, and matrix glass were analyzed for major elements by electron microprobe. Melt inclusions and phenocrysts contained in the 1977 sample were analyzed for copper content by electron microprobe. Melt inclusions and matrix glasses from the 1988 and 1989 samples were further analyzed for trace element and volatile content by ion microprobe. Multiphase silicate melt inclusions hosted in orthopyroxene from the 1991 sample were selected and doubly polished for homogenization. These homogenized inclusions were then analyzed for major element content by electron microprobe.

Major element and copper concentrations were determined using a Cameca SX50 electron microprobe, equipped with both wave and energy dispersive spectrometers (WDS and EDS,

respectively) at Virginia Tech. Quantitative analyses were conducted using the WDS. Back scattered electron imaging was used to determine whether an inclusion was silicate melt or mineral, as well as to determine if the area for analysis in a matrix glass was crystallite free. Natural and synthetic silicate and oxide standards were used as appropriate, and data were corrected using PAP methodology according to Pouchou and Pichoir (1985). Analyses were performed at 15 kV, and the beam current was 10 nA with a 5 μm beam size.

Ion microprobe analyses were performed on a Cameca IMS-6F ion microprobe equipped with both oxygen and cesium guns at the Department of Terrestrial Magnetism at the Carnegie Institution of Washington. Trace elements were analyzed *in situ* using a 12.7 kV primary beam of O^- ions with a current of 0.5-2 nA focused to a diameter of 10-20 μm . Positively charged secondary ions were analyzed at a nominal accelerating voltage of +10 kV. The secondary ion beam was energy-filtered using an energy offset of -70 eV and an energy window of $\pm 25\text{eV}$. Secondary ions were counted by an ETP electron multiplier feeding into an ECL counting system with a deadtime of 13 ns. Secondary ion counts were referenced to counts for ^{30}Si (e.g. $^{90}\text{Zr}/^{30}\text{Si}$, $^{93}\text{Nb}/^{30}\text{Si}$) and absolute abundances of trace elements were calculated from calibration curves for silicates. The scatter of standards about the calibration curves was generally less than 10%, similar to the reproducibility of individual analyses on homogeneous standards. Thus, analytical uncertainty on individual analyses is typically $\pm 10\%$ except where low numbers of ions indicate a larger standard deviation.

Volatile elements (H, C, F, S, and Cl) were analyzed *in situ* using a 10 kV primary beam of Cs^+ ions with a current of 3-8 nA focused to a diameter of 20-30 μm . Negatively charged secondary ions were analyzed at a nominal accelerating voltage of +5 kV. The ion probe was tuned to a mass resolving power of 2200, sufficient to separate interferences of ^{18}OH on ^{19}F and $^{16}\text{O}_2$ on ^{32}S . No energy filtering was used and the energy slit was kept open wide ($\pm 125\text{ eV}$). A small-field aperture was inserted into the secondary ion beam path in order to accept only those ions coming from the central 8 μm of the sputtered crater. This has the effect of filtering out ions from the edge of the crater and the sample surface, resulting in a very low detection limit for H_2O (<30 ppm). Secondary ions (^1H , ^{12}C , ^{19}F , ^{30}Si , ^{32}S , and ^{35}Cl) were counted by an ETP electron multiplier feeding into an ECL counting system with a deadtime of 13 ns. Secondary ion counts were referenced to counts for ^{30}Si (e.g. $^1\text{H}/^{30}\text{Si}$, $^{12}\text{C}/^{30}\text{Si}$). Analytical uncertainty on individual analyses is typically $\pm 10\%$ except where low numbers of ions indicate a larger standard deviation.

Homogenization of multiphase silicate melt inclusions was performed on a Linkam TS 1500 stage (linked to a TMS 92 programmer) mounted on an Olympus petrographic microscope at Virginia Tech. All experiments were conducted in flowing nitrogen to minimize oxidation of the sample at high temperature. Samples were heated to 900°C at a rate of 30°C/minute, the rate was then lowered to 3°C/minute until homogenization at 1209°C. After homogenization, samples were

cooled to 300°C at 200°C/minute, which is the fastest cooling rate possible with this stage. This was done in an attempt to produce homogenous glass which could be analyzed by electron microprobe to determine the bulk composition of the melt.

Results

Petrography

Samples are vesicular porphyritic andesites, which are representative of juvenile ejecta during eruptions. Hand samples range in color from light to dark gray with some alteration evident. Phenocrysts of plagioclase, clinopyroxene, and orthopyroxene, and matrix glass are visible in hand samples. In thin section, phenocrysts are euhedral to anhedral and range in size from 0.5 - 3 μm (Figure 2). The order of abundance of phenocrysts is orthopyroxene > plagioclase > clinopyroxene. Minor phases include Ti-magnetite and acicular apatite. All phenocrysts appear homogeneous in cross-polarized transmitted light, however, plagioclase phenocrysts exhibit chemical zoning (Figure 3) when viewed with differential interference contrast microscopy after etching in fluoboric acid (Anderson, 1983). Phenocrysts comprise from 50 to 70% by volume of most samples. Phenocrysts are surrounded by matrix glass that contains crystallites of pyroxene, plagioclase, and Ti-magnetite.

Phenocrysts contain both mineral and silicate melt inclusions, with a notable absence of fluid inclusions containing liquid and/or vapor water, CO_2 or other volatile phase. Silicate melt inclusions generally range in size from 5 to 50 μm , with the majority ranging between 10 and 25 μm . Shapes of melt inclusions range from spherical to negative crystal shape. The melt inclusions were subdivided into four sub-types based on the phase assemblage at room temperature. Type I inclusions contain only glass; type II inclusions contain glass plus a vapor bubble; type III inclusions contain glass plus one or more solids; type IV inclusions contain glass, a vapor bubble, and one or more solids. All four types of inclusions have been observed along growth zones in phenocrysts (Figure 4) and as isolated, randomly distributed occurrences throughout crystals. The inclusion assemblages in the 1977, 1988, and 1989 samples appear to be similar, whereas the assemblage in the 1991 sample is noticeably different. In the 1977-89 group of samples, type I all-glass inclusions and type II glass plus vapor inclusions occur in all three phenocryst minerals (plagioclase, ortho- and clinopyroxene). The type I inclusions are very small (1-5 μm) and abundant in some portions of plagioclase phenocrysts. The vapor bubble in the type II inclusions shows consistent phase behavior in all inclusions and occupies about 10 volume % of the inclusion. Type III melt inclusions containing glass and a plagioclase crystal were observed in

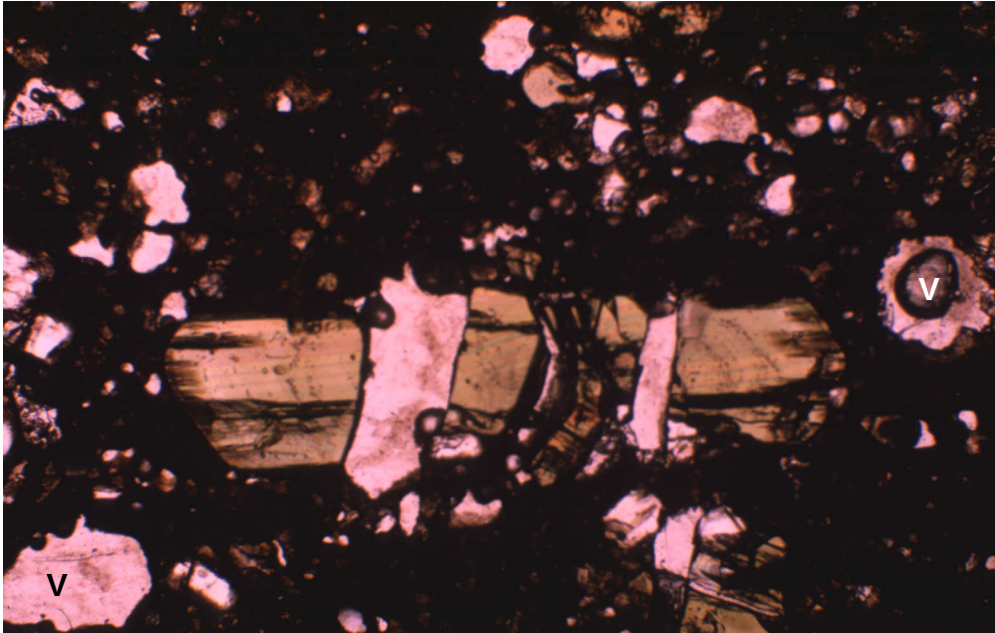


Figure 2. Photomicrograph of an orthopyroxene phenocryst that is cut by plagioclase. Other pieces of anhedral phenocrysts are visible throughout the photo. Dark brown material is matrix glass. Large vesicles are present in the lower left corner and on the right edge of the photo (marked by "V"). Field of view is 5 mm.

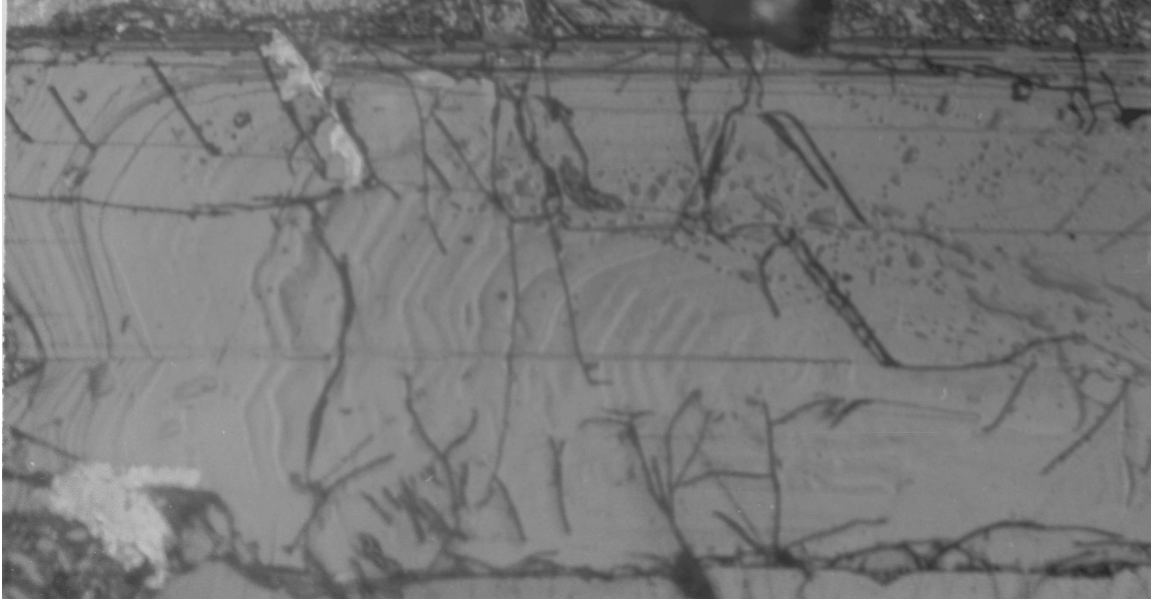


Figure 3. Photomicrograph of plagioclase phenocryst viewed with differential interference contrast after etching in fluoboric acid. Chemical zoning can be seen throughout the phenocryst as dark and light bands. Melt inclusions occur along those zones. Field of view is 1 mm.

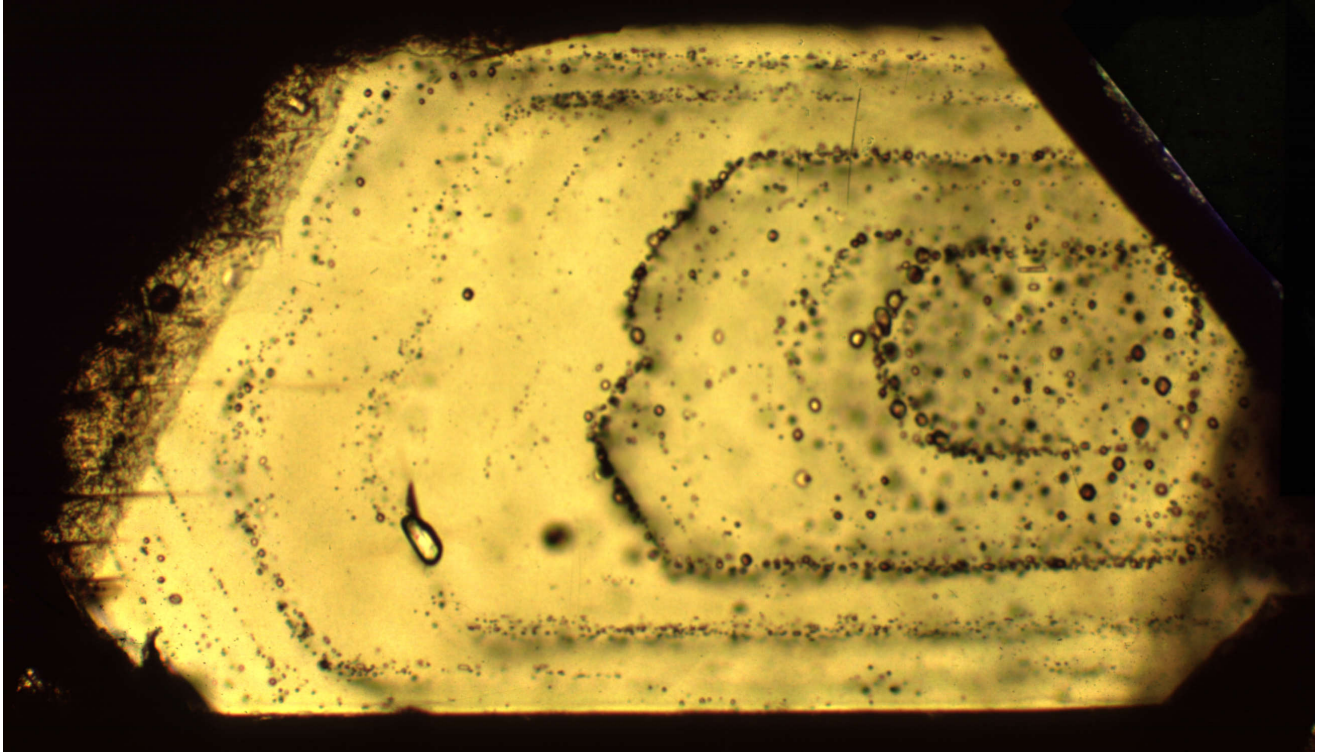


Figure 4. Photomicrograph of orthopyroxene phenocryst. Bands of primary inclusions can be seen in the crystal, trapped along a growing crystal face. Both melt inclusions and plagioclase inclusions occur within these bands. Field of view is 2 mm.

ortho- and clinopyroxenes in the 1977-89 group of samples, and the glass/crystal ratio was highly variable suggesting that the plagioclase crystals represent trapped solids.

Phenocrysts from the 1991 eruption contain almost exclusively type IV melt inclusions. Among the crystals identified in these inclusions are plagioclase, pyroxene, and Ti-magnetite. Unlike the type IV inclusions in the 1977-89 group of samples, the type IV inclusions in the 1991 samples showed uniform phase ratios within a group of presumably contemporaneous inclusions, suggesting that the solids in the 1991 samples are daughter minerals that precipitated from the melt during cooling. This interpretation is supported by the fact that the solids dissolved when the inclusions were heated. When the homogenized inclusions were subsequently quenched, they were similar to the all-glass type I inclusions seen in the 1977-89 samples (Figure 5).

Mineral inclusions are common in phenocrysts from all eruptions. The mineral inclusions are typically larger than melt inclusions, ranging in size from 30 to 150 μm , and in cross section they appear rounded. Inclusions of plagioclase occur in pyroxenes, and both ortho- and clinopyroxene inclusions occur in plagioclase. Silicate melt and mineral inclusions commonly occur within the same phenocryst, as well as in the same growth zone (Figure 4).

Major element chemistry

Electron microprobe data described below includes some preliminary data that were previously collected by Dr. Stuart Simmons of The Geothermal Institute, University of Auckland, from samples from the 1977, 1986, 1988 and 1991 eruptions. These analyses are indicated in Appendix A, and the data have been incorporated into the summaries given below.

Pyroxenes Phenocrysts of orthopyroxene and clinopyroxene plot in the enstatite and augite fields, respectively (Figure 6a). Analyses from all samples yield a narrow range of compositions: En_{69-72} , Fs_{23-26} , Wo_{3-5} , with $\text{mg\#} [100\text{Mg}/(\text{Mg}+\text{Fe}_\text{t})] = 72-76$ and En_{45-46} , Fs_{14-16} , Wo_{38-40} , with $\text{mg\#} = 74-76$. Pyroxene inclusions in plagioclase have compositions that are similar to compositions of pyroxene phenocrysts: En_{72-73} , Fs_{23-24} , Wo_4 , with $\text{mg\#} = 72-73$ and En_{47-49} , Fs_{13-15} , Wo_{37-39} , with $\text{mg\#} = 76-79$ (Figure 6a). Average compositions of phenocrysts and mineral inclusions are listed in Table 1.

Plagioclase Plagioclase phenocrysts range in composition from An_{62} to An_{68} , and plot in the labradorite field (Figure 6b). Although phenocrysts exhibit chemical zoning in Figure 3, the zones are too narrow to be reflected in any single electron microprobe analysis. The compositions of plagioclase inclusions in orthopyroxene (An_{62} to An_{74}) and clinopyroxene (An_{62} to An_{68}) include the range of compositions for plagioclase phenocrysts, but extend to higher anorthite contents, into

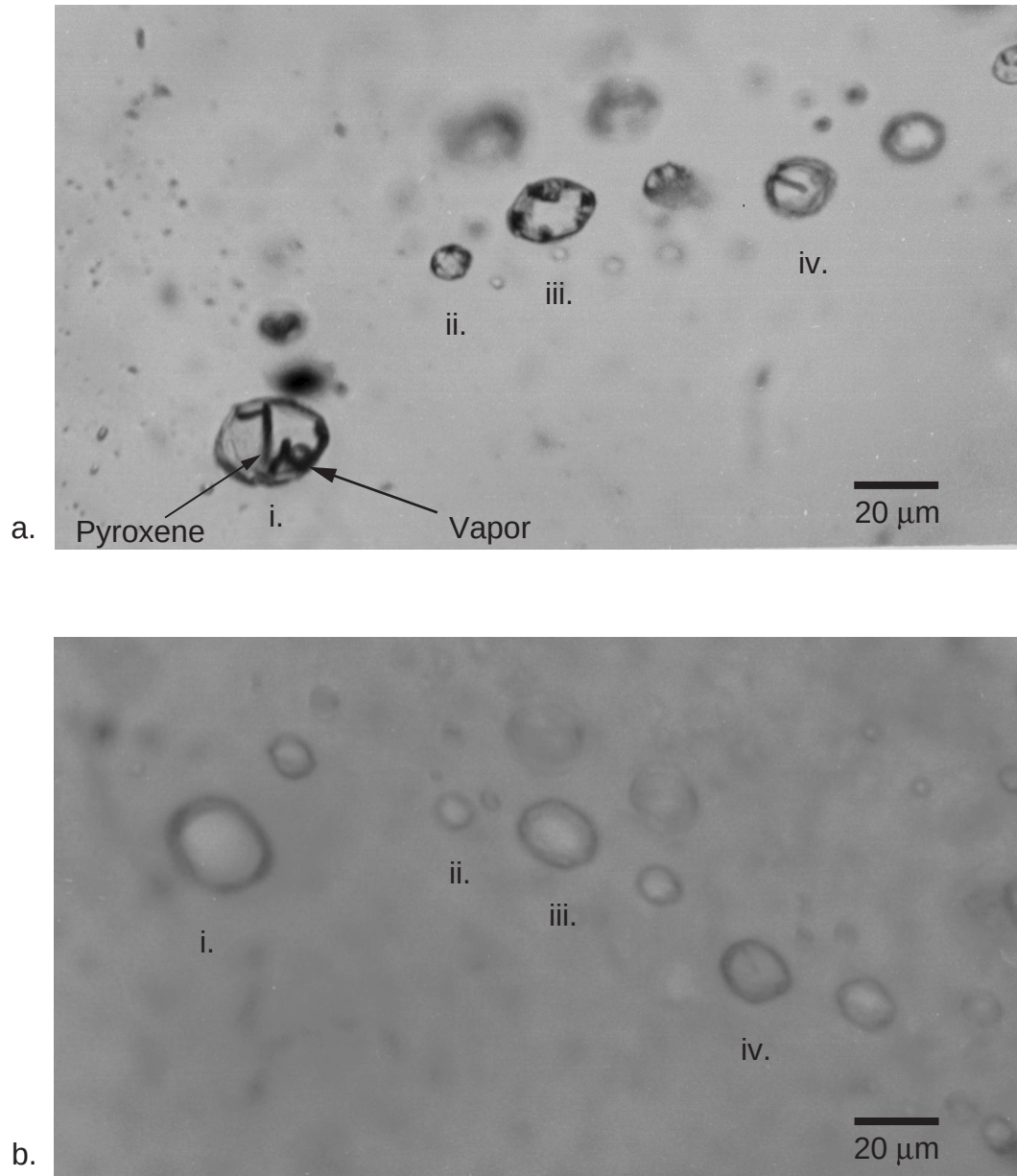


Figure 5. Melt inclusions from the 1991 eruption shown prior to homogenization (a) and after homogenization (b). Melt inclusions prior to homogenization were type IV multiphase melt inclusions containing a pyroxene needle and a vapor bubble. After homogenization melt inclusions are type I single phase. Field of view is rotated in the lower picture; Roman numerals are provided to indicate corresponding melt inclusions in the two photos.

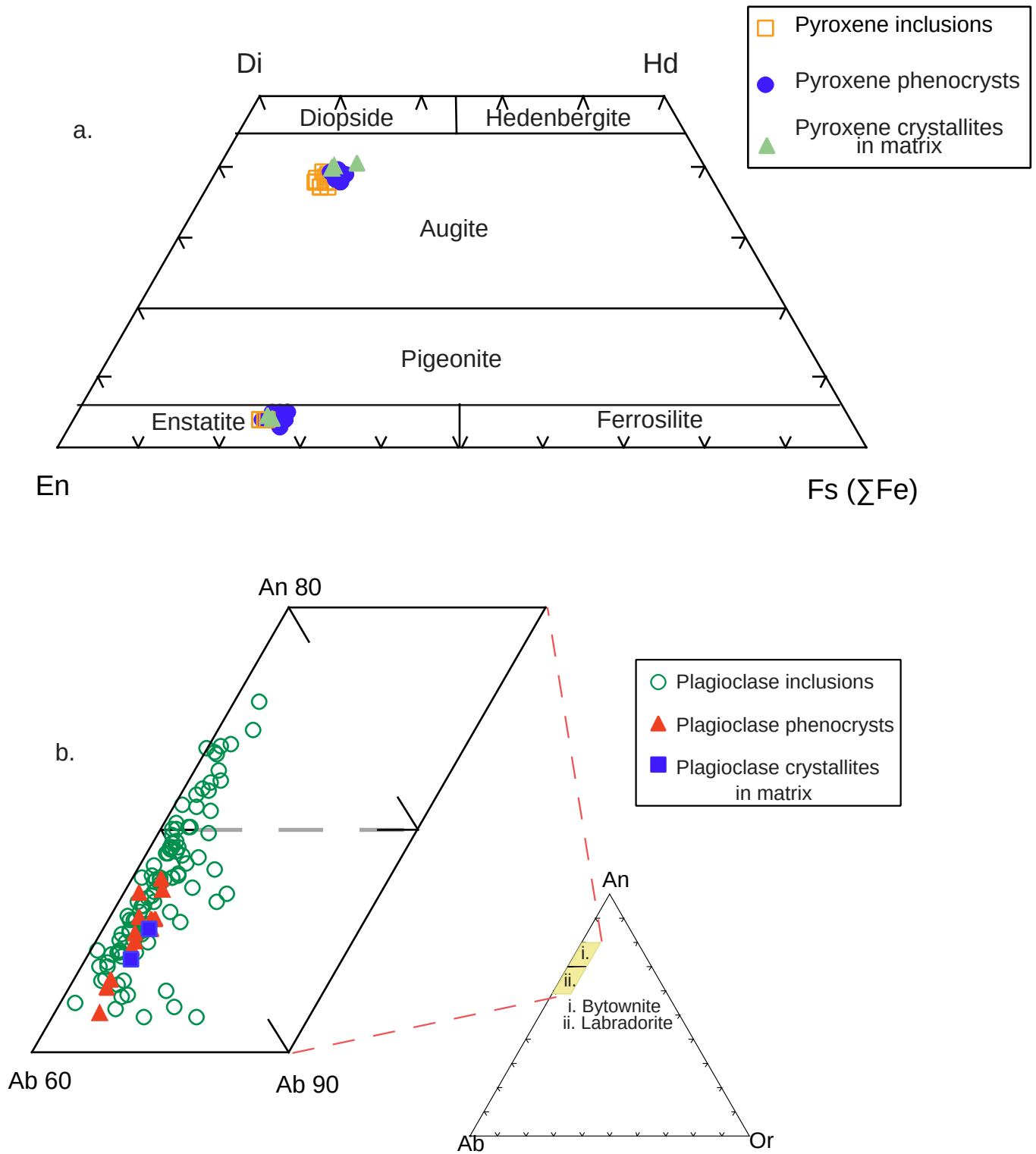


Figure 6. Compositions of phenocrysts, mineral inclusions, and matrix crystallites for (a) pyroxene and (b) plagioclase. Pyroxene nomenclature after Morimoto, 1988.

Table 1. Electron microprobe analyses in weight percent oxide of pyroxene phenocrysts and mineral inclusions. Numbers in italics are the range for that analysis.

Weight Percent Oxide	Clinopyroxene Phenocryst n=22	Clinopyroxene Inclusions in Plagioclase n=15	Orthopyroxene Phenocryst n=40	Orthopyroxene Inclusions in Plagioclase n=5
SiO ₂	52.71 <i>50.93 - 54.87</i>	52.15 <i>50.97 - 53.26</i>	53.81 <i>51.73 - 55.72</i>	51.66 <i>48.75 - 54.2</i>
TiO ₂	0.49 <i>0.39 - 0.63</i>	0.44 <i>0.30 - 0.60</i>	0.23* <i>0.09 - 0.34</i>	0.28 <i>0.20 - 0.30</i>
Al ₂ O ₃	1.85 <i>1.58 - 2.08</i>	1.93 <i>1.79 - 2.00</i>	1.14 <i>0.82 - 1.52</i>	1.13 <i>1.07 - 1.24</i>
MgO	16.15 <i>15.53 - 16.60</i>	17.19 <i>16.51 - 17.80</i>	26.13 <i>25.3 - 27.14</i>	26.74 <i>25.86 - 27.77</i>
CaO	18.94 <i>18.25 - 19.72</i>	18.98 <i>18.16 - 19.44</i>	2.10 <i>1.7 - 2.6</i>	2.02 <i>1.86 - 2.14</i>
MnO	0.37 <i>0.27 - 0.46</i>	na	0.41 <i>0.17 - 0.67</i>	na
FeO	9.72 <i>9.08 - 10.35</i>	8.78 <i>8.07 - 9.63</i>	16.44 <i>15.11 - 18.38</i>	15.12 <i>14.90 - 15.35</i>
Na ₂ O	0.22 <i>0.14 - 0.33</i>	0.27 <i>0.16 - 0.35</i>	0.04 <i>bd - 0.11</i>	0.06 <i>0.10 - 0.07</i>
K ₂ O	bd	0.04 <i>bd - 0.09</i>	bd	0.04 <i>bd - 0.06</i>
F	0.14 <i>bd - 0.34</i>	na	0.10* <i>bd - 0.32</i>	na
Cl	bd	na	bd	na
Total	100.62 <i>97.46 - 103.25</i>	99.78 <i>97.58 - 100.71</i>	100.42 <i>97.46 - 103.25</i>	97.05 <i>93.52 - 100.68</i>

bd = below detection limits

na = not analyzed for those samples

* = number analyzed is less for this value

the field of bytownite. There is no correlation between the range in An content and the year in which the sample was ejected from the magma chamber (Figure 7). Also, there is no systematic correlation between the An content of plagioclase inclusions and the location of the inclusion within the phenocryst (i.e., there is no apparent zoning in plagioclase composition from the core to the rim of phenocrysts) (Figure 8). Average compositions of phenocrysts and mineral inclusions are listed in Table 2.

Melt inclusions Compositions of melt inclusions hosted in all three phenocryst minerals (plagioclase, ortho- and clinopyroxene) were determined. Composition ranges and averages, and CIPW norms are listed by year in Table 3 and by host in Table 4. Compositions of melt inclusions trapped in samples from the 1977, 1986, 1988, and 1989 eruptions (77/89) are similar and independent of host phase (Figure 9) or year in which they were erupted (Figure 10). No correlation was found between the location of the inclusion in the host mineral and the composition of the melt (Figures 11 and 12). Glass in unhomogenized multiphase melt inclusions from 1991 has a composition that differs from compositions and CIPW norms of glass in samples from the other four years. However, compositions of homogenized melt inclusions hosted by a clinopyroxene from 1991 are similar to the 77/89 compositions with the exception of the alkalis. (Table 3 and Figure 13). Analytical totals for the glasses range from 93-99%, which is interpreted to indicate the presence of unanalyzed volatiles in the melts.

Matrix glass Matrix glass has a composition similar to that of glass in melt inclusions from the 77/89 samples, and similar to glass in homogenized 1991 melt inclusions (Figure 9 and 10). Crystallites in matrix glass have compositions that are similar to compositions of phenocrysts in the same samples (Figure 6).

Copper concentrations

Copper concentrations were determined for matrix glass and for two melt inclusions hosted by an orthopyroxene erupted in 1977. Background concentrations of copper in the orthopyroxene range from 10-30 ppm. The copper concentration in silicate melt inclusions is significantly higher, ranging from 160 - 280 ppm with an average of 230 ± 10 ppm. Matrix glass was slightly lower with a range of 170 - 220 ppm and an average of 188 ppm. The average copper concentration in andesites is reported to be 60 ppm, with a range from 10 to 150 ppm (Gill, 1981). An electron microprobe traverse for copper through a melt inclusion and enclosing pyroxene host phase is shown in Figure 14. As shown, the copper concentration in the melt inclusion is clearly elevated relative to the copper concentration in the host phase.

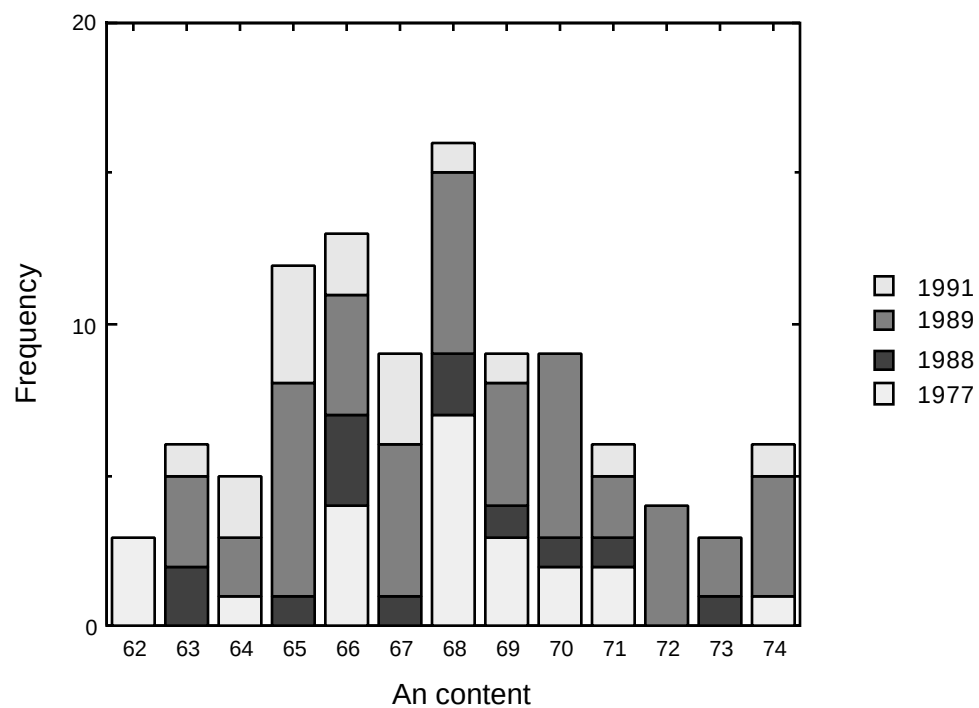
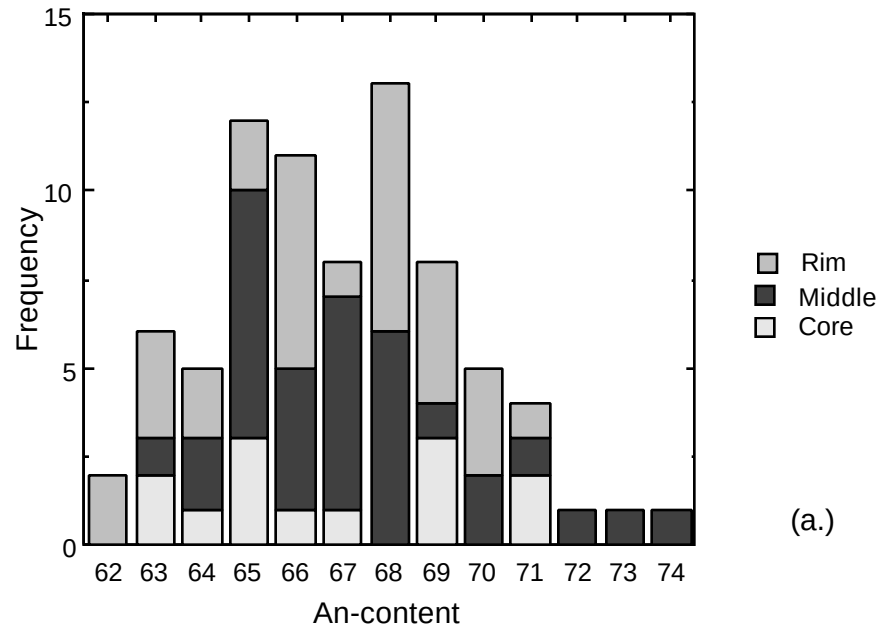
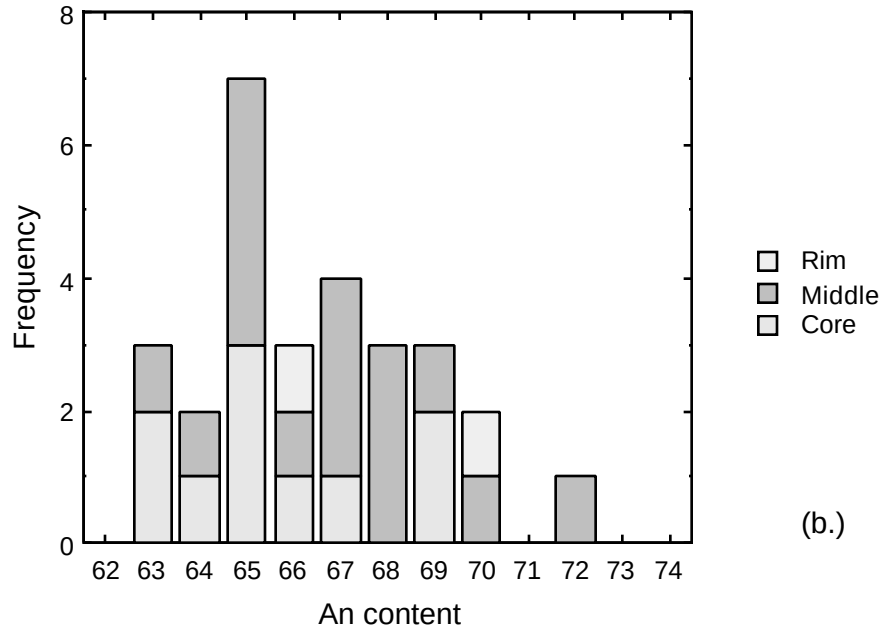


Figure 7. Variation of An-contents of plagioclase inclusions grouped by eruption year. An-content ranges overlap from all years sampled.



(a.)



(b.)

Figure 8. Variations of An-contents of plagioclase mineral inclusions grouped according to location within phenocrysts for (a) inclusions from all samples and (b) inclusions within a single phenocryst. All ranges overlap in both cases.

Table 2. Electron microprobe analyses in weight percent oxide of plagioclase phenocrysts and mineral inclusions. Numbers in italics are the range for that analysis.

Weight Percent Oxide	Plagioclase Phenocryst n=14	Plagioclase Inclusions in Clinopyroxene n=14	Plagioclase Inclusions in Orthopyroxene n=74
SiO ₂	51.65 <i>48.53 - 53.14</i>	51.85 <i>49.72 - 55.19</i>	51.41 <i>48.67 - 55.96</i>
TiO ₂	0.05 <i>bd - 0.10</i>	0.09 <i>0.04 - 0.26</i>	0.11* <i>bd - 0.37</i>
Al ₂ O ₃	29.09 <i>28.75 - 29.50</i>	28.92 <i>24.34 - 31.58</i>	29.10 <i>24.99 - 31.11</i>
MgO	0.16 <i>0.10 - 0.23</i>	0.65 <i>0.16 - 3.08</i>	0.36 <i>0.08 - 1.90</i>
CaO	13.35 <i>12.68 - 14.15</i>	13.86 <i>12.31 - 15.32</i>	13.41 <i>10.97 - 14.81</i>
MnO	0.06* <i>bd - 0.13</i>	0.09 <i>bd - 0.15</i>	0.10 <i>bd - 0.36</i>
FeO	0.71 <i>0.59 - 0.89</i>	1.36 <i>0.81 - 2.79</i>	1.58 <i>0.86 - 3.08</i>
Na ₂ O	3.76 <i>3.54 - 4.13</i>	3.34 <i>2.61 - 3.74</i>	3.48 <i>2.75 - 4.44</i>
K ₂ O	0.25 <i>0.11 - 0.33</i>	0.26 <i>0.15 - 0.61</i>	0.24* <i>0.05 - 0.85</i>
F	0.14* <i>bd - 0.46</i>	0.03 <i>bd - 0.14</i>	0.13* <i>bd - 0.30</i>
Cl	bd	bd	bd
Total	99.19 <i>95.83 - 100.81</i>	100.44 <i>98.15 - 101.82</i>	99.71 <i>96.79 - 101.98</i>

bd = below detection limits

na = not analyzed for those samples

* = number analyzed is less for this value

Table 3. Major element compositions microprobe in weight percent oxide of melt inclusions as determined by electron microprobe. Numbers in italics are the range for the melt inclusion compositions for that year. CIPW-norms were calculated for the averages given in this table.

Weight Percent Oxide	1977 average n = 14	1986 average n = 16	1988 average n = 25	1989 average n = 20	1991 average unhomogenized n = 19	1991 average homogenized n = 9
SiO ₂	64.25	63.75	63.88	64.23	68.28	64.88
	<i>61.07 - 66.12</i>	<i>62.87 - 64.59</i>	<i>59.99 - 65.87</i>	<i>61.28 - 67.25</i>	<i>63.24 - 71.39</i>	<i>63.11 - 66.54</i>
TiO ₂	1.18	1.08	0.96	1.08*	1.00	1.33
	<i>0.68 - 1.6</i>	<i>0.95 - 1.20</i>	<i>0.70 - 1.30</i>	<i>0.90 - 1.40</i>	<i>0.65 - 1.49</i>	<i>1.04 - 1.50</i>
Al ₂ O ₃	12.68	13.81	14.39	13.67	14.68	13.41
	<i>11.3 - 13.80</i>	<i>13.36 - 14.27</i>	<i>13.35 - 15.83</i>	<i>13.17 - 14.58</i>	<i>12.57 - 16.2</i>	<i>12.48 - 14.94</i>
MgO	1.93	2.16	2.07	1.96	0.9	1.81
	<i>0.98 - 2.43</i>	<i>1.96 - 2.31</i>	<i>1.43 - 2.63</i>	<i>0.81 - 2.56</i>	<i>0.14 - 4.06</i>	<i>1.62 - 2.01</i>
CaO	4.70	5.14	5.13	4.85	3.05	5.44
	<i>4.08 - 5.60</i>	<i>4.55 - 5.55</i>	<i>4.43 - 5.97</i>	<i>3.73 - 6.15</i>	<i>2.1 - 4.55</i>	<i>5.06 - 5.89</i>
MnO	0.15	0.09	0.17	0.14*	0.07	0.20
	<i>0.05 - 0.29</i>	<i>0.02 - 0.21</i>	<i>0.12 - 0.26</i>	<i>0.12 - 0.30</i>	<i>bd - 0.17</i>	<i>0.09 - 0.28</i>
FeO	7.05	6.19	6.42	6.31	2.15	8.08
	<i>6.27 - 7.84</i>	<i>5.45 - 6.88</i>	<i>5.22 - 7.94</i>	<i>5.25 - 7.68</i>	<i>1.29 - 3.79</i>	<i>7.35 - 8.53</i>
Na ₂ O	2.45	2.87	2.60	2.24	2.06	0.87
	<i>1.75 - 3.13</i>	<i>2.50 - 3.08</i>	<i>1.79 - 3.18</i>	<i>1.54 - 2.99</i>	<i>1.24 - 3.27</i>	<i>0.54 - 1.24</i>
K ₂ O	2.87	2.49	2.66	2.58	2.77	1.71
	<i>2.54 - 3.11</i>	<i>2.30 - 2.68</i>	<i>1.86 - 3.24</i>	<i>1.74 - 2.84</i>	<i>1.91 - 3.53</i>	<i>1.50 - 1.97</i>
F	0.07	0.13	0.05	na	0.11	0.04
	<i>bd - 0.20</i>	<i>bd - 0.30</i>	<i>bd - 0.17</i>		<i>bd - 0.29</i>	<i>bd - 0.17</i>
Cl	0.14	0.12	0.13	na	0.27	0.14
	<i>0.14 - 0.08</i>	<i>0.09 - 0.18</i>	<i>0.09 - 0.17</i>		<i>0.10 - 0.82</i>	<i>0.11 - 0.18</i>
Total	97.45	97.83	98.46	96.72	95.34	97.90
	<i>97.45 - 99.11</i>	<i>96.72 - 98.59</i>	<i>94.62 - 99.95</i>	<i>93.41 - 99.01</i>	<i>91.94 - 97.78</i>	<i>94.60 - 99.47</i>
Q	27.49	24.96	25.31	28.84	40.05	38.70
C	0.00	0.00	0.00	0.00	3.87	0.92
Or	16.94	14.70	15.70	15.23	16.35	10.09
Ab	19.68	23.38	21.02	17.91	15.42	6.32
An	15.65	17.89	20.22	20.14	13.11	25.64
Di	4.99	4.46	3.13	1.64	0.00	0.00
Hy	4.75	5.16	5.90	6.03	2.23	6.99
Il	2.24	2.05	1.83	2.05	1.90	2.53
Mt	4.60	4.05	4.19	4.12	1.09	5.28
Hm	0.00	0.00	0.00	0.00	0.22	0.00
Ap	0.44	0.44	0.44	0.44	0.44	0.44
Hl	0.23	0.2	0.21	0.23	0.44	0.23
Fl	0.10	0.18	0.07	0.14	0.15	0.06

bd = below detection limits

na = not analyzed for those samples

* = number analyzed is less for this value

Table 4. Major element compositions in weight percent oxide of melt inclusions grouped by phenocryst host. Numbers in italics are the range for the melt inclusion compositions for that host. CIPW-norms were calculated for the averages given in this table.

Weight Percent Oxide	Melt inclusions in clinopyroxene n=22	Melt inclusions in orthopyroxene n=17	Melt inclusions in plagioclase n=33
SiO ₂	63.44 <i>59.99 - 65.44</i>	64.34 <i>61.97 - 65.87</i>	64.19 <i>31.07 - 67.25</i>
TiO ₂	1.02 <i>0.70 - 1.30</i>	0.96 <i>0.68 - 1.14</i>	1.13 <i>0.90 - 1.60</i>
Al ₂ O ₃	14.05 <i>13.35 - 15.83</i>	14.03 <i>13.22 - 15.21</i>	13.31 <i>11.30 - 14.27</i>
MgO	2.12 <i>1.75 - 2.63</i>	1.65 <i>0.81 - 2.36</i>	2.16 <i>1.30 - 2.56</i>
CaO	5.20 <i>4.43 - 5.97</i>	5.29 <i>4.53 - 6.15</i>	4.65 <i>3.73 - 5.42</i>
MnO	0.14 <i>0.002 - 0.23</i>	0.17* <i>bd - 0.30</i>	0.11* <i>0.05 - 0.19</i>
FeO	6.44 <i>5.22 - 7.94</i>	6.79 <i>5.74 - 7.68</i>	6.32 <i>5.25 - 7.84</i>
Na ₂ O	2.75 <i>1.79 - 3.09</i>	2.51 <i>1.75 - 3.18</i>	2.42 <i>1.54 - 2.42</i>
K ₂ O	2.57 <i>1.86 - 3.24</i>	2.60 <i>1.74 - 2.84</i>	2.70 <i>2.37 - 3.11</i>
F	0.07 <i>bd - 0.30</i>	0.07* <i>bd - 0.20</i>	0.10* <i>bd - 0.30</i>
Cl	0.12 <i>0.09 - 0.16</i>	0.13* <i>0.08 - 0.18</i>	0.13* <i>0.09 - 0.22</i>
Total	97.93 <i>94.62 - 99.34</i>	98.53 <i>95.87 - 99.95</i>	97.08 <i>93.41 - 99.11</i>
Q	24.54	27.00	27.68
Or	15.17	15.35	15.94
Ab	22.37	20.26	19.50
An	18.84	19.82	17.96
Di	4.40	3.96	2.63
Hy	5.36	4.67	6.01
Il	1.94	1.83	2.15
Mt	4.21	4.44	4.12
Ap	0.44	0.44	0.44
Hl	0.20	0.21	0.21
Fl	0.10	0.10	0.14

bd = below detection limits

na = not analyzed for those samples

* = number analyzed is less for this value

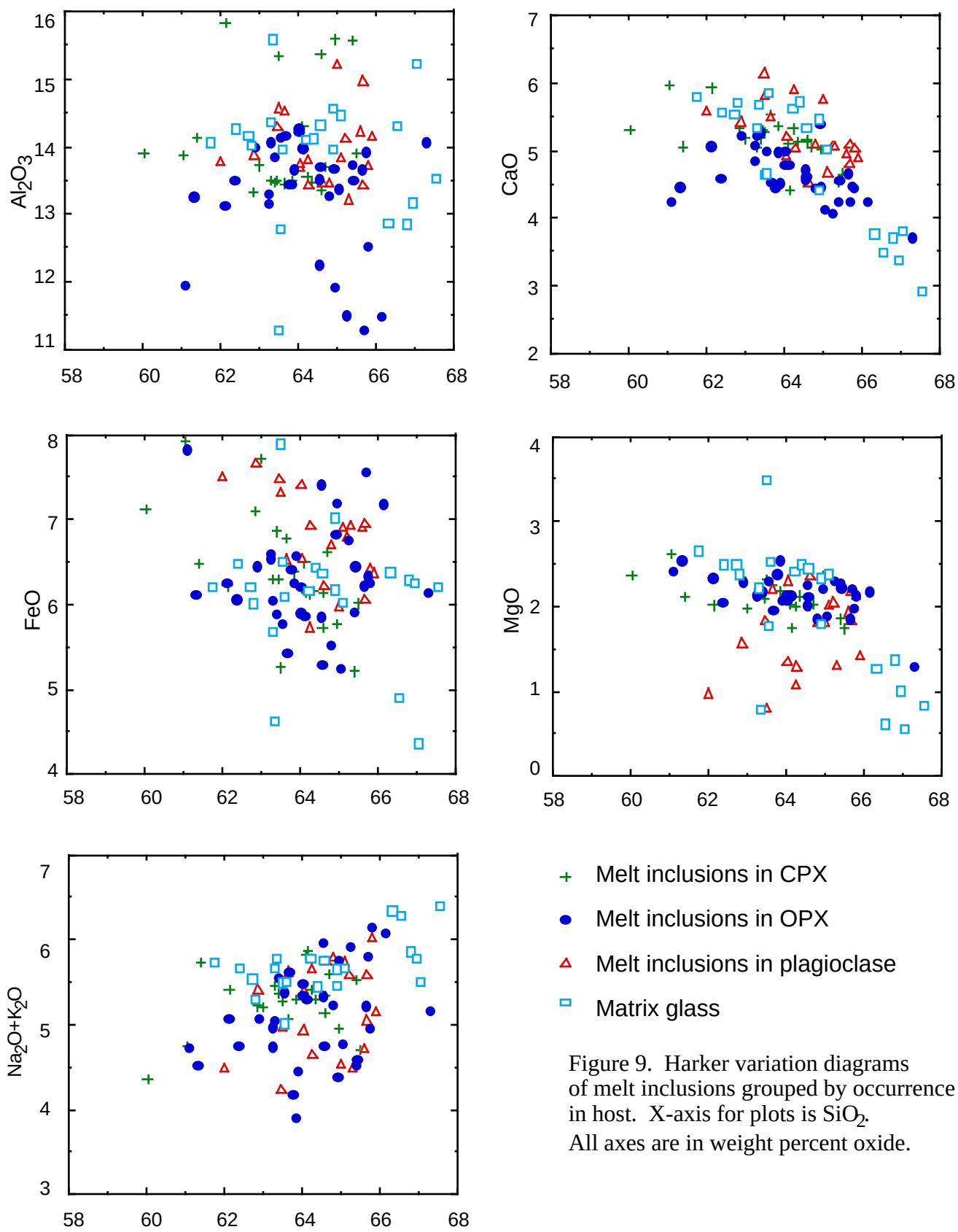
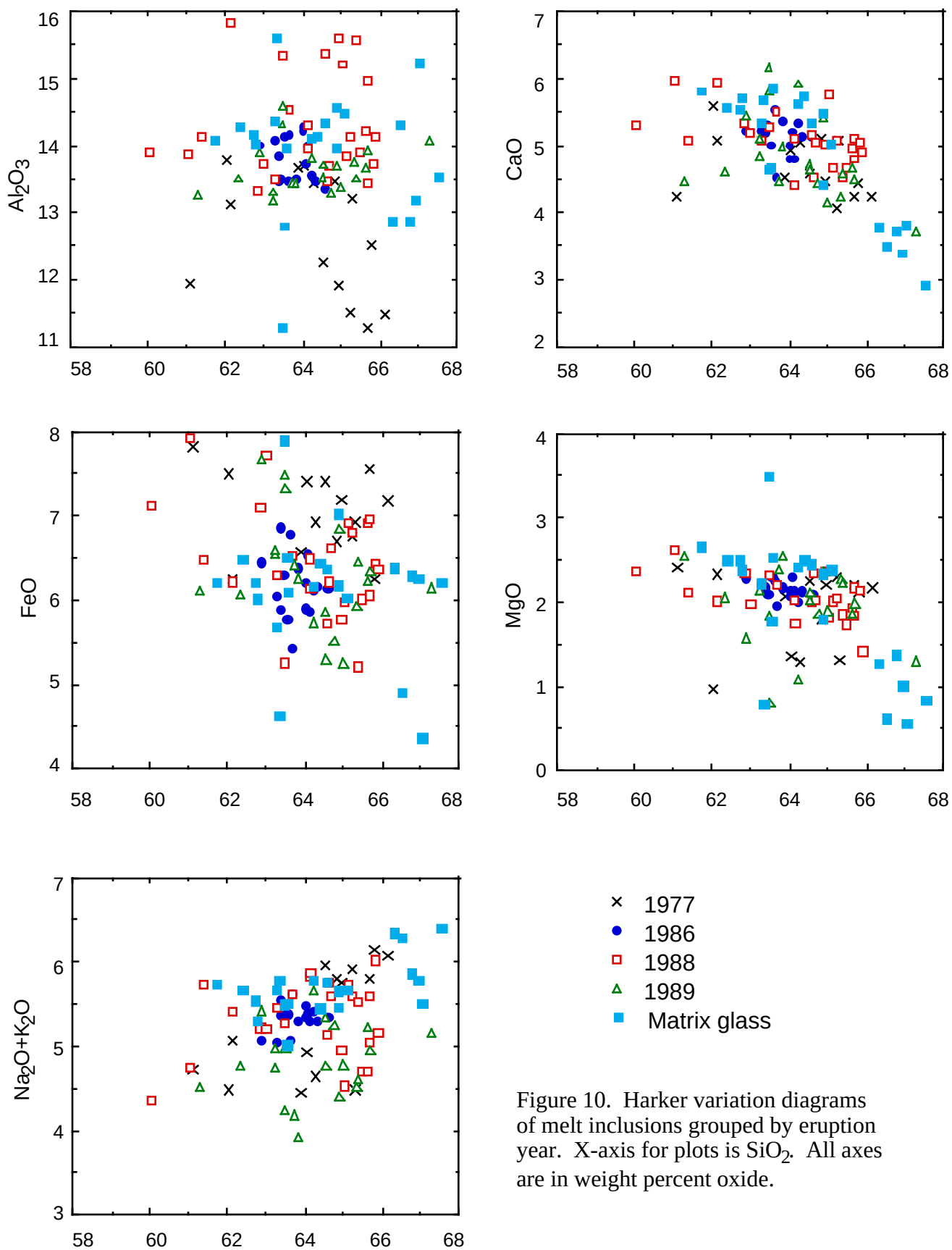


Figure 9. Harker variation diagrams of melt inclusions grouped by occurrence in host. X-axis for plots is SiO_2 . All axes are in weight percent oxide.



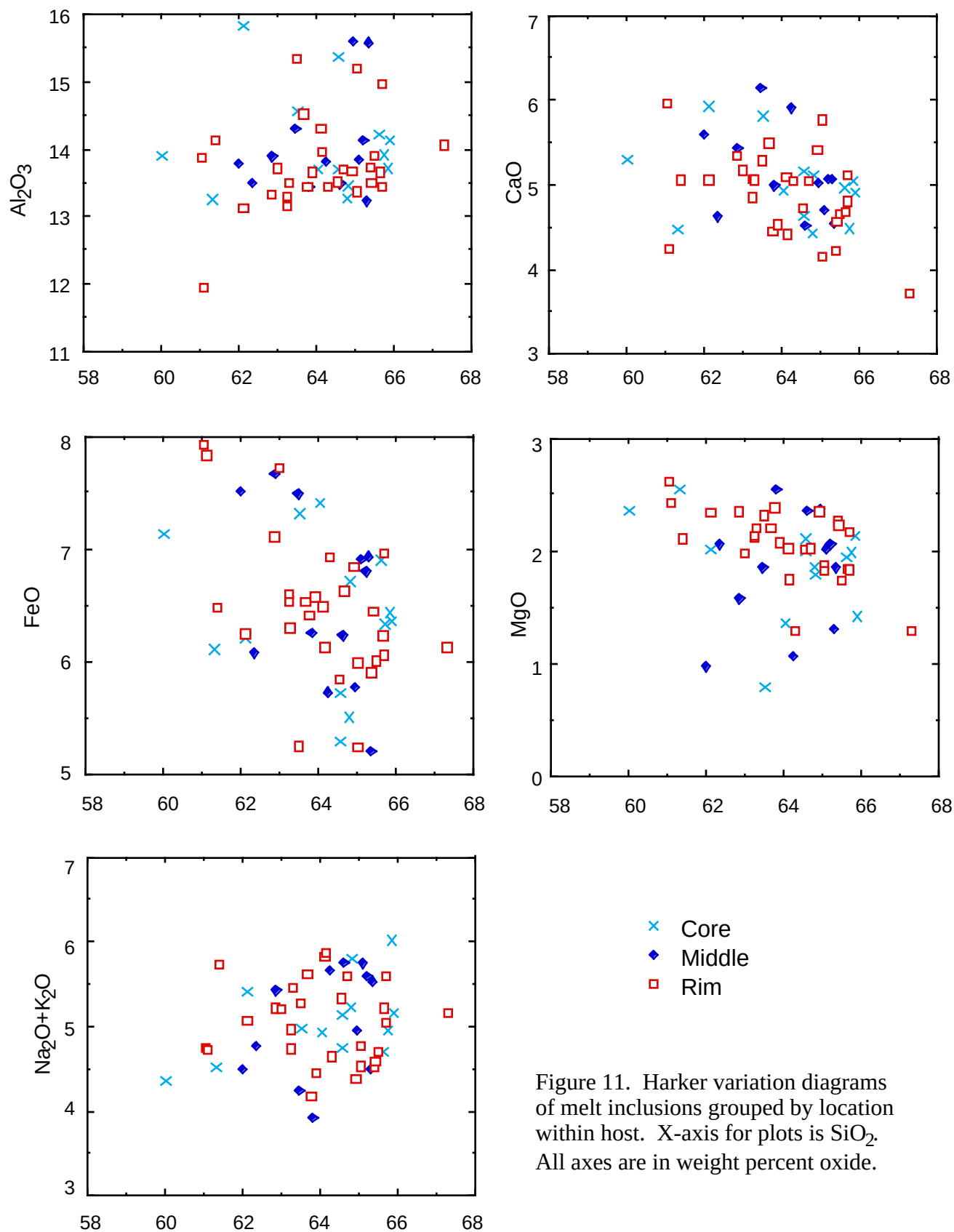
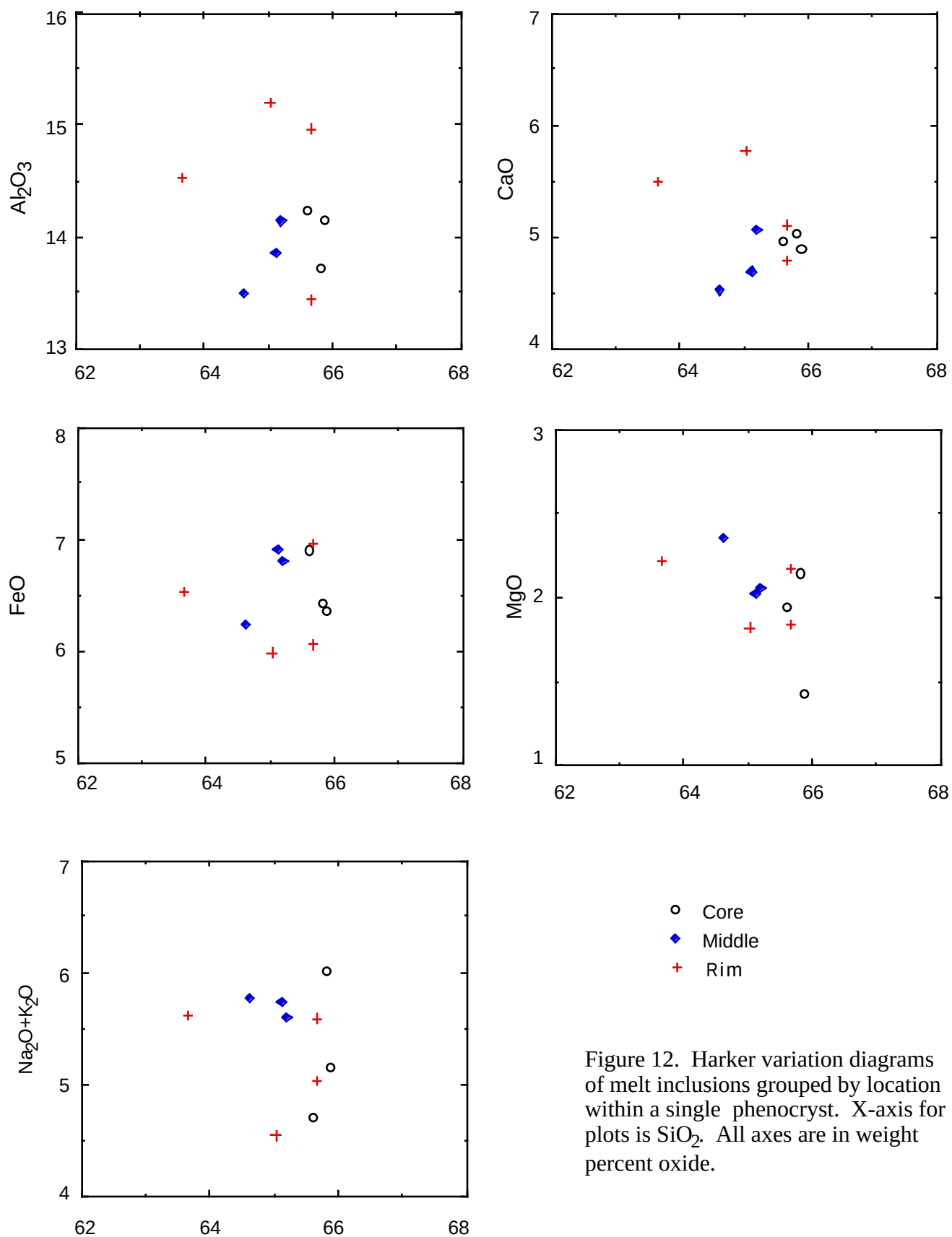


Figure 11. Harker variation diagrams of melt inclusions grouped by location within host. X-axis for plots is SiO_2 . All axes are in weight percent oxide.



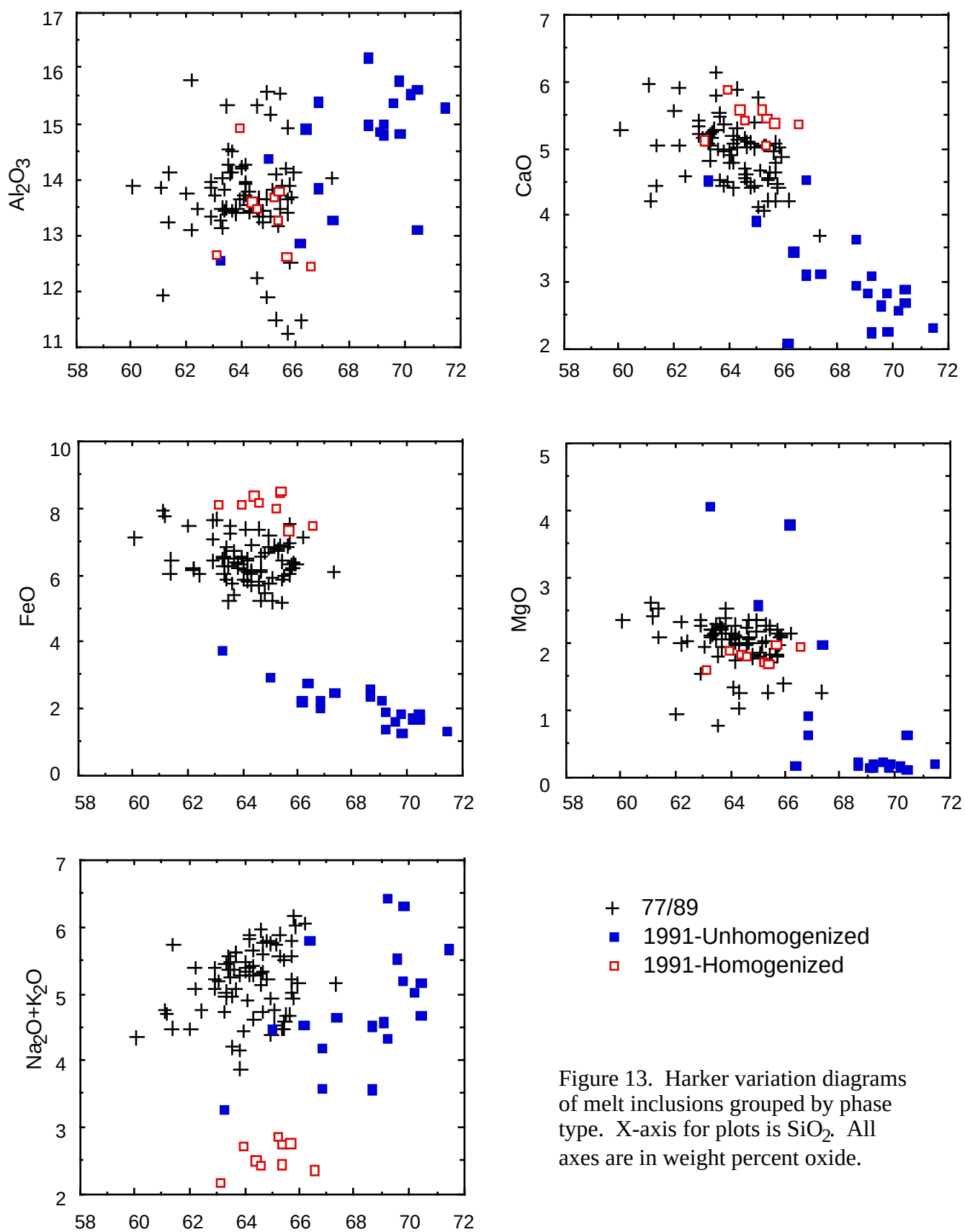


Figure 13. Harker variation diagrams of melt inclusions grouped by phase type. X-axis for plots is SiO_2 . All axes are in weight percent oxide.

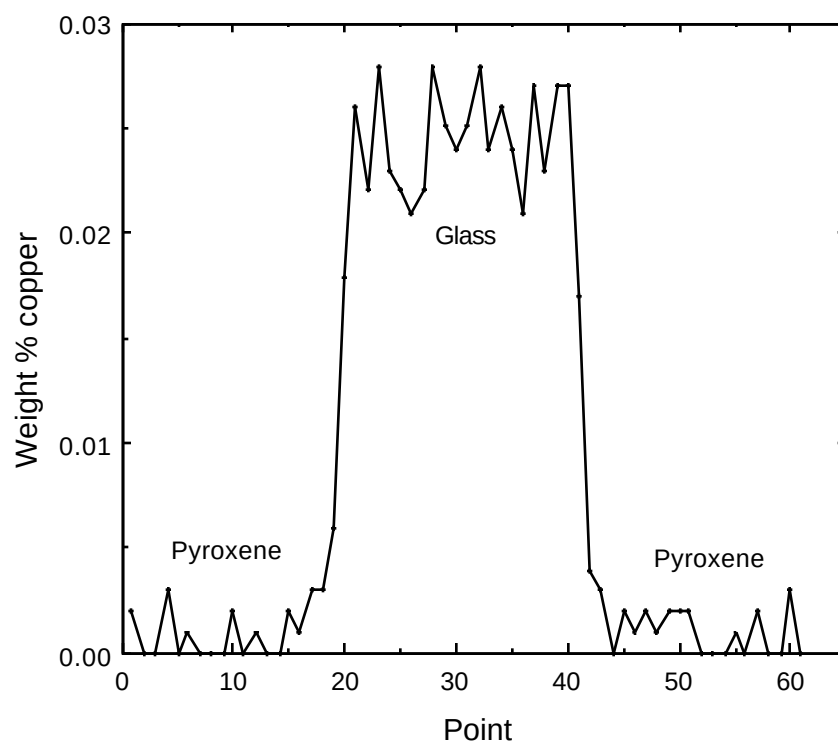


Figure 14. Electron microprobe traverse across a silicate melt inclusion and surrounding host pyroxene showing concentrations of copper. The melt inclusion has an average copper concentration of 240 ± 10 ppm, while the pyroxene host has only background traces of copper.

Trace elements

Melt inclusion glass and matrix glass from the 1988 and 1989 samples were analyzed for trace elements. The melt inclusions were hosted by orthopyroxene and plagioclase. Phenocrysts adjacent to melt inclusions were analyzed for background trace element content in order to compare melt inclusions trapped in different host minerals (Table 5). Trace element concentrations for the inclusions show no variation as a function of host phase (Figure 15). Trace element concentrations of matrix glass are similar to melt inclusion glass except that matrix glass lacks a positive Eu anomaly. Flynn and Burnham (1978) showed that trivalent rare earth elements, especially Eu, are fractionated into chlorine rich vapors relative to melt. This is consistent with the interpretation that the matrix glass is degassed, as discussed below.

Volatiles

Volatile-component concentrations were determined in the same melt inclusions and matrix glass that were analyzed for trace elements. The n/Si ratios are listed in Table 6, with n being the negative ion of interest. Calculated volatile concentrations are also listed in Table 6, along with the equations used to obtain those values. All values were calculated using equations appropriate for mafic magmas, except those for water. Water concentrations were calculated for a melt containing 50 wt% SiO₂, and these values were extrapolated to the silica concentration corresponding to the glasses analyzed.

H₂O contents (Figure 16) are consistently higher in the melt inclusions (0.27 - 0.89 wt%) than in the matrix glass (0.07 - 0.20 wt%), suggesting that the matrix glass lost water during eruption. In contrast, CO₂ concentrations for melt inclusion glass (0.01 - 0.31 wt%) and matrix glass (0.06 - 0.27 wt%) overlap, suggesting that CO₂ was lost from the melt at depth, before the melt was trapped as inclusions and before it was erupted onto the surface. The Cl⁻ and F⁻ contents of matrix glass are highly variable, with some higher and some lower than melt inclusion concentrations. Matrix glass generally has a lower S⁻ concentration (0.3 - 58 ppm) compared to melt inclusions (31 - 88 ppm), suggesting near-surface loss of sulfur from the melt (matrix glass) during eruption. Melt inclusion values are within the range of sulfur reported for blocks and bombs erupted in 1977 from White Island, which were generated from degassed magma and contain between 30 and 250 ppm (as reported in Houghton and Nairn, 1989b). Most matrix glass values are below the reported range for degassed blocks and bombs. The expected value for andesites is 200 - 2000 ppm (Gill, 1981) which suggests that both melt inclusion glass and matrix glass represent melt which has been degassed, although to different degrees, and thus yield low and differing values of sulfur. However, if melt inclusion glass is degassed with respect to sulfur,

Table 5. Trace element concentrations in parts per million of melt inclusions and matrix glass as determined by ion microprobe.

ppm	Melt inclusion in orthopyroxene n=2	Melt inclusion in clinopyroxene n=1	Melt inclusion in plagioclase n=1	Matrix glass n=1
Ba	808	734	594	750
Rb	58	56	29	47
Nb	7	6	5	6
La	14	14	12	14
Ce	30	31	25	30
Sr	135	115	172	144
Be	1	2	2	1
Nd	15	16	13	14
Hf	6	6	3	6
Zr	177	155	142	178
Sm	3	5	6	4
Eu	3	5	2	1
Gd	4	5	3	3
Ti	5377	4825	4463	5121
Dy	4	8	5	5
Er	2	2	3	3
Y	21	28	22	22
Yb	18	4	5	3
Li	17	17	15	16
Sc	30	33	17	15
Cr	85	292	25	33

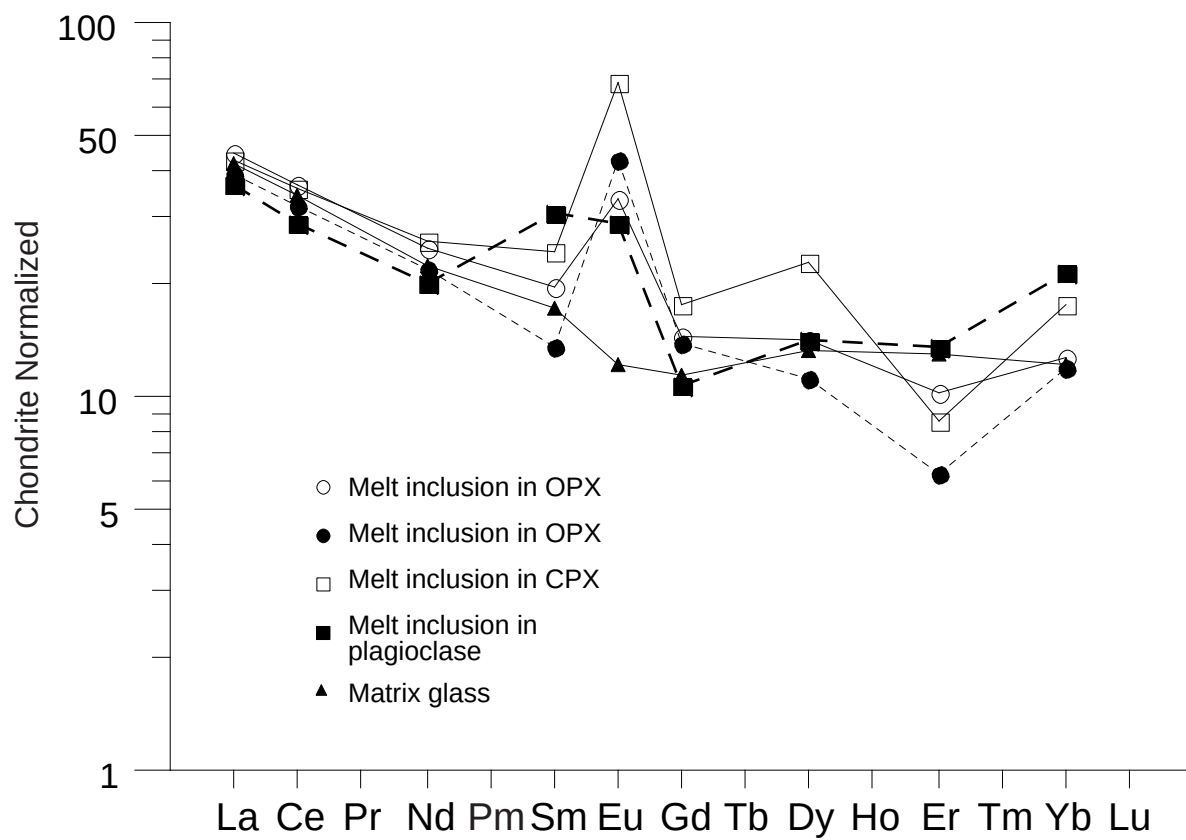


Figure 15. Chondrite normalized REE profiles for melt inclusions and matrix glass, using values from Anders and Grevasse (1989). Patterns are similar for each glass independent of host. Matrix glass shows a similar pattern except a lack of a positive Eu anomaly as discussed in text.

Table 6. Volatile concentrations of melt inclusions and matrix glass determined by the ion microprobe. Values in the upper portion of the table are reported numbers from the probe. Values in the lower portion of the table are calculated weight percents according to listed equations. Reported water value is an interpolation between the listed mafic and silicic equations.

$\left[\frac{n_{X^-}}{^{30}\text{Si}^-} \right]$	Mi in 1988 CPX	Mi in 1988 CPX	Mi in 1988 OPX	Mi in 1988 OPX	MI in 1989 Plag	1988 Matrix	1988 Matrix	1989 Matrix	1989 Matrix	1989 Matrix
Cl	0.59	0.48	1.03	1.04	0.75	1.02	1.14E-03	1.02E-03	0.91	0.80
F	0.55	0.49	0.83	0.87	0.42	0.92	0.02	0.02	0.84	0.74
S	0.08	0.09	0.07	0.14	0.05	0.09	4.15E-04	4.80E-04	0.02	0.02
C	4.33E-03	0.05	0.19	0.09	0.03	0.09	0.06	0.04	0.16	0.11
H	0.45	0.44	1.04	0.57	0.32	0.18	0.01	4.79E-03	0.21	0.14

Weight Percent	Mi in 1988 CPX	Mi in 1988 CPX	Mi in 1988 OPX	Mi in 1988 OPX	MI in 1989 Plag	1988 Matrix	1988 Matrix	1989 Matrix	1989 Matrix	1989 Matrix
Cl	0.06	0.05	0.10	0.10	0.07	0.09	0.08	0.10	1.07E-04	9.63E-05
F	0.05	0.04	0.07	0.08	0.04	0.08	0.07	0.08	1.72E-03	1.50E-03
S	0.01	0.01	0.01	0.01	3.96E-03	1.31E-03	1.30E-03	0.01	3.35E-05	3.87E-05
CO ₂	0.01	0.08	0.31	0.15	0.05	0.27	0.19	0.14	0.11	0.06
H ₂ O	0.42	0.36	0.89	0.46	0.27	0.20	0.15	0.18	0.07	0.07

$$\text{Cl(ppm)} = 736 \left[\frac{^{35}\text{Cl}^-}{^{30}\text{Si}^-} \right]_{\text{N}} \quad \text{F(ppm)} = 700 \left[\frac{^{19}\text{F}^-}{^{30}\text{Si}^-} \right]_{\text{N}} \quad \text{S(ppm)} = 630 \left[\frac{^{32}\text{S}^-}{^{30}\text{Si}^-} \right]_{\text{N}} \quad \text{CO}_2(\text{ppm}) = 12907 \left[\frac{^{12}\text{C}^-}{^{30}\text{Si}^-} \right]_{\text{N}}$$

$$\text{Silicic glass H}_2\text{O (wt\%)} = 0.103 + 0.332 \left[\frac{^1\text{H}^-}{^{30}\text{Si}^-} \right]_{\text{N}} + 0.0544 \left[\frac{^1\text{H}^-}{^{30}\text{Si}^-} \right]_{\text{N}}^2$$

$$\text{Mafic glass H}_2\text{O (wt\%)} = 0.039 + 0.55667 \left[\frac{^1\text{H}^-}{^{30}\text{Si}^-} \right]_{\text{N}} + 0.17787 \left[\frac{^1\text{H}^-}{^{30}\text{Si}^-} \right]_{\text{N}}^2$$

$$\text{Where } \left[\frac{x}{^{30}\text{Si}^-} \right]_{\text{N}} = \left[\frac{x}{^{30}\text{Si}^-} \right] \times \frac{\text{Si value in sample}}{50 \text{ (Si value for mafic magma)}}$$

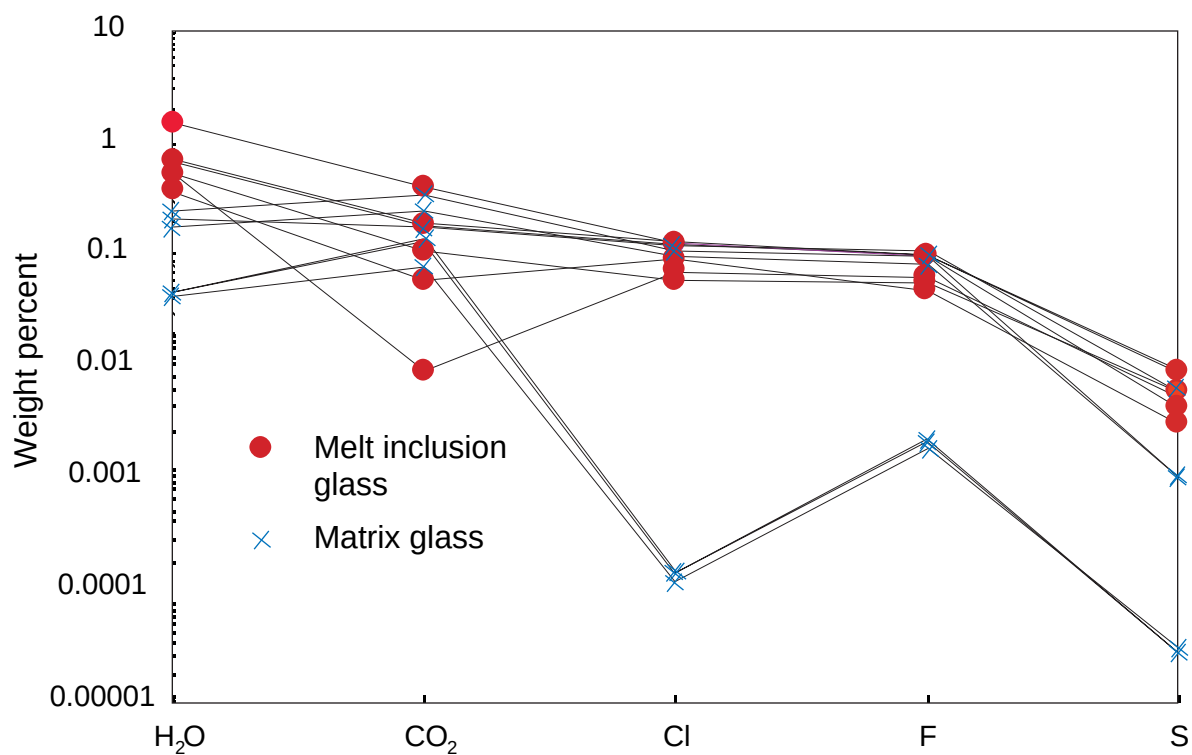


Figure 16. Concentrations of volatiles for melt inclusion glass and matrix glass. Concentrations were determined using equations listed in Table 5.

there should be an accompanying depletion of Eu as seen with matrix glass, but there is not. This suggests that the White Island magma may be anomalously low in sulfur. Elevated values of sulfur in the blocks and bombs could be attributed to surface contamination if alteration was present. Hedenquist et al.(1993) found that sulfur contents of altered rocks were an order of magnitude higher than in fresh samples.

Temperature

Temperature was estimated graphically from the compositions of coexisting pyroxenes (Lindsley, 1983). This method yielded a temperature of $\sim 1100^{\circ}\text{C}$, which is within reasonable agreement with homogenization temperatures of melt inclusions from the 1991 sample (1210°C). According to Gill (1981) the temperature range for andesitic eruptions is 1050° to 1150°C , and the experimentally determined temperature for the andesite liquidus is 1180° - 1250°C at atmospheric pressure.

Pressure estimates from the graphical Lindsley method were not attained however, as the compositions of the pyroxenes in this study are not on the pressure sensitive side (Fs-Hd) of the pyroxene quadrangle.

Discussion

Conditions in the magma chamber

Although the years in which the samples were erupted from the magma chamber are known, it was not possible to determine when the individual phenocrysts in each sample formed, or when the solid and melt inclusions were trapped in the phenocrysts. Each phenocryst and its contained melt and mineral inclusions is therefore considered to represent a random sampling of the phases that were present in the magma chamber at some unknown location and time in the past. Petrographic and electron microprobe data indicate that plagioclase, orthopyroxene and clinopyroxene were the only three phases crystallizing during the unknown magma-residence time represented by the ejecta. Each of the three phenocryst minerals occurs as solid (mineral) inclusions in at least one other type of phenocryst, and the mineral inclusions have compositions that are similar to the compositions of phenocrysts of that mineral in the same sample. The compositions of plagioclase, orthopyroxene, and clinopyroxene are independent of their mode of occurrence. That is, phenocrysts of a given phase have the same composition as solid inclusions of that same phase. This is interpreted to indicate that all three minerals were in equilibrium and precipitating from the melt at the same time. Moreover, since the phenocrysts and their contained

mineral and melt inclusions presumably represent trapping over some extended range of time and location within the magma chamber, the data suggest that the magma chamber is relatively well mixed and that crystallization has not significantly changed the composition of the melt over the time period represented by the melt inclusions.

The relative chronology of trapping of melt or solid inclusions within a crystal can be estimated based on the position within the crystal, with melt inclusions towards the core presumably trapped earlier than those found near the edge. This interpretation obviously only applies to primary inclusions trapped during growth of the crystal, and does not include any secondary inclusions in the crystals. However, no significant change in melt chemistry as a function of position within the crystal was observed for primary inclusions along growth zones. Plagioclase inclusions, which show variable chemistry (Figure 6a), show no systematic change in composition from cores to rims of phenocrysts (Figure 8).

As noted above, melt inclusions in the 1991 eruption sample are petrographically different from the inclusions in earlier eruption samples. Specifically, the 1991 inclusions contain daughter minerals, suggesting that the 1991 samples experienced a different P-T history than the other samples. Possible scenarios that could result in a different P-T history might be a longer residence time in the magma following entrapment, and/or a slower cooling history after entrapment (either in the magma chamber or after eruption to the surface), and/or eruption from a different location within the magma chamber. An alternative explanation for the presence of daughter minerals in the 1991 samples, and their absence from the other samples, is that the 1991 samples trapped a melt of different composition. However, the composition of glass within homogenized melt inclusions from the 1991 samples is similar to that of glass (melt) in the 1977-89 group of samples. Calculations indicate that glass in unhomogenized multiphase melt inclusions from 1991 represents the composition that the 1977-89 melt would have after 20% crystallization. In order to attain the composition of the 1991 glass in unhomogenized inclusions through fractional crystallization requires a crystal assemblage comprised of 42% plagioclase (An_{65}), 31% clinopyroxene (En_{46} , Fs_{15} , Wo_{39}), 17% iron oxide, and 9% orthopyroxene (En_{71} , Fs_{25} , Wo_4) (Table 7). These proportions are different from modal relations estimated optically in thin section, which were 41% orthopyroxene, 41% plagioclase, 15% clinopyroxene, and 2% iron oxides. However, modal proportions of minerals observed in thin section may not be representative of modal proportions of these phases in the entire magma chamber, but instead only the portion from which samples were ejected.

Table 7. Calculation of fractionating assemblage to account for variation in major element chemistry in melt inclusion compositions.

	SiO ₂	TiO ₂	Al ₂ O ₃	MgO	CaO	MnO	FeO	Na ₂ O	K ₂ O
1977, 1986, 1988 and 1989 average melt composition*	65.64	1.10	13.98	2.08	5.08	0.14	6.66	2.60	2.72
Average composition of OPX	53.64	0.23	1.14	26.05	2.09	0.41	16.39	0.04	0.01
Average composition of plagioclase	52.14	0.04	29.37	0.16	13.48	0.04	0.72	3.80	0.25
Average composition of CPX	52.41	0.49	1.84	16.11	18.90	0.36	9.67	0.22	0.01
Average composition of iron oxides	0.60	5.21	3.94	3.31	0.34	0.71	85.80	0.00	0.09
Composition of melt after phenocrysts [†] were subtracted	71.15	1.11	14.05	0.54	3.40	0.10	3.44	2.84	3.36
Average melt composition of 1991	71.90	1.05	15.46	0.95	3.21	0.07	2.26	2.17	2.92

*All compositions in this table have been normalized to 100 wt%.

[†]Calculation was with 20% phenocrysts crystallizing out of the combination melt. Of that 20%, the relative proportions of the phenocrysts subtracted to reach the 1991 average composition is:

Plagioclase	42%
CPX	31%
Iron-oxide	17%
OPX	10%

Is there a porphyry copper deposit in White Island's future?

The generally accepted model for the formation of porphyry copper-type mineralization involves the emplacement and crystallization of a hydrous silicic magma at shallow levels in the earth's crust (Burnham, 1979, 1998). During crystallization, the water concentration of the melt increases, eventually reaching saturation and resulting in the exsolution of a magmatic aqueous phase. Chlorine, copper, and other metals would be partitioned into the magmatic aqueous phase (Burnham, 1979; Candela, 1989; Bodnar, 1995). As a result of numerous theoretical, experimental and field studies of the porphyry copper environment, we now have a fairly comprehensive database of those features that are required, or are favorable, for the formation of economic mineralization (c.f., Candela, 1989; Cline and Bodnar, 1991).

Although there appear to be genetic links between shallow high-sulfidation Cu-Au deposits and deeper porphyry-style mineralization at places such as Red Mountain, Arizona (Bodnar and Beane, 1980) and Lapanto-Far Southeast in the Philippines (Arribas et al., 1995), the timing of formation of these two types of mineralization is not clear. Thus, although it has been suggested that high-sulfidation Cu-Au mineralization may presently be forming in the shallow subsurface at White Island (Hedenquist et al., 1993), it is also likely that the White Island system has not yet reached the productive stages of porphyry copper formation. White Island has been an active magmatic-hydrothermal system for only about 10,000 years (Giggenbach and Glasby, 1977). The temperature of the magma derived from homogenization of silicate melt inclusions is estimated to be about 1200°C and the magma chamber beneath White Island is probably still dominantly molten (Houghton and Nairn, 1989b). Based on numerous field studies, as well as fluid inclusion and stable isotope studies of porphyry copper deposits, it appears that the main stage of copper mineralization occurs late in the magmatic history when most or all of the melt has crystallized. Numerical models by Norton (1982) suggest that for a single emplacement of melt, it takes from 20,000 - 30,000 years for a 4 km tall pluton, with a diameter of 2 km, to cool below its solidus. This, combined with observations from melt inclusions, suggests that at the present time the deeper levels at White Island are not yet within the porphyry copper formation window.

If porphyry copper mineralization is not currently forming at depth at White Island, what is the likelihood that such mineralization will develop in the future? If we assume that the melt found in melt inclusions in this study is the same melt that will continue to evolve and eventually crystallize to form an intrusive body at depth beneath White Island, we can compare the chemical characteristics of the melt inclusions with observations from known porphyry copper deposits, as well as with similar but barren intrusive rocks. Certainly the copper concentration of the melt is sufficiently high to generate ore-forming fluids. Burnham (1998) has approximated the copper concentration of porphyry copper parent magmas by showing that 32% melting of a normal

tholeiite containing 75 ppm copper will produce a melt with about 230 ppm copper, similar to the values of 160 - 280 ppm found in melt inclusions from White Island, and much higher than the 50 ppm required to form economic concentrations of copper in various models for porphyry copper formation (c.f., Candela, 1989; Cline and Bodnar, 1991). Moreover, simple melt-aqueous fluid partition calculations (c.f., Bodnar, 1982; Burnham, 1998) show that copper concentrations in magmatic fluids exsolved from such melts can have copper concentrations of thousands of ppm.

Feiss (1978) and Mason and Feiss (1979) have measured the $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})$ ratios of rocks from a number of productive and barren intrusives, including many from the southwest Pacific region. They found that intrusive rocks associated with productive porphyry systems have higher ratios than those associated with barren systems. More specifically, most mineralized systems have ratios above about 1.3, whereas ratios lower than this are characteristic of barren systems. Using the average concentrations of Al_2O_3 , Na_2O , K_2O and CaO listed in Table 3, all of the melt inclusions have ratios ≥ 1.3 , and the glass in the unhomogenized melt inclusions from 1991 has a value of 1.9. If we consider this glass composition to represent the composition that the melt will evolve towards with continued crystallization, the $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})$ ratio of the magma beneath White Island is characteristic of rocks associated with economic porphyry copper mineralization elsewhere. Similarly, Urabe (1985) showed that the partitioning of metals into the magmatic aqueous phase was higher for aluminous (corundum normative) melts than for alkaline melts. The residual melt (glass) in the 1991 samples contains 3.9% normative corundum. Based on Urabe's data, this melt has good potential to generate magmatic aqueous fluids with high concentrations of metals.

Creasey (1984) compared the geochemistry of mineralized (Schultze Granite) to barren (Tea Cup Granodiorite and Granite Basin Porphyry) Laramide stocks. Ratios of major element cations showed a distinct division between mineralized and unmineralized stocks. Specifically, stocks with a $\text{Si}/(\text{Si}+\text{Ca}+\text{Mg}+\text{Fe}_c)$ ratio higher than 0.91 and a $\text{K}/(\text{K}+\text{Ca}+\text{Mg}+\text{Fe}_c)$ higher than 0.36 were associated with mineralization, whereas all barren stocks had lower ratios. Melt inclusions from the 1977-1989 samples have ratios that fall into the barren category. However, the cation ratios of the unhomogenized fractionated melt inclusions from the 1991 sample have ratios that are in the mineralized range. Assuming that the 1991 glass represents the composition to which the melt in the magma chamber will evolve, White Island will fall in the productive intrusion category.

Lang and Titley (1998) studied the geochemical and isotopic characteristics of a large number of Laramide magmatic systems in the southwestern U.S. These workers noted that productive intrusions show positive europium anomalies, whereas barren intrusions show negative Eu anomalies. The melt inclusions from White Island (Figure 15) all show positive Eu anomalies, again suggesting that the magma beneath White Island shows strong potential for forming

porphyry copper mineralization in the future. Fields of alkalinity of Laramide intrusions for barren and productive intrusions overlapped, however data from this study plot within their field of productive intrusions. It should be noted, however, that the Y-Mn systematics of the melt inclusions at White Island are more characteristic of barren intrusions, according to the results of Lang and Titley (1998, their Figure 8).

Candela (1989) and Cline and Bodnar (1991) have documented the importance of the initial Cl/H₂O ratio of the melt in terms of the ability of the magmatic aqueous fluid to extract metal from the melt. The Cl/H₂O ratio for melt inclusions at White Island is about 0.15, which is beyond the range of data in either of the studies listed above. However, both papers note that the higher the Cl/H₂O, the more efficient the aqueous phase is in removing copper from the melt. Stated differently, using data extrapolated from Figure 6 in Cline and Bodnar (1991), only about 5 km³ of melt would be needed to produce a copper deposit containing 250 million tons of 0.75% copper ore. For comparison, the size of the causative intrusive at the Yerington porphyry copper deposit is about 65 km³. Thus, it appears that the Cl/H₂O ratio of White Island melts will lead to very efficient extraction of copper from the melt into the magmatic aqueous phase, and its subsequent deposition in veins within and above the intrusion. It should also be noted that at the present time pyrrhotite, amphibole, biotite or other phases that might serve as sinks for copper (Candela, 1989) do not appear to be crystallizing at depth. In fact, the presence of magnetite in samples indicates an f_{O_2} value higher than the pyrrhotite stability field (Whitney, 1980). Also, melt inclusions from this study indicate that the sulfur content in the melt is lower than in a typical andesitic melt. The low sulfur content coupled with the apparent high f_{O_2} conditions, results in iron being removed from the melt as an oxide phase rather than a sulfide phase. This suggests that the copper concentration in the melt will increase with crystallization history as non-copper-bearing phases are removed from the melt.

Houghton and Nairn (1989b) have constructed a cross section of White Island based on seismic, chemical and structural data, and estimate that the main portion of the magma chamber occurs at a depth of ~3-4 km beneath White Island. With an average density of 2.4 to 2.8 g/cm³ for andesitic liquids and 2.4 to 2.9 g/cm³ for crust adjacent to andesitic volcanoes (Gill, 1981) the pressure at that depth would be 720 - 1160. Candela and Piccoli (1995) report that the maximum efficiency for partitioning copper into the aqueous phase occurs at 1 kbar. The efficiency decreases at pressures above and below this value. Thus, the magma chamber at White Island is located at a depth (pressure) ideal for maximum extraction of copper from the melt.

Recommendations

The ultimate goal of most minerals exploration companies is to be the first to discover an ore district or a mineral occurrence with economic potential. White Island offers an extraordinary opportunity for an adventurous mining company to secure future leases on a modern ore-forming system that is likely to contain economic copper mineralization after magmatic hydrothermal activity ceases in 20,000 - 30,000 years. The tectonic environment, near-surface gas and water chemistry, and deep melt chemistry (as evidenced by melt inclusions) all show features that are characteristic of metal-rich hydrothermal systems and economic porphyry copper deposits. So, explorationists, grab your claim stakes and head on out to White Island!

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Appendix A
Major element electron microprobe data

1977 ejecta
Sample WI008

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
Plag	Host	50.26	0.03	29.44	0.12	14.15	0.04	0.59	3.58	0.21	0.38	0.02	98.82
	Host	48.53	0.04	29.04	0.16	13.30	0.09	0.78	3.64	0.19	0.04	0.02	95.83
	Host	50.24	0.03	28.75	0.20	13.13	0.13	0.68	3.80	0.26	0.04	0.03	97.29
	Host	51.69	0.01	28.82	0.10	13.41	0.05	0.69	3.56	0.11	0.00	0.02	98.46
	MI 1	62.09	0.96	13.14	2.35	5.08	0.11	6.27	2.50	2.59	0.00	0.22	95.31
	MI 2	63.87	1.04	13.67	2.09	4.54	0.17	6.59	1.75	2.71	0.00	0.12	96.55
	MI 3	61.07	1.34	11.96	2.43	4.25	0.17	7.84	1.77	2.97	0.12	0.13	94.05
OPX	Host	53.86	0.22	1.10	25.97	2.14	0.33	16.27	0.05	0.06	0.00	0.01	100.01
	Host	53.71	0.33	1.02	25.59	2.13	0.34	16.55	0.09	0.00	0.04	0.02	99.82
	Host	53.88	0.34	1.13	25.96	2.06	0.48	15.88	0.04	0.00	0.07	0.00	99.84
	Host	53.08	0.25	1.47	25.84	2.23	0.51	16.38	0.06	0.03	0.21	0.02	100.08
	MI 1	61.97	1.17	13.80	0.98	5.60	0.15	7.52	1.96	2.54	0.00	0.18	95.87
	Plag inclusion-1	51.06	0.00	29.36	0.22	13.87	0.03	1.38	3.54	0.13	0.13	0.00	99.72
	Plag inclusion-2	50.29	0.00	29.10	0.39	14.10	0.11	1.53	3.03	0.27	0.00	0.00	98.82
	Plag inclusion-3	54.08	0.29	25.16	0.29	10.97	0.03	2.30	3.22	0.85	0.09	0.11	97.39
	Plag inclusion-4	50.82	0.03	29.96	0.17	13.53	0.01	1.30	3.52	0.20	0.21	0.04	99.79
	Plag inclusion-5	51.36	0.24	28.03	0.20	12.33	0.07	1.75	2.93	0.63	0.00	0.00	97.54
	Plag inclusion-6	52.70	0.16	27.71	0.30	12.57	0.00	1.66	3.29	0.47	0.00	0.01	98.87
	Plag inclusion-7	51.24	0.11	27.96	0.44	13.27	0.06	1.26	3.68	0.28	0.00	0.04	98.34
	Plag inclusion-8	51.11	0.08	29.67	0.21	13.74	0.12	1.24	3.49	0.20	0.25	0.01	100.12
OPX	Host	53.81	0.13	1.17	25.76	2.06	0.31	16.60	0.06	0.00	0.21	0.02	100.13
	Host	53.43	0.33	0.98	26.05	2.26	0.48	15.89	0.00	0.00	0.14	0.00	99.56

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Host	54.02	0.25	1.12	25.78	2.07	0.45	15.76	0.02	0.00	0.18	0.00	99.65
	Plag inclusion-1	52.32	0.09	27.82	0.20	12.11	0.03	1.94	3.87	0.39	0.17	0.05	98.99
	Plag inclusion-2	50.87	0.05	29.16	0.18	13.78	0.03	1.47	3.30	0.20	0.04	0.05	99.13
	Plag inclusion-3	51.35	0.12	28.71	0.49	13.36	0.12	1.59	3.19	0.20	0.13	0.02	99.28
	Plag inclusion-4	53.39	0.15	26.59	0.24	12.77	0.05	1.85	2.97	0.48	0.25	0.03	98.77
	Plag inclusion-5	50.63	0.09	27.04	1.69	12.99	0.06	2.02	3.20	0.29	0.00	0.04	98.05
	Plag inclusion-6	51.91	0.01	28.13	0.25	13.86	0.05	1.30	3.41	0.30	0.30	0.02	99.54
	Plag inclusion-7	48.67	0.05	29.45	0.13	13.89	0.00	1.51	3.51	0.20	0.09	0.00	97.50
	Plag inclusion-8	50.53	0.04	29.37	0.19	13.90	0.00	1.48	3.30	0.19	0.17	0.01	99.18
	Plag inclusion-9	50.66	0.12	28.89	0.73	13.61	0.01	1.43	3.04	0.34	0.00	0.00	98.83
	Plag inclusion-10	51.74	0.03	28.88	0.16	12.69	0.00	1.37	3.93	0.22	0.00	0.00	99.02
	Plag inclusion-11	50.87	0.00	29.63	0.24	14.12	0.00	1.16	3.27	0.12	0.00	0.02	99.43
OPX	Host	53.56	0.09	0.94	26.22	1.86	0.48	16.97	0.02	0.00	0.07	0.00	100.21
	Host	51.73	0.15	1.19	26.09	1.90	0.35	15.84	0.04	0.01	0.14	0.02	97.46
	Host	53.82	0.14	1.08	25.81	2.01	0.39	15.48	0.04	0.00	0.07	0.00	98.84
	MI 1	64.77	0.68	13.47	1.81	5.12	0.13	6.72	3.05	2.76	0.00	0.11	98.62
	MI 2	65.28	1.14	13.22	1.31	5.08	0.17	6.94	1.75	2.74	0.20	0.08	97.91
	MI 3	64.27	0.90	13.45	1.30	5.05	0.29	6.94	1.82	2.84	0.20	0.14	97.20
	MI 4	64.01	1.02	13.71	1.37	4.94	0.16	7.42	2.15	2.79	0.00	0.10	97.67
	Plag inclusion-1	50.34	0.00	29.05	0.23	13.06	0.05	1.28	3.74	0.15	0.00	0.03	97.93
	Plag inclusion-2	54.71	0.14	26.09	0.85	11.30	0.14	2.35	3.53	0.56	0.04	0.00	99.71
OPX*	Host	54.33	0.33	1.23	26.45	1.87	0.38	16.43	0.00	0.03	0.12	0.01	101.18
Plag*	Host	52.58	0.03	28.92	0.15	13.45	0.02	0.66	3.78	0.23	0.07	0.00	99.89
	Host	52.34	0.03	29.38	0.17	13.81	0.00	0.85	3.93	0.26	0.04	0.00	100.81
	MI 1	65.75	1.28	12.54	2.13	4.44	0.11	6.27	3.10	3.07	0.17	0.10	98.96
	MI 2	65.21	1.27	11.53	2.31	4.08	0.05	6.76	2.85	3.07	0.00	0.13	97.26
	MI 3	66.12	1.32	11.51	2.19	4.25	0.13	7.20	3.13	2.95	0.17	0.14	99.11

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	MI 4	65.65	1.60	11.30	2.22	4.25	0.19	7.56	2.70	3.11	0.00	0.19	98.77
	MI 5	64.52	1.35	12.27	2.26	4.59	0.14	7.42	2.99	2.98	0.07	0.17	98.76
	MI 6	64.91	1.41	11.95	2.21	4.47	0.14	7.21	2.73	3.04	0.07	0.15	98.29
OPX*	Host	53.25	0.19	1.07	26.59	1.82	0.31	16.76	0.00	0.00	0.09	0.00	100.08
	Host	54.58	0.17	1.15	26.22	1.70	0.34	17.10	0.00	0.00	0.18	0.02	101.46
Matrix*	Matrix glass	66.30	1.27	12.89	1.29	3.78	0.09	6.39	3.09	3.26	0.03	0.10	98.49
	Matrix glass	66.74	1.25	12.87	1.38	3.73	0.15	6.29	2.67	3.20	0.07	0.10	98.45
	Matrix glass	66.90	1.22	13.19	1.02	3.41	0.07	6.26	2.46	3.33	0.00	0.12	97.98
	Iron oxide	0.24	9.36	3.15	3.03	0.16	0.67	76.34	0.00	0.08	0.11	0.01	93.15
	Iron oxide	9.55	8.58	4.46	2.11	0.52	0.42	68.33	0.38	0.43	0.23	0.04	95.05

1986 ejecta

Sample - 86 0210

Plag*	Host	52.34	0.05	28.99	0.19	13.16	0.00	0.60	3.56	0.28	0.18	0.01	99.36
	Host	51.58	0.02	29.50	0.12	13.81	0.00	0.65	3.54	0.26	0.00	0.00	99.48
	Host	53.14	0.00	28.92	0.16	12.88	0.00	0.73	4.03	0.25	0.14	0.02	100.27
	MI 1	63.51	1.01	14.16	2.31	5.02	0.13	5.79	2.89	2.51	0.24	0.11	97.68
	MI 2	62.87	1.08	14.02	2.29	5.23	0.05	6.45	2.50	2.59	0.30	0.13	97.51
	MI 3	63.23	1.19	14.07	2.22	5.23	0.08	6.06	2.53	2.53	0.14	0.12	97.40
	MI 4	63.99	1.00	14.27	2.16	4.82	0.08	6.22	2.78	2.58	0.30	0.09	98.29
	MI 5	64.10	1.00	13.99	2.14	4.81	0.06	5.88	2.78	2.53	0.07	0.18	97.54
	MI 6	63.34	1.01	13.86	2.18	5.27	0.05	5.89	3.00	2.57	0.03	0.12	97.32
	MI 7	63.98	0.98	14.24	2.09	5.02	0.18	5.91	2.87	2.62	0.07	0.10	98.06
	MI 8	63.62	1.16	14.17	1.96	4.55	0.08	5.45	2.96	2.68	0.00	0.09	96.72
CPX*	Host	52.97	0.52	1.67	16.23	19.55	0.39	9.68	0.23	0.01	0.03	0.00	101.28
	Host	52.71	0.48	1.77	16.40	19.46	0.30	9.08	0.22	0.01	0.10	0.00	100.53
	MI 1a	64.20	1.14	13.57	2.01	5.34	0.06	6.12	2.95	2.48	0.17	0.11	98.15

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	MI 1b	64.59	1.16	13.36	2.11	5.14	0.08	6.15	2.84	2.52	0.14	0.13	98.22
	MI 2	63.80	1.04	13.52	2.18	5.38	0.05	6.40	3.01	2.31	0.10	0.12	97.91
	MI 3	63.60	1.12	13.47	2.26	5.55	0.11	6.80	2.77	2.32	0.30	0.12	98.42
	MI 2	63.35	1.07	13.48	2.18	5.20	0.14	6.88	3.08	2.30	0.07	0.12	97.87
	MI 4	63.42	1.13	13.52	2.10	5.31	0.12	6.31	3.02	2.50	0.03	0.11	97.57
	MI 5	64.29	1.20	13.49	2.13	5.16	0.02	6.17	2.87	2.45	0.14	0.13	98.05
OPX*	Host	54.44	0.20	0.97	26.54	2.00	0.38	16.45	0.00	0.00	0.03	0.00	101.01
	MI 1	64.05	0.95	13.76	2.31	5.21	0.21	6.55	3.02	2.39	0.03	0.11	98.59
Matrix*	Matrix glass	61.69	1.05	14.08	2.67	5.81	0.18	6.22	3.37	2.37	0.00	0.08	97.52
	Matrix glass	63.57	1.01	13.98	2.54	5.86	0.06	6.11	3.18	2.34	0.03	0.11	98.79
	Matrix glass	63.25	0.98	14.38	2.23	5.35	0.10	5.68	3.13	2.56	0.20	0.10	97.96
	Matrix glass	62.77	1.00	14.03	2.39	5.72	0.08	6.02	2.98	2.33	0.00	0.12	97.44
	Matrix glass	62.67	1.05	14.17	2.50	5.56	0.13	6.21	3.21	2.34	0.17	0.11	98.12
	Matrix glass	62.37	1.10	14.27	2.50	5.57	0.04	6.49	3.28	2.41	0.20	0.13	98.36
1988 ejecta													
Sample 880325													
CPX	Host	51.33	0.43	2.01	16.35	18.99	0.35	9.84	0.22	0.02	0.05	0.01	99.60
	Host	52.03	0.53	1.98	16.10	19.66	0.33	10.08	0.24	0.05	0.07	0.00	101.07
	Host	52.66	0.45	2.05	16.25	19.03	0.41	9.56	0.26	0.02	0.10	0.00	100.79
	MI1a	64.63	0.83	13.71	2.04	5.06	0.14	6.64	2.95	2.66	0.14	0.10	98.90
	MI1b	64.10	1.03	14.31	2.04	5.11	0.17	6.51	2.96	2.88	0.12	0.11	99.34
	MI1c	61.34	0.96	14.16	2.12	5.07	0.16	6.49	2.96	2.79	0.02	0.11	96.18
	MI 2	62.84	1.15	13.35	2.36	5.36	0.19	7.12	2.86	2.37	0.05	0.12	97.77
	MI 3	62.97	1.20	13.74	1.99	5.19	0.20	7.73	2.92	2.29	0.00	0.14	98.37
	MI 4	64.11	0.96	13.97	1.76	4.43	0.14	6.15	2.98	2.91	0.00	0.10	97.51
	MI 5	63.23	0.88	13.52	2.22	5.08	0.15	6.31	2.79	2.68	0.00	0.11	96.97
	MI 6	65.44	0.87	13.91	1.75	4.67	0.12	6.02	1.79	2.93	0.00	0.09	97.59

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	MI 7	61.02	1.30	13.89	2.63	5.97	0.21	7.94	2.91	1.86	0.00	0.11	97.84
	Plag inclusion 1a	51.23	0.17	24.34	3.08	14.79	0.15	2.79	3.23	0.17	0.02	0.00	99.97
	Plag inclusion 1b	52.71	0.15	26.08	2.07	14.27	0.10	1.92	3.39	0.16	0.11	0.00	100.96
	Plag inclusion 2	55.19	0.26	27.32	0.56	12.31	0.10	2.39	3.02	0.61	0.04	0.02	101.82
OPX	Host	54.67	0.34	1.16	25.99	2.14	0.48	17.35	0.06	0.01	0.09	0.01	102.30
	Host	54.16	0.28	1.18	26.05	2.16	0.54	17.45	0.03	0.03	0.13	0.00	102.01
	MI 1	63.63	0.85	14.54	2.22	5.51	0.12	6.54	3.02	2.61	0.05	0.17	99.26
	MI 2	65.65	0.76	14.98	1.84	5.12	0.18	6.07	2.28	2.77	0.14	0.16	99.95
	MI 3	65.87	1.04	14.16	1.43	4.92	0.15	6.37	2.46	2.71	0.17	0.13	99.41
	MI 4	65.10	1.07	13.86	2.02	4.70	0.16	6.92	3.13	2.62	0.00	0.13	99.71
	MI 5	64.60	1.01	13.49	2.36	4.53	0.16	6.24	3.18	2.59	0.07	0.11	98.34
	MI 6	65.01	0.76	15.21	1.83	5.78	0.12	6.00	1.79	2.76	0.09	0.15	99.50
	MI 7	65.59	1.14	14.24	1.95	4.98	0.26	6.92	2.10	2.62	0.00	0.11	99.91
	Plag inclusion 1	55.96	0.37	25.36	0.79	11.30	0.07	3.08	3.37	0.70	0.05	0.03	101.08
	Plag inclusion 2	55.48	0.30	24.99	1.17	11.33	0.08	2.71	3.33	0.59	0.00	0.02	100.00
CPX	Host	52.27	0.49	1.92	17.33	19.51	0.32	7.92	0.24	0.00	0.02	0.00	100.02
	MI 1a	59.99	1.11	13.91	2.37	5.31	0.20	7.14	2.00	2.36	0.12	0.11	94.62
	MI 1b	62.09	0.89	15.83	2.03	5.94	0.23	6.23	3.09	2.33	0.00	0.12	98.78
	MI 2	63.45	0.70	15.35	2.33	5.30	0.16	5.27	2.28	3.00	0.00	0.13	97.97
	MI 3	64.53	0.89	15.37	2.01	5.17	0.16	5.73	2.34	2.81	0.00	0.14	99.15
	MI 4	64.92	0.89	15.60	2.37	5.03	0.13	5.78	2.18	2.78	0.00	0.15	99.83
	MI 5	65.35	0.86	15.57	1.86	4.55	0.18	5.22	2.30	3.24	0.02	0.16	99.31
	Plag inclusion 1a	52.09	0.05	29.31	0.32	13.53	0.07	0.98	3.73	0.31	0.00	0.00	100.39
	Plag inclusion 1b	52.21	0.05	29.86	0.20	13.08	0.08	0.99	3.74	0.25	0.00	0.00	100.46
	Plag inclusion 1c	51.13	0.09	28.92	0.17	13.03	0.07	0.81	3.60	0.28	0.05	0.00	98.15
	Plag inclusion 2a	49.98	0.07	30.36	0.19	14.55	0.09	1.00	3.00	0.16	0.14	0.00	99.54
	Plag inclusion 2b	49.72	0.07	31.58	0.18	15.32	0.10	0.91	2.61	0.18	0.02	0.00	100.69
	Plag inclusion 3a	52.35	0.10	28.89	0.84	13.71	0.05	1.31	3.22	0.37	0.00	0.01	100.85

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Plag inclusion 3b	52.02	0.04	30.37	0.19	13.90	0.13	1.01	3.47	0.28	0.00	0.00	101.41
	Plag inclusion 4a	51.49	0.09	28.69	0.81	13.96	0.15	1.35	3.49	0.28	0.00	0.00	100.31
	Plag inclusion 4b	52.48	0.05	29.94	0.18	13.35	0.06	0.97	3.70	0.28	0.00	0.00	101.01
Matrix	Matrix glass	64.18	1.00	14.11	2.42	5.64	0.20	6.17	3.25	2.55	0.07	0.11	99.70
	Matrix glass	64.38	1.09	14.13	2.50	5.73	0.19	6.44	3.05	2.40	0.14	0.12	100.17
	Matrix glass	64.86	0.97	14.57	2.35	5.47	0.22	6.18	3.13	2.54	0.00	0.06	100.35
	Matrix glass	64.53	1.09	14.34	2.45	5.36	0.22	6.38	3.20	2.56	0.00	0.07	100.20
	Matrix glass	65.06	1.15	14.48	2.39	5.04	0.16	6.04	3.24	2.45	0.05	0.08	100.14
	Plag	52.36	0.07	29.93	0.17	13.63	0.02	0.86	3.75	0.31	0.07	0.00	101.17
	Plag	53.58	0.08	29.48	0.19	13.20	0.08	0.71	3.87	0.31	0.00	0.00	101.50

1989 ejecta

Sample 891129

OPX	Host	55.09	na	1.15	25.92	1.86	0.67	16.83	0.08	0.00	na	na	101.60
	Host	53.76	na	1.23	27.14	2.06	0.55	18.38	0.08	0.00	na	na	103.20
	Host	54.44	na	1.12	25.84	2.37	0.35	17.40	0.00	0.00	na	na	101.52
	Host	53.19	na	0.82	26.42	2.04	0.64	16.06	0.00	0.00	na	na	99.17
	Host	53.07	na	1.29	26.97	2.42	0.38	17.67	0.08	0.05	na	na	101.93
	Host	53.52	na	1.28	26.81	2.00	0.20	16.80	0.11	0.05	na	na	100.77
	Host	55.72	na	1.22	26.24	2.60	0.17	17.27	0.00	0.03	na	na	103.26
	Host	54.41	na	1.10	26.29	2.24	0.64	16.41	0.11	0.00	na	na	101.20
	Host	54.99	na	1.33	26.32	2.38	0.44	17.09	0.02	0.00	na	na	102.57
	Host	54.80	na	1.10	26.32	2.29	0.38	16.49	0.08	0.00	na	na	101.45
	MI 1	63.47	na	14.31	1.85	6.15	0.15	7.49	2.49	1.74	na	na	97.64
	MI 2	64.22	na	13.82	1.07	5.91	0.30	5.74	2.99	2.68	na	na	96.72
	MI 3	62.85	na	13.90	1.58	5.44	0.00	7.68	2.87	2.55	na	na	96.86
	MI 4	63.48	na	14.58	0.81	5.82	0.12	7.32	2.55	2.45	na	na	97.13
	Plag inclusion 1	49.91	na	27.06	0.13	13.56	0.00	1.29	2.43	0.21	na	na	94.60

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Plag inclusion 2	51.25	na	30.40	0.12	14.51	0.00	1.58	3.69	0.23	na	na	101.78
	Plag inclusion 3	50.93	na	31.02	0.18	14.28	0.00	1.43	3.36	0.11	na	na	101.32
	Plag inclusion 4	51.21	na	28.90	0.20	12.90	0.00	1.33	3.65	0.19	na	na	98.39
	Plag inclusion 5	51.26	na	30.01	0.13	14.60	0.00	1.58	3.44	0.17	na	na	101.20
	Plag inclusion 6	51.69	na	29.65	0.46	13.50	0.12	1.73	3.79	0.37	na	na	101.30
	Plag inclusion 7	51.55	na	29.64	0.22	13.76	0.24	1.73	3.48	0.23	na	na	100.86
	Plag inclusion 8	51.09	na	30.79	0.29	13.41	0.06	1.33	3.88	0.17	na	na	101.02
	Plag inclusion 9	52.28	na	30.85	0.24	14.20	0.33	1.62	4.43	0.21	na	na	104.15
	Plag inclusion 10	52.63	na	29.27	0.56	14.13	0.18	1.80	3.71	0.41	na	na	102.69
	Plag inclusion 11	52.53	na	30.04	0.15	13.74	0.03	1.62	3.62	0.25	na	na	101.98
	Plag inclusion 12	50.95	na	28.91	0.67	14.81	0.30	1.73	3.28	0.07	na	na	100.72
	Plag inclusion 13	51.76	na	30.77	0.20	12.48	0.03	1.88	3.89	0.39	na	na	101.40
	Plag inclusion 14	52.32	na	30.64	0.24	13.86	0.00	1.59	3.72	0.19	na	na	102.56
	Plag inclusion 15	51.50	na	30.48	0.25	13.00	0.03	1.88	3.92	0.17	na	na	101.23
	Plag inclusion 16	52.65	na	27.56	1.90	12.53	0.03	1.99	3.09	0.41	na	na	100.16
	Plag inclusion 17	50.95	na	29.60	0.18	13.29	0.00	1.62	3.44	0.07	na	na	99.15
	Plag inclusion 18	52.38	na	28.58	0.17	13.61	0.27	1.62	3.93	0.33	na	na	100.89
	Plag inclusion 19	50.77	na	30.69	0.29	14.47	0.00	1.95	3.51	0.15	na	na	101.83
	Plag inclusion 20	51.37	na	28.75	0.12	13.99	0.03	1.36	3.89	0.29	na	na	99.80
	Plag inclusion 30	52.67	na	30.39	0.18	13.23	0.03	1.36	3.88	0.21	na	na	101.95
	Plag inclusion 31	50.96	na	29.42	0.41	13.28	0.03	1.55	3.19	0.29	na	na	99.13
	Plag inclusion 32	54.50	na	27.69	0.91	11.25	0.12	2.21	3.47	0.38	na	na	100.53
	Plag inclusion 33	51.49	na	30.37	0.13	14.58	0.00	1.18	3.66	0.11	na	na	101.52
	Plag inclusion 34	50.97	na	30.26	0.25	13.37	0.00	2.17	3.94	0.21	na	na	101.17
	Plag inclusion 35	51.27	na	30.61	0.22	12.64	0.12	1.33	3.80	0.05	na	na	100.04
	Plag inclusion 36	50.60	na	29.29	0.08	13.00	0.27	1.22	3.54	0.19	na	na	98.19
	Plag inclusion 37	51.59	na	30.14	0.17	12.54	0.12	2.02	3.47	0.17	na	na	100.22
	Plag inclusion 38	52.76	na	31.04	0.15	12.66	0.00	1.80	3.89	0.13	na	na	102.43
	Plag inclusion 39	49.99	na	31.11	0.38	13.42	0.36	1.33	4.44	0.11	na	na	101.14
	Plag inclusion 40	50.96	na	29.70	0.39	14.68	0.06	1.69	3.48	0.15	na	na	101.11

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Plag inclusion 41	50.72	na	28.25	0.94	12.64	0.09	1.69	3.57	0.19	na	na	98.09
	Plag inclusion 42	51.50	na	29.74	0.31	13.29	0.09	1.63	3.69	0.19	na	na	100.45
	average n=17												
Plag	Host	52.86	0.10	28.76	0.17	12.68	na	0.67	4.13	0.31	na	na	99.68
	Host	52.12	0.10	29.39	0.17	13.13	na	0.74	4.05	0.25	na	na	99.95
	MI 1	63.79	1.20	13.45	2.56	4.99	na	6.27	1.54	2.37	na	na	96.17
	MI 2	61.28	1.20	13.27	2.55	4.47	na	6.12	1.91	2.61	na	na	93.41
	CPX inclusion 1	52.31	0.40	1.97	17.30	19.09	na	8.63	0.27	0.00	na	na	99.97
	CPX inclusion 2a	51.72	0.30	1.83	17.80	19.05	na	8.98	0.27	0.05	na	na	100.00
	CPX inclusion 2b	51.71	0.50	1.84	17.05	18.62	na	8.57	0.28	0.05	na	na	98.62
	CPX inclusion 3	51.63	0.40	1.89	16.72	19.44	na	8.57	0.31	0.00	na	na	98.96
	CPX inclusion 4	50.97	0.40	1.99	17.32	18.83	na	8.07	0.16	0.05	na	na	97.79
	CPX inclusion 5a	51.72	0.60	1.99	16.96	19.34	na	9.63	0.35	0.02	na	na	100.61
	CPX inclusion 5b	52.91	0.50	2.00	17.35	19.03	na	8.38	0.28	0.09	na	na	100.54
	CPX inclusion 6	52.76	0.40	2.00	17.70	18.39	na	8.81	0.30	0.02	na	na	100.38
	CPX inclusion 7	52.01	0.50	1.95	17.53	19.28	na	8.79	0.20	0.02	na	na	100.28
	CPX inclusion 8	51.69	0.40	1.96	17.04	19.14	na	8.66	0.34	0.04	na	na	99.27
	CPX inclusion 9	52.29	0.40	1.94	16.51	19.24	na	8.40	0.22	0.01	na	na	99.01
	CPX inclusion 10	51.49	0.50	1.97	17.17	19.06	na	8.63	0.23	0.08	na	na	99.13
	CPX inclusion 11	53.22	0.40	1.79	17.54	18.81	na	8.92	0.29	0.06	na	na	101.03
	OPX inclusion 1a	54.20	0.30	1.07	27.77	2.14	na	15.20	0.10	0.01	na	na	100.79
	OPX inclusion 1b	53.94	0.20	1.24	27.14	2.07	na	14.90	0.07	0.05	na	na	99.61
Plag	Host	52.51	0.10	29.17	0.16	12.83	na	0.67	3.70	0.27	na	na	99.41
	MI 1	67.25	1.00	14.07	1.30	3.73	na	6.15	2.39	2.78	na	na	98.67
	MI 2	65.39	0.90	13.51	2.24	4.58	na	6.46	2.24	2.37	na	na	97.69
	MI 3	64.99	0.90	13.39	1.89	4.15	na	5.25	1.99	2.79	na	na	95.35
	MI 4	63.73	1.30	13.44	2.40	4.46	na	6.42	1.72	2.47	na	na	95.94
	MI 5	65.35	1.10	13.75	2.28	4.24	na	5.92	1.84	2.68	na	na	97.16

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	MI 6	64.54	1.00	13.71	2.12	4.64	na	5.30	2.16	2.60	na	na	96.07
	MI 7	65.69	1.00	13.94	2.00	4.49	na	6.35	2.12	2.84	na	na	98.43
	MI 8	64.76	1.00	13.29	1.87	4.44	na	5.52	2.41	2.84	na	na	96.13
	CPX inclusion 1	52.55	0.50	1.95	17.04	18.16	na	9.44	0.25	0.04	na	na	99.93
Plag	Host	51.82	0.00	29.15	0.17	13.41	na	0.89	3.68	0.33	na	na	99.45
	MI 1	64.52	1.00	13.54	2.03	4.73	na	5.86	2.50	2.84	na	na	97.02
	MI 2	65.62	0.90	13.67	1.86	4.68	na	6.24	2.47	2.76	na	na	98.20
	MI 3	63.21	1.20	13.31	2.13	5.09	na	6.55	1.98	2.77	na	na	96.24
	MI 4	63.22	1.10	13.17	2.15	4.86	na	6.61	2.42	2.55	na	na	96.08
	MI 5	64.88	1.40	13.70	2.36	5.42	na	6.85	2.02	2.38	na	na	99.01
	MI 6	62.35	1.00	13.51	2.06	4.62	na	6.08	2.28	2.49	na	na	94.39
	CPX inclusion 1	53.26	0.40	1.82	16.85	19.22	na	9.16	0.33	0.02	na	na	101.06
	OPX inclusion 2a	48.75	0.30	1.12	26.17	1.99	na	15.19	0.02	0.04	na	na	93.58
	OPX inclusion 2b	49.67	0.30	1.13	25.86	1.86	na	14.94	0.05	0.06	na	na	93.87
	OPX inclusion 3	51.76	0.30	1.11	26.77	2.05	na	15.35	0.04	0.03	na	na	97.41
Matrix	OPX	50.53	0.30	1.10	24.73	2.02	na	14.61	0.02	0.04	na	na	93.35
	Matrix glass	63.51	1.10	12.81	1.79	4.67	na	6.52	2.32	2.71	na	na	95.43
1991 ejecta													
Sample 911206A - unhomogenized													
OPX	Host	53.24	0.17	1.14	25.66	2.05	0.38	15.58	0.02	0.01	0.00	0.01	98.26
	Host	52.48	0.26	1.01	25.70	2.11	0.34	16.74	0.01	0.01	0.14	0.01	98.81
	Host	53.45	0.26	1.13	25.30	2.20	0.42	15.76	0.04	0.00	0.00	0.02	98.58
	Host	53.33	0.18	1.00	26.21	2.12	0.31	15.11	0.00	0.01	0.21	0.00	98.48
	Host	52.43	0.23	1.25	26.10	2.08	0.32	15.81	0.03	0.00	0.25	0.00	98.50
	MI 1	69.18	1.32	15.03	0.19	3.10	0.08	1.93	1.62	2.73	0.00	0.45	95.63
	MI 2a	66.34	1.42	14.92	0.20	3.47	0.16	2.82	3.27	2.55	0.00	0.82	95.97
	MI 2b	68.64	1.49	16.20	0.21	3.64	0.11	2.42	1.48	2.11	0.04	0.76	97.10

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	MI 3	69.01	1.19	14.87	0.17	2.84	0.02	2.29	1.81	2.79	0.25	0.23	95.47
	MI 4	66.11	0.75	12.89	3.80	2.10	0.01	2.26	1.50	3.06	0.08	0.22	92.78
	MI 5	68.60	0.96	15.00	0.24	2.97	0.13	2.62	1.70	2.84	0.13	0.13	95.32
	MI 6	63.24	1.00	12.57	4.06	4.53	0.17	3.79	1.24	2.05	0.04	0.10	92.79
	MI 7	66.75	0.95	15.42	0.64	4.55	0.16	2.29	1.69	1.91	0.29	0.53	95.18
	MI 8	64.96	0.95	14.39	2.59	3.93	0.07	2.97	2.39	2.09	0.21	0.40	94.95
	Plag inclusion 1a	49.97	0.04	29.23	0.16	14.03	0.03	1.46	3.21	0.09	0.00	0.02	98.24
	Plag inclusion 1b	50.38	0.02	29.04	0.20	13.71	0.08	1.63	3.33	0.13	0.25	0.00	98.77
	Plag inclusion 2	51.26	0.02	29.42	0.16	13.58	0.01	1.37	3.65	0.14	0.00	0.01	99.62
	Plag inclusion 3	49.93	0.11	27.93	0.18	13.52	0.07	1.24	3.56	0.19	0.04	0.02	96.79
	Plag inclusion 4	51.37	0.09	29.07	0.17	13.22	0.00	1.04	3.90	0.20	0.13	0.00	99.19
	Plag inclusion 5	51.11	0.08	29.02	0.18	13.33	0.00	1.45	3.71	0.15	0.00	0.00	99.03
	Plag inclusion 6	51.39	0.14	28.78	0.19	13.15	0.01	1.47	3.92	0.16	0.00	0.00	99.21
	Plag inclusion 7	52.56	0.19	26.96	3.42	11.20	0.13	2.11	3.41	0.30	0.13	0.00	100.41
	Plag inclusion 8	51.65	0.04	28.36	0.24	13.05	0.00	1.28	3.97	0.19	0.00	0.02	98.80
	CPX w/in MI 3	55.35	2.88	11.74	3.76	12.28	0.40	12.36	1.18	1.63	0.00	0.39	101.97
	Plag w/in MI 3	50.64	0.05	28.68	0.23	13.60	0.10	1.32	3.47	0.15	0.17	0.01	98.42
	Plag w/in MI4	50.59	0.10	27.46	0.17	13.69	0.07	1.22	3.80	0.09	0.00	0.02	97.21
OPX	Host	53.93	0.17	0.92	26.01	1.88	0.34	15.49	0.04	0.00	0.04	0.00	98.82
	Host	53.76	0.16	1.15	25.73	2.16	0.42	16.01	0.07	0.05	0.04	0.01	99.56
	MI 1a	69.69	0.65	15.80	0.17	2.84	0.08	1.90	2.08	3.14	0.08	0.22	96.65
	MI 1b	70.40	0.90	15.63	0.14	2.71	0.06	1.85	1.97	3.21	0.00	0.19	97.06
	MI 2	67.32	0.67	13.29	2.01	3.14	0.08	2.48	2.08	2.57	0.04	0.13	93.81
	MI 3	66.78	0.71	13.87	0.94	3.12	0.02	2.03	1.79	2.42	0.08	0.18	91.94
	Plag inclusion 1	49.91	0.00	30.12	0.19	14.81	0.00	1.41	2.86	0.09	0.04	0.00	99.43
	Plag inclusion 2	50.99	0.09	28.04	0.18	13.00	0.06	1.13	3.60	0.12	0.00	0.00	97.21
	Plag inclusion 3	51.27	0.08	27.59	0.85	12.86	0.11	1.36	3.70	0.20	0.00	0.00	98.02
	Plag inclusion 4	52.67	0.07	26.48	3.20	11.49	0.02	1.57	3.54	0.29	0.08	0.00	99.41
	Plag inclusion 5a	51.04	0.00	28.46	0.17	12.68	0.00	1.22	3.54	0.25	0.00	0.00	97.36

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Plag inclusion 5b	48.16	0.06	27.02	0.25	12.45	0.01	1.10	3.67	0.22	0.04	0.00	92.98
OPX	Host	54.22	0.22	1.21	25.92	2.03	0.42	16.21	0.06	0.00	0.00	0.00	100.29
	Host	53.76	0.29	1.13	26.38	2.23	0.27	16.62	0.04	0.01	0.04	0.01	100.78
	MI 1a	70.16	0.91	15.55	0.19	2.61	0.00	1.74	2.02	3.02	0.12	0.12	96.44
	MI 1b	69.49	0.81	15.38	0.25	2.66	0.06	1.66	2.23	3.30	0.00	0.20	96.04
	Plag inclusion 1	52.21	0.02	29.27	0.21	13.28	0.01	1.21	3.39	0.16	0.00	0.00	99.76
OPX	Host	54.44	0.31	1.09	26.31	1.87	0.32	15.87	0.03	0.00	0.07	0.05	100.36
	Host	53.43	0.22	1.52	26.14	2.17	0.41	15.64	0.01	0.01	0.00	0.00	99.55
	Host	53.28	0.27	1.23	26.16	2.47	0.46	15.65	0.02	0.00	0.32	0.01	99.87
CPX*	Host	47.42	0.40	1.61	15.62	18.63	0.23	8.75	0.18	0.02	0.17	0.00	93.03
	Host	52.24	0.50	1.83	16.29	19.72	0.31	9.34	0.24	0.00	0.31	0.00	100.78
	Host	51.41	0.48	1.83	16.23	19.37	0.37	9.21	0.19	0.00	0.24	0.00	99.33
	MI 1a	69.75	1.21	14.85	0.23	2.28	0.04	1.29	2.84	3.47	0.11	0.15	96.22
	MI 1b	69.18	1.03	14.83	0.22	2.26	0.00	1.39	2.90	3.53	0.28	0.14	95.76
	MI 2	70.37	0.77	13.12	0.65	2.91	0.02	1.69	1.75	2.95	0.21	0.12	94.56
	Fe phase w/in MI 1	24.78	1.29	7.23	2.00	4.23	0.34	57.06	0.47	0.74	0.07	0.01	98.22
	Plag w/in MI 2	49.35	0.05	29.35	0.19	14.43	0.00	1.06	3.30	0.19	0.11	0.02	98.05
	Fe oxide w/in MI 2	29.78	1.68	7.85	3.14	4.34	0.34	59.43	0.49	0.87	0.21	0.03	108.16
CPX*	Host	52.10	0.51	1.97	16.15	19.17	0.41	10.07	0.14	0.00	0.34	0.00	100.86
	Host	52.25	0.45	1.79	16.18	18.79	0.33	10.28	0.15	0.01	0.10	0.02	100.35
	MI 1	71.39	1.24	15.31	0.23	2.34	0.02	1.36	2.86	2.81	0.10	0.12	97.78
	Plag w/in MI 1	53.55	0.05	28.45	0.18	12.75	0.09	0.91	4.11	0.20	0.14	0.00	100.43
	Fe oxide w/in MI 1	1.35	1.68	3.26	1.53	0.95	0.63	83.54	0.00	0.08	0.17	0.04	93.23
Matrix	Matrix glass	67.01	1.17	15.23	0.56	3.83	0.04	4.37	3.61	1.92	0.28	0.20	98.22
	Matrix glass	63.33	0.83	15.59	0.81	5.70	0.09	4.64	4.14	1.65	0.36	0.19	97.33
	Matrix glass	66.48	0.93	14.32	0.62	3.51	0.27	4.91	4.46	1.84	0.00	0.23	97.57

Host type	Analysis type	SiO2	TiO2	Al2O3	MgO	CaO	MnO	FeO	Na2O	K2O	F	Cl	Total
	Matrix glass*	63.47	1.24	11.30	3.51	4.66	0.23	7.91	2.17	3.33	0.00	0.09	97.91
	Matrix glass*	67.50	1.04	13.56	0.84	2.95	0.12	6.22	2.80	3.60	0.24	0.10	98.97
	CPX	50.98	0.56	1.94	16.25	19.73	0.36	9.08	0.25	0.00	0.16	0.03	99.34
	CPX	51.53	0.43	2.12	16.24	19.43	0.36	8.81	0.26	0.00	0.16	0.04	99.38
	CPX*	48.73	1.30	4.81	14.10	18.64	0.32	10.10	0.24	0.08	0.14	0.00	98.46

Sample 911206A - homogenized

CPX	Host	52.69	0.55	1.79	15.90	18.70	0.42	9.97	0.25	0.00	0.00	0.03	100.30
	Host	53.40	0.48	1.81	16.41	18.80	0.34	9.79	0.31	0.02	0.00	0.05	101.40
	Host	52.78	0.51	2.08	16.00	18.38	0.34	9.82	0.19	0.01	0.07	0.00	100.15
	Host	52.56	0.47	2.04	15.78	18.54	0.38	9.60	0.32	0.01	0.20	0.02	99.82
	Host	53.66	0.52	1.89	15.53	19.14	0.34	9.57	0.28	0.02	0.00	0.05	100.98
	Host	52.98	0.49	1.58	15.81	18.25	0.38	9.16	0.14	0.01	0.20	0.02	98.93
	Host	53.20	0.63	1.94	16.08	18.79	0.42	9.40	0.17	0.00	0.00	0.02	100.64
	Host	54.75	0.55	1.75	15.92	19.21	0.46	9.94	0.23	0.01	0.13	0.00	102.90
	Host	53.38	0.43	1.83	16.32	18.33	0.38	9.71	0.22	0.00	0.04	0.03	100.66
	Host	53.48	0.47	1.88	16.29	18.41	0.37	9.54	0.17	0.01	0.07	0.03	100.68
	Host	54.87	0.39	1.71	16.19	18.36	0.40	10.35	0.22	0.02	0.00	0.03	102.53
	MI 1	63.90	1.24	14.94	1.90	5.89	0.21	8.12	1.24	1.50	0.07	0.18	99.11
	MI 2	65.62	1.04	12.65	2.01	5.40	0.17	7.35	0.81	1.97	0.17	0.12	97.19
	MI 3	66.54	1.08	12.48	1.96	5.38	0.11	7.50	0.54	1.85	0.00	0.11	97.53
	MI 4	65.36	1.42	13.81	1.70	5.46	0.28	8.53	1.03	1.73	0.03	0.12	99.41
	MI 5	64.37	1.31	13.63	1.85	5.59	0.23	8.41	0.83	1.70	0.03	0.14	98.05
	MI 6	64.55	1.46	13.50	1.82	5.44	0.20	8.21	0.82	1.63	0.04	0.12	97.75
	MI 7	65.27	1.39	13.29	1.70	5.06	0.24	8.47	0.81	1.65	0.00	0.11	97.98
	MI 8	63.11	1.50	12.69	1.62	5.13	0.09	8.10	0.66	1.55	0.00	0.15	94.55
	MI 9	65.21	1.50	13.69	1.74	5.59	0.27	8.02	1.06	1.82	0.04	0.18	99.09

* Data collected by Stuart Simmons

Appendix B

Copper concentrations for electron microprobe

Traverse 1
 Sample WiOO8
 Pyroxene - melt inclusion - pyroxene

Point #	Cu (ppm)	Phase	Point #	Cu (ppm)	Phase
1	20	Pyroxene	31	250	Melt Inclusion
2	0	Pyroxene	32	280	Melt Inclusion
3	0	Pyroxene	33	240	Melt Inclusion
4	30	Pyroxene	34	260	Melt Inclusion
5	0	Pyroxene	35	240	Melt Inclusion
6	10	Pyroxene	36	210	Melt Inclusion
7	0	Pyroxene	37	270	Melt Inclusion
8	0	Pyroxene	38	230	Melt Inclusion
9	0	Pyroxene	39	270	Melt Inclusion
10	20	Pyroxene	40	270	Melt Inclusion
11	0	Pyroxene	41	170	Pyroxene-melt interface
12	10	Pyroxene	42	40	Pyroxene
13	0	Pyroxene	43	30	Pyroxene
14	0	Pyroxene	44	0	Pyroxene
15	20	Pyroxene	45	20	Pyroxene
16	10	Pyroxene	46	10	Pyroxene
17	30	Pyroxene	47	20	Pyroxene
18	30	Pyroxene	48	10	Pyroxene
19	60	Pyroxene-melt interface	49	20	Pyroxene
20	180	Pyroxene-melt interface	50	20	Pyroxene
21	260	Melt Inclusion	51	20	Pyroxene
22	220	Melt Inclusion	52	0	Pyroxene
23	280	Melt Inclusion	53	0	Pyroxene
24	230	Melt Inclusion	54	0	Pyroxene
25	220	Melt Inclusion	55	10	Pyroxene
26	210	Melt Inclusion	56	0	Pyroxene
27	220	Melt Inclusion	57	20	Pyroxene
28	280	Melt Inclusion	58	0	Pyroxene
29	250	Melt Inclusion	59	0	Pyroxene
30	240	Melt Inclusion	60	30	Pyroxene

Traverse 2
 Sample WiOO8
 Pyroxene-melt inclusion-pyroxene-plagioclase

Point	Cu (ppm)	Phase
1	30	Pyroxene
2	0	Pyroxene
3	10	Pyroxene
4	20	Pyroxene
5	0	Pyroxene
6	30	Pyroxene
7	90	Pyroxene-melt interface
8	170	Melt inclusion
9	160	Melt inclusion
10	170	Melt inclusion
11	160	Melt inclusion
12	190	Melt inclusion
13	130	Pyroxene-melt interface
14	20	Pyroxene
15	40	Pyroxene
16	10	Pyroxene
17	0	Pyroxene
18	50	Pyroxene
19	0	Pyroxene
20	10	Pyroxene
21	0	Pyroxene
22	0	Plagioclase
23	0	Plagioclase
24	30	Plagioclase
25	50	Plagioclase
26	0	Plagioclase
27	50	Plagioclase
28	10	Plagioclase
29	0	Plagioclase
30	0	Plagioclase

Traverse 3
 Sample WiOO8
 Crystallite rich matrix - pyroxene

Point	Cu (ppm)	Phase
1	110	Crystallite/glass interface
2	60	Crystallite
3	90	Crystallite
4	130	Crystallite/glass interface
5	170	Matrix glass
6	190	Matrix glass
7	70	Crystallite
8	140	Crystallite/glass interface
9	140	Matrix glass
10	90	Crystallite
11	120	Crystallite/glass interface
12	110	Crystallite/glass interface
13	120	Crystallite/glass interface
14	140	Crystallite/glass interface
15	170	Matrix glass
16	220	Matrix glass
17	100	Crystallite/glass interface
18	130	Crystallite/glass interface
19	50	Crystallite
20	70	Crystallite
21	120	Crystallite/glass interface
22	20	Pyroxene
23	0	Pyroxene
24	20	Pyroxene
25	10	Pyroxene
26	0	Pyroxene
27	0	Pyroxene
28	0	Pyroxene
29	30	Pyroxene
30	0	Pyroxene
31	0	Pyroxene
32	0	Pyroxene
33	0	Pyroxene
34	30	Pyroxene
35	10	Pyroxene
36	0	Pyroxene
37	0	Pyroxene
38	10	Pyroxene
39	0	Pyroxene
40	0	Pyroxene

Appendix C
Trace elements from Ion microprobe

Sample number (ppm)	880325 OPX	880325 CPX	891129 Plagioclase
Li	1	3	5
Be	0	0	3
Sc	28	101	17
Ti	1413	2671	236
Cr	739	1908	4
Rb	9	6	1
Sr	1	19	410
Y	4	28	0
Zr	6	28	1
Nb	0	0	0
Ba	0	0	196
La	0	2	2
Ce	0	8	3
Nd	0	9	2
Sm	0	3	0
Eu	0	1	0
Gd	0	3	0
Dy	1	6	0
Er	1	4	0
Yb	1	4	0
Hf	0	2	0

Sample number (ppm)	880325 MI-1 in OPX	880325 MI-2 in OPX	880325 MI in CPX	891129 MI in plag	891129 Matrix glass
Li	17	17	17	15	16
Be	1	1	2	2	1
Sc	23	37	33	17	15
Ti	5509	5245	4825	4463	5121
Cr	30	140	292	25	33
Rb	57	59	56	29	47
Sr	135	135	115	172	144
Y	22	21	28	22	22
Zr	188	166	155	142	178
Nb	7	6	6	5	6
Ba	839	777	734	594	750
La	15	13	14	12	14
Ce	32	28	31	25	30
Nd	16	14	16	13	14
Sm	4	3	5	6	4
Eu	3	3	5	2	1
Gd	4	4	5	3	3
Dy	5	4	8	5	5
Er	2	1	2	3	3
Yb	33	3	4	5	3
Hf	7	5	6	3	6

Vita

Maria Helen Rapien was born in Cincinnati, Ohio June 10, 1972. She graduated from St. Ursula Academy in 1990. She received a Bachelor's of Science degree in Geology from the University of Cincinnati in 1994. In 1995, she began graduate study at Virginia Polytechnic Institute and State University, where she received a Master's Degree from the Department of Geological Sciences. Currently, Maria is pursuing a career in teaching.