Microlite transfer by disaggregation of mafic inclusions following magma mixing at Soufrière Hills Volcano, Montserrat

Madeleine C.S. Humphreys*[1], Thomas Christopher[2] & Vicky Hards[2]†

* Corresponding author
[1]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK. Tel: +44 (0)1223 333433; Fax: +44 (0)1223 333450; mcsh2@cam.ac.uk
[2]Montserrat Volcano Observatory, Flemings, Montserrat, West Indies
† Current address: British Geological Survey, Keyworth, Nottingham, NG12 5GG

ABSTRACT
The Soufrière Hills Volcano on Montserrat has for the past twelve years been erupting andesite with basaltic to basaltic-andesite inclusions. The andesite contains a wide variety of phenocryst textures and strongly zoned microlites. Analysis of minor elements in both phenocrysts and microlites allows us to put detailed constraints on their origins. Compositions of clinopyroxene, from overgrowth rims on quartz and orthopyroxene and coarse-grained breakdown rims on hornblende, are identical to those from the mafic inclusions, indicating that these rims form during interaction with mafic magma. In contrast, resorbed quartz and reversely zoned orthopyroxenes form during heating. Microlites of plagioclase and orthopyroxene are chemically distinct from the phenocrysts, being enriched in Fe and Mg, and Al and Ca respectively. However, microlites of plagioclase, orthopyroxene and clinopyroxene are indistinguishable from the compositions of these phases in the mafic inclusions. We infer that the inclusions disaggregated under conditions of high shear stress during ascent in the conduit, transferring mafic material into the andesite groundmass. The mafic component of the system is therefore greater than previously thought. The presence of mafic-derived microlites in the andesite groundmass also means that care must be taken when using this as a starting material for phase equilibrium experiments.

Keywords: magma mixing, mafic inclusions, microlites, hybridisation, disaggregation; Soufrière Hills volcano; Montserrat

INTRODUCTION

Magma mingling (incomplete mixing, resulting in macroscopic enclaves or compositional banding) and mixing or hybridisation (complete mixing) have long been recognised at intermediate arc volcanoes (e.g. Anderson 1976; Eichelberger 1980; Bacon 1986; Feeley & Dungan 1996; Clynne 1999). Mixing tends to occur between a relatively silicic resident magma and a more mafic replenishing magma (typically basalt to basaltic andesite). Petrological characteristics indicating mixing span a wide range of scales, from macroscopic mafic inclusions and compositional banding, to partially reacted xenocrysts or strongly zoned phenocrysts (e.g. Eichelberger 1978, Clynne 1999).

The degree of interaction between the resident silicic magma and the replenishing magma depends strongly on the relative viscosities, temperatures, compositions and volumes of the two end-members (Sparks & Marshall 1986). For example, if the volume proportion of silicic magma is relatively large, significant mixing can only take place with a relatively evolved incoming magma. For significant mixing to occur with a more mafic incoming magma, the volume proportion of the mafic component must be large (Sparks & Marshall 1986). The presence of mafic inclusions indicates rapid quenching of the mafic magma against the cooler silicic host, and suggests only limited contact between the two end-members. However, a recent study suggested that plagioclase microlites were transferred from basaltic andesite to andesite during mixing at Mont Pelée volcano, Martinique (Martel et al.2006), suggesting a more intricate interaction. Evaluating the extent, timing and nature of such mixing is important because it will affect the viscosity, and thus the ascent and eruption of magma (Melnik & Sparks 1999).

This study will address the nature and mechanism of magma mingling and hybridisation at Soufrière Hills Volcano, Montserrat. Mixing between the host andesite and incoming basaltic to basaltic-andesite magma initially formed quenched magmatic inclusions. We present evidence that substantial quantities of plagioclase, orthopyroxene, clinopyroxene and titanomagnetite microlites were later transferred from basaltic andesite inclusions into the host andesite. We discuss possible mechanisms for the transfer of material and the effects on viscosity and temperature.

SAMPLES AND METHODS

The 14 samples studied include 13 samples of andesite and one macroscopic mafic inclusion (table 1). The samples were deposited between July 2001 and May 2006 and represent dome and pyroclastic flow material. Modal analysis was done by point-counting approximately 1500-2000 points in every thin section, with a spacing of ~0.5 mm. Vesicles were counted separately from the groundmass where possible.

Electron micro-probe analyses were carried out using a Cameca 5-spectrometer SX-100 instrument. Minerals were analysed using a 2 μm, 15 kV, 10 nA beam for major elements and a 100 nA beam for minor and trace elements. Structural formulae were recalculated on the basis of 23 O atoms for hornblende (Schumacher 1997) and using Stormer (1983) for oxide minerals.

ANDESITE PETROLOGY

The samples are crystal rich (typically 35-40 vol% phenocrysts, table 2) and similar to previously described samples from earlier in the eruptive episode (e.g. Devine et al.1998; Barclay et al.1998; Murphy et al.2000; Couch et al.2001). In this study, the term ‘phenocryst’ is used for large crystals, regardless of their origin (c.f. Davidson et al. 2007); ‘microlite’ is used for crystals smaller than ~100 μm, and ‘microphenocryst’ is used for crystals approximately 100-300 μm, following Murphy et al. (2000). In the andesite, the phenocryst assemblage is plagioclase + hornblende + orthopyroxene + Fe-Ti oxides, with minor apatite, quartz and clinopyroxene, and rare zircon. The groundmass comprises plagioclase + orthopyroxene + clinopyroxene + Fe-Ti oxides + rhyolitic glass. In some samples, the glass is partly devitrified or has undergone phase separation to patches of glass enriched in Ca+Na and patches enriched in K+Fe (Cashman, 1992). Quartz is present in the groundmass of some samples, where it can act as a nucleation point for intergrowths of feldspar and quartz. Vesicles are commonly partially filled with cristobalite. Plagioclase microlites may have calcic cores overgrown by more sodic material. In some samples, two populations of microlites are observed, with a population of small, skeletal crystals inferred to have formed during a second nucleation event.

Andesite phenocryst textures

Plagioclase crystals show varied textures, including oscillatory zoning, sieve textures and patchy cores. Quartz is present in all samples, but is resorbed and embayed or overgrown by clinopyroxene. Clinopyroxene occurs as single crystals or clusters of oscillatory- and sector-zoned microphenocrysts. Hornblende phenocrysts are typically euhedral and variably replaced by ‘opacite’, a very fine-grained aggregate of Fe-Ti oxides and pyroxene (Garcia & Jacobson 1979; Murphy et al. 2000; Plechov et al. 2008a). Replacement by opacite (figure 1a) initiates preferentially adjacent to vesicles, suggesting an origin in the circulation of oxidising fluids during shallow storage, and implying high permeability. Hornblende phenocrysts may show oscillatory zoning or distinct zoned rims. They commonly have a breakdown rim due to decompression (figure 1a; Rutherford & Hill 1993; Rutherford & Devine 2003; Buckley et al. 2006); the width of the rim varies from a few microns to several hundred microns. Almost all samples also contain a minority of hornblende phenocrysts with thick, cpx-rich, thermal reaction rims (Rutherford & Devine 2003) of plagioclase + pyroxene (aligned parallel to the c-axis of the amphibole grain) + oxides + glass (figure 1b). These result from heating the amphibole above its thermal stability limit, which is thought to be ~ 880 °C (Barclay et al. 1998). In these phenocrysts, any included plagioclase are commonly sieved and any orthopyroxene inclusions have Mg-rich rims or clinopyroxene overgrowths. Orthopyroxene phenocrysts are euhedral and may have Mg-rich rims or, less commonly, overgrowths of clinopyroxene. These are interpreted as indicators of heating (Rutherford & Devine 2003). Some of the reversely zoned rims comprise two distinct zones of Mg-enrichment (figure 1c) followed by normal zoning, suggesting multiple episodes of heating.

Mafic inclusions

The andesite contains macroscopic mafic inclusions as observed in previous stages of the eruption (Murphy et al. 2000). The mafic inclusions are vesicular, with interstitial rhyolitic glass, and occur in all sizes, down to mm-sized inclusions. The vesicles typically inhabit voids between crystals (figure 1d,e), suggesting that vesiculation was induced by crystallisation (Browne et al. 2006; Martin et al. 2006). They typically contain elongate, randomly oriented crystals (figure 1d) of An-rich plagioclase + clinopyroxene ± orthopyroxene. Fe-Ti oxides are abundant, and yellowish, subhedral amphibole is common. Ilmenite is more common than it is in the andesite. Amphibole is dominant in larger inclusions, whereas pyroxene dominates in smaller inclusions (Murphy et al. 2000). This variation in mineral assemblage may be related to variations in degree of undercooling for different sizes of inclusion (Blundy & Sparks 1992) or to slight differences in composition of the incoming magmas. Large, sieve-textured plagioclase and clear plagioclase phenocrysts are also seen, together with euhedral clinopyroxene and rare olivine (Fo_{75}) microphenocrysts. Large hornblende crystals are present, but always show a thermal reaction rim, and the larger feldspars are usually sieved (see above). Similarly, orthopyroxene phenocrysts are also present, but show reverse-zoned rims or clinopyroxene overgrowths. These hornblende, large sieve-textured plagioclase and orthopyroxene crystals are interpreted from their textural characteristics as xenocrysts that originated in the andesite.

'Crystal cluster' is used here to describe material, found in the andesite, that is similar to the mafic inclusions in terms of mineralogy and texture, but typically comprises only a few grains together with glass ± microlites (figure 1e). Yellowish amphibole is common in these small crystal clusters. In some cases, amphibole may be overgrown by clinopyroxene.

Crystal clots

Crystal clots are texturally distinct from the mafic inclusions and crystal clusters. Clots typically comprise euhedral, equant grains of orthopyroxene + Fe-Ti oxides + apatite ± plagioclase (figure 1f) + clear glass. Apatite is clear to brownish; the brown colour apparently results in part from lots of tiny, oriented inclusions of an opaque mineral. Euhedral zircon grains are also found. Some of the crystal clots show evidence of having been recently heated, in that the plagioclase grains are sieve-textured and there is reverse zoning in the orthopyroxene.

GEOCHEMISTRY OF PHENOCRYSTS, MICROLITES AND MAFIC MATERIAL

Plagioclase

Plagioclase compositions span a wide range, from An_{31} to An_{95} (table 3). Crystals with different textures show clear compositional differences (figure 2). Most phenocryst analyses lie between An_{45} and An_{80}, and show a slight positive correlation with FeO content. However, some phenocryst analyses, typically from traverses which cross narrow sieve zones or resorption surfaces, follow a curved trend at higher FeO (figure 2). The same trend is followed by the rims of sieve-textured plagioclase, while the cores have compositions that are indistinguishable from other phenocrysts (An_{45}-An_{80} and "normal" FeO). Material just outside the sieved zone is very calcic, up to An_{91}, and becomes more sodic with increasing FeO. The outermost rims are intermediate (typically An_{50}-An_{80}) with high FeO. Thus the Fe-enriched phenocryst compositions overlap with the rims of sieved crystals. Microlite compositions range from An_{49} to An_{83} and follow the same Fe-enrichment trend as the rims of sieved crystals. Microlite cores tend to be more anorthitic and more Fe-rich than rims (figure 2). Material from crystal clusters and mafic inclusions has composition An_{52}-An_{89} and also follows the Fe-enrichment trend, overlapping almost exactly with the microlites. Similar patterns can be seen for MgO (figure 2).

Amphibole

Amphibole compositions (table 4) range from Mg-hornblende to pargasite (Leake et al. 1997). The phenocrysts show limited correlation among cations. Al^T correlates positively (R^2 ~ 0.6, figure 3a) with $(Na+K)^A$ reflecting the edenite substitution, $Si^T + [\ ] = Al^T + (Na+K)^A$. In contrast, there is a poor correlation between Al^T and Al^{vi} or Mg^{vi} (figure 3b), or between Mn^{vi} and Ti^{vi}, reflecting little control by the Tschermakite substitutions, $Si^T + Mg^{vi} = Al^T + Al^{vi}$ and $Si^T + Mn^{vi} = Al^T + Ti^{vi}$. Microphenocrysts, microlites, amphibole fragments and mafic amphiboles cover a much wider range of compositions (figure 3). They extend the correlation of Al^T with $(Na+K)^A$ to higher Al^T, and also show a good correlation between Al^T and Al^{vi}, in contrast to the phenocrysts. For phenocrysts, Al^T correlates negatively with Mg^{vi}. However, the microlites, microphenocrysts, fragments and mafic amphiboles show a positive correlation (figure 3b). Mg-number is also higher for the mafic amphiboles (Mg# 68-89) and microlites and microphenocrysts (Mg# 63-84) than that of the phenocrysts (Mg# 61-70).

Orthopyroxene

Orthopyroxene phenocrysts (table 5) are fairly homogeneous, with Mg# 58-62 and 2-4 mol% Wo. Some orthopyroxene phenocrysts have euhedral, zoned rims, which are significantly more Mg-rich in composition (Mg# 63-74) than the cores. Mg-number shows a negative correlation with Mn, although not with other minor elements (Ti, Al). Microphenocrysts overlap in composition with the phenocrysts, with Mg# 59-63). However, microlites are significantly richer in Al, Ca, Ti and Mg (Mg# 58-74), and poorer in Mn than the phenocrysts (figure 4). The microlites overlap in composition with orthopyroxene from mafic inclusions and crystal clusters (Mg# 59-74).

Clinopyroxene

Microphenocrysts, microlites, mafic clinopyroxenes and overgrowths on orthopyroxene phenocrysts are all indistinguishable in composition, typically with Wo_{30-47} and En_{40-50} (figure 5). Mg decreases as Ca increases, while of the minor elements, Al correlates positively with Ti and negatively with Mn.

Fe-Ti oxides

Magnetite occurs as microphenocrysts, microlites and in mafic inclusions and crystal clusters. The compositions differ only in TiO_2 content (table 6; figure 6). Microlites and mafic titanomagnetites are more Ti-rich than microphenocrysts. In general, microphenocryst rims are slightly enriched in Ti compared with the cores. Minor elements (Al, Mg and Mn) show no consistent variation. Rare crystals of pure magnetite are found.

ESTIMATES OF TEMPERATURE AND OXYGEN FUGACITY

2-pyroxene temperatures

Temperature estimates were made from coexisting orthopyroxene-clinopyroxene microlite or microphenocryst pairs, using the method of Andersen et al. (1993). Temperatures estimated in this way vary widely, from 903 °C to 1142 °C (n = 15), with an average of ~ 1070 °C. Temperatures estimated from mafic inclusions and crystal clusters are higher, 1074 - 1196 °C (n = 5), with an average of ~ 1110 °C. In particular, orthopyroxene phenocrysts are more Fe-rich and Ca-poor than the microlites, zoned phenocryst rims and mafic orthopyroxene, consistent with lower temperatures. QUILF (Andersen et al. 1993) used in single-pyroxene mode (Murphy et al. 2000) gave typical orthopyroxene phenocryst core temperatures of 800-900 °C (average ~ 850 °C, n=77). Phenocryst rims are typically slightly hotter (average ~870 °C, n=61), with clearly zoned phenocryst rims significantly hotter but variable (average ~1000 °C, n=30). Microphenocryst core and rim temperatures compare closely to those of the phenocrysts. These temperatures are consistent with those estimated for phenocrysts from Phase I of the eruption (Murphy et al. 2000). Mafic inclusion orthopyroxenes consistently gave higher orthopyroxene temperatures (average ~ 1070 °C, n=19). We note that orthopyroxenes in sample MVO1521 are slightly richer in Ca and Al, and have lower Mn, than those in other samples. This results in hotter calculated temperatures (~1000 °C for both cores and rims). The reason for this discrepancy is not clear.

Ilmenite-titanomagnetite geothermobarometry

Ilmenite occurs relatively rarely. However, temperature estimates were obtained from seven coexisting ilmenite-titanomagnetite pairs (Andersen et al. 1993). Oxide inclusions in hornblende, and oxides from glass-bearing crystal clots gave low temperatures and relatively oxidising conditions (791-809 °C, NNO + 1.3, n = 4). Zoned microphenocrysts and microlites gave higher temperatures and were slightly less oxidising (958-1017 °C, NNO + 0.5, n = 3).

Hornblende-plagioclase temperature

Temperature estimates were also obtained using the hornblende-plagioclase geothermometer of Holland & Blundy (1994). One phenocryst pair gave a temperature of 844 °C. Mafic inclusions and crystal clusters gave significantly higher temperatures, 809-947 °C (n=10), although some of these temperatures fall outside the range recommended for the thermometer.

DISCUSSION

Origin of crystal clots

The crystal clots are coarse-grained and contain pristine glass, rather than a microcrystalline groundmass. They consistently give low temperatures (790-810 °C) and relatively oxidised conditions (NNO + 1.2 to NNO + 1.4) relative to the host andesite (~ NNO + 0.5). Similar clots have been observed at island arc volcanoes worldwide (e.g. Garcia & Jacobson 1979). It has been suggested that the clots may represent clusters of phenocrysts, breakdown products of hornblende, cooler wall-rock material, disrupted cumulates or micro-xenoliths (e.g. Garcia & Jacobson 1979; Stewart 1975; Scarfe & Fuji 1987; Arculus 1976; Arculus & Wills 1980). At Soufrière Hills, the low temperatures, oxidising conditions and lack of hornblende suggest that the most likely origin is a highly crystalline part of the chamber, probably close to the walls. This is also consistent with previous interpretations of the origin of low-temperature orthopyroxenes and quartz (Murphy et al. 2000).

Minor element partitioning in minerals

Fe and Mg partitioning in plagioclase

Microlites, microphenocrysts and mafic plagioclase all follow a trend of Fe-enrichment, in comparison with typical phenocryst compositions, which describe a shallow trend. The same pattern, although with greater scatter, is also seen for Mg contents. Partitioning of Fe and Mg in plagioclase varies as a function of temperature and anorthite content (Bindeman et al. 1998). D_{Fe} also varies with oxygen fugacity (e.g. Phinney 1992; Wilke & Behrens 1999). However, the range of fO_2 measured at Soufrière Hills is only ~ 1 log unit (this study; Murphy et al. 2000), which is insufficient to produce strong changes in D_{Fe} according to the relationships described by Phinney (1992) and Wilke & Behrens (1999).

However, the predicted partitioning behaviour does not fit the data well if only temperature and X_{An} effects are taken into account (figure 7). The predicted effects of temperature are relatively small, with FeO_{pl} contents increasing by 0.1 wt% for an increase in temperature from 850°C to 1050 °C. Predicted FeO_{pl} decreases smoothly by 0.45 wt% with an increase of X_{An} from 0.4 to 0.75. However, the analytical data show a positive trend for phenocrysts which cannot be produced even by the combined effects of T and X_{An} and suggests an effect of melt composition as well as temperature. This is confirmed by using the partitioning data of Bindeman et al. (1998) to calculate $FeO_{(pl)}$ and $MgO_{(pl)}$ for the experimental, H_2O-saturated plagioclase-glass compositions of Couch et al. (2003a). The experimental glasses show a small decrease in both $FeO_{(m)}$ and $MgO_{(m)}$ associated with crystallisation, over a temperature range from 970 °C to 830 °C (Couch et al. 2003a). No plagioclase compositions are reported, however X_{An} are given. We calculated $FeO_{(pl)}$ and $MgO_{(pl)}$ corresponding to experimental X_{An} and T from Couch et al. (2003a), using Bindeman et al. (1998) partitioning data. The results (black diamonds, figure 7) match the observed positive correlations for phenocrysts, although $MgO_{(pl)}$ is a little low. This is consistent with the conclusions of Ruprecht & Wörner (2007) for El Misti volcano, Peru. They identified major resorptions associated with increased $FeO_{(pl)}$, which showed a steep, positive Fe-X_{An} correlation. They ascribed these to compositional mixing through mafic recharge. In contrast, resorptions with no change in $FeO_{(pl)}$ showed a flat Fe-X_{An} profile and were attributed to thermal effects (Ruprecht & Wörner 2007), whether due to latent heat (Blundy et al. 2006) or a self-mixing scenario involving convection in the resident magma (Couch et al. 2001).

Decompression crystallisation can occur rapidly (e.g. Couch et al. 2003b) so kinetic effects should also be considered as a possible explanation for enrichment in Fe and Mg. If crystal growth is more rapid than incompatible element diffusion in the melt, then a boundary layer may form around the growing crystal, that is enriched in incompatible elements. For elements moderately incompatible in plagioclase (such as Fe and Mg), these effects may result in approximately 30-50% enrichment in the melt (Bottinga et al. 1966; Bacon 1989). Therefore, it is plausible that some of the Fe-enrichment of microlites and mafic plagioclase at lower X_{An} (e.g. An_{50}-An_{70}) may have been affected by kinetics. However, the positive correlation of Fe with X_{An} still requires Fe variation in the melt; kinetic effects also cannot account for the very high X_{An} contents (up to An_{90}) in microlites. Finally, microlite rims are less An-rich and have lower Fe contents than the cores, which is inconsistent with crystallisation dominated by kinetic factors.

The whole-rock FeO and MgO contents of basaltic andesite inclusions (Zellmer et al. 2003a) are substantially higher (~9 wt%, ~4.2 wt%) than those of the andesite (~ 6.5 wt% FeO, ~3 wt% MgO). The temperatures calculated from 2-pyroxene geothermometry are also considerably higher for the basaltic andesite (~1050 – 1100 °C) than the andesite (~ 850 °C). The high-Fe, high-Mg, high-X_{An} analyses of sieved and mafic inclusion plagioclase are therefore consistent with crystallisation from the hotter, more mafic environment in the basaltic andesite. The microlite analyses are chemically indistinguishable from the mafic plagioclase, thus it seems likely that they also crystallised in a hotter, more mafic environment. The inflection in FeO at approximately An_{75} in the Montserrat data (not observed for El Misti) suggests that the trend described by the sieved and mafic plagioclase reflects fractional crystallisation, with $FeO_{(m)}$ initially increasing, before starting to decrease with continued crystallisation. We suggest that this is probably related to early crystallisation of pyroxenes in the mafic inclusions, followed by Fe-Ti oxides, which would result in falling $FeO_{(m)}$. This implies that the basaltic andesite inclusions were largely liquid when they mixed into the andesite.

Mg, Ca, Ti and Al partitioning in pyroxene

Orthopyroxene microlites, zoned phenocryst rims and mafic inclusion orthopyroxenes all have higher contents of Al, Ti, Ca and Mg, as well as higher Mg#, than phenocryst and microphenocryst orthopyroxene. For a given Mg#, the solubility of the Ca-component increases with increasing temperature, while at constant Ca content, the Mg# increase with temperature (Lindsley 1983). Ti and Al concentrations in orthopyroxene also increase with temperature (Beattie 1993). These data therefore indicate that the mafic orthopyroxene, microlites and zoned phenocryst rims all formed at hotter temperatures than the phenocrysts and microphenocrysts.

For clinopyroxene, the solubility of the enstatite component increases with increasing temperature, while the solubility of the diopside component decreases (Sepp & Kunzman 2001; Lindsley 1983). There are no clinopyroxene phenocrysts to compare with the microlites and mafic clinopyroxene, but the spread of Ca-Mg compositional data (see figure 5) suggests a range of crystallisation temperatures. This is consistent with the high temperatures calculated from coexisting clinopyroxene and orthopyroxene microlites (903-1142 °C), mafic pyroxenes (1074-1196 °C) and zoned orthopyroxene rims (870-1040 °C), compared with the low phenocryst temperatures (800-900 °C). Clinopyroxenes also show a wide variation in Ti and Al contents. This has previously been ascribed to variation in growth rate, with high Ti-Al pyroxenes forming during rapid growth, for example at high cooling rates as might be expected for the mafic inclusions (Feeley & Dungan 1996).

Ti in titanomagnetite

The oxide microlites and mafic inclusion crystals are very similar in composition to the microphenocrysts, but with higher Ti content. Increased Ti in titanomagnetite can result from increasing temperature or decreasing oxygen fugacity (Frost & Lindsley 1991; Devine et al. 2003). The change in composition therefore suggests that the microlites crystallised at higher temperatures than the microphenocrysts in the andesite.

Interpretation of microlite and phenocryst compositions

Taken together, the chemical data indicate that the microlites of plagioclase, orthopyroxene and clinopyroxene crystallised in a hotter and more mafic environment than the phenocrysts of the andesite, one similar to the mafic inclusions. The temperature of the mafic magma was initially approximately 1050-1150 °C, on the basis of pyroxene compositions. Previously, anomalously hot 2-pyroxene microlite temperatures were assumed to result from disequilibrium growth (e.g. Murphy et al. 2000). We suggest instead that the microlites probably originated in the mafic inclusions, and were transferred into the andesite following initial mingling. Transfer of calcic plagioclase microlites is also envisaged for Mont Pelée, Martinique (Martel et al. 2006). Continued decompression of the hybrid andesite causes continued crystallisation on the mafic microlite cores, producing zoned microlites and microphenocrysts (e.g. Couch et al. 2003a, Murphy et al. 2000).

Reversely zoned and cpx-rimmed orthopyroxene phenocrysts both indicate heating. Clinopyroxene from the reaction rims is compositionally indistinguishable from mafic inclusion clinopyroxene, so we infer that these reaction rims form when orthopyroxene phenocrysts are incorporated into the basaltic andesite. In contrast, the reversely zoned orthopyroxenes experienced conductive heating in the andesite. Multiple rim zones imply more than one episode of heating, suggesting multiple injections of mafic material. This is consistent with the occurrence of seismic crises at Montserrat in 1896-1897, 1933-1937 and 1966-1967, which were interpreted as periods of magma intrusion (MacGregor 1938; Perret 1939; Shepherd et al. 1971). These textures are analogous to the thermal breakdown rims seen in hornblende (see earlier).

The amphibole data show a good positive correlation of Al^T and $(Na+K)^A$, suggesting a strong role of the temperature-sensitive edenite substitution. Mafic amphiboles and small grains have higher Al^T while phenocrysts have low Al^T. This is consistent with the mafic material crystallising at higher temperatures (e.g. Bachmann & Dungan 2002). In contrast, there is only a weak trend of decreasing Mg^{vi} with increasing Al^T, indicating much weaker role for the pressure-dependent Tschermakite substitution. However, mafic amphiboles and small grains are enriched in both Mg and Al (see figure 3). This is consistent with lower silica activity in the melt due to the presence of more mafic magma (Sato et al. 2005). We therefore suggest that the small grains predominantly represent material that originated in the mafic inclusions and was transferred to the magma. This explains the occurrence of hornblende in the groundmass; experiments have consistently shown that hornblende is not stable in the andesite at low pressures (e.g. Barclay et al. 1998; Rutherford & Devine 2003).

The high TiO_2 contents of the microlites are also consistent with hotter crystallisation conditions. Some titanomagnetite microphenocryst rims are zoned, with slightly more Ti-rich compositions than their cores. This has previously been ascribed to heating of the andesite (Devine et al. 1998; Devine et al. 2003), which could be related to the release of latent heat during decompression crystallisation (Blundy et al. 2006) or to mafic recharge (Devine et al. 2003). However, heating due to crystallisation should affect all titanomagnetite crystals equally, whereas varying degrees of Ti-enrichment are observed. These zoned crystals therefore probably experienced transient heating in the vicinity of the influxing basaltic andesite, analogous to the zoned orthopyroxene phenocrysts.

Interpretation of zoned plagioclase phenocryst compositions

Previously, oscillatory zoning in plagioclase has been attributed to various processes, including mixing with mafic or silicic magma (e.g. Singer et al. 1995; Ginibre et al. 2002), thermal perturbations (e.g. Couch et al. 2001); kinetics (Bottinga et al. 1966; Allegre et al. 1981), or decompression (Nelson & Montana 1992). However, this study shows that the enrichment of Fe and Mg in plagioclase at intermediate anorthite content seems to be a robust method for identifying plagioclase that crystallised in a more mafic environment. We therefore apply this to traverses of plagioclase phenocrysts in the andesite. Figure 8 shows Fe-X_{An} compositions for traverses across oscillatory zoned phenocrysts. The data show that very few points in the oscillatory zoned crystals are related to influx of mafic magma. Conversely, most of the points analysed describe a flat Fe-X_{An} profile. The few Fe-enriched points are mostly found in the outermost crystal rim, or where a narrow sieved zone is present in the traverse. Traverses through the clear rims of strongly sieved crystals show that the mafic crystallisation trend starts at ~ An_{85} and passes through the inflection point at ~0.6 wt% FeO (figure 8), as previously described. The lack of Fe-enriched compositions in oscillatory zoned crystals suggests that most of the oscillatory zonation is produced by other processes, and that most of the resorption horizons observed relate to perturbations of temperature and/or pH_2O in the storage chamber. Some plagioclase from Montserrat have constant Sr contents despite strong variations in X_{An} (Zellmer et al. 2003b); these are also consistent with this interpretation. The occurrence of Fe-rich outer rims suggests that contact with mafic magma was one of the last things to happen prior to eruption of these crystals.

Transfer of crystals between mafic inclusions and andesite

The nature of interaction between mafic and silicic magmas depends strongly on the relative proportion of the incoming mafic magma, as well as the contrast of temperature and viscosity between the two end-members (Sparks & Marshall 1986). In the Soufrière Hills magma, the macroscopic mafic inclusions are typically rounded to ellipsoidal, with well-defined, smooth or crenulated margins that may be chilled (Murphy et al. 2000; J. Barclay, personal communication), indicating strong undercooling of the mafic magma against the host andesite. Given these observations and the strong temperature contrast between the end-members (~1100 °C for the basaltic andesite, *c.f.* ~ 840 °C for the andesite; Barclay et al. 1998), it is unlikely that efficient stirring and hybridisation took place while the two magmas were liquid (Sparks & Marshall 1986). The presence in the mafic inclusions of sieved plagioclase, orthopyroxene overgrown by clinopyroxene, and strongly reacted hornblende, originally derived from the andesite, shows that some mixing did take place, in the form of transfer of phenocrysts from the andesite to the mafic magma. However, the sieved plagioclase crystals have clear, calcic overgrowths with an inflection in Fe-X_{An}, indicating crystallisation in the mafic magma, so incorporation of the crystals must have occurred soon after injection of the basaltic andesite, while it was still largely liquid. The void-filling shape of the vesicles in the mafic inclusions and crystal clusters (see figure 1) suggests that the cooling magma formed a strong crystal framework and that vesiculation occurred during cooling. The strong framework of crystals would make the inclusions susceptible to later mechanical disaggregation (Martin et al. 2006), and we suggest that this is the most likely mechanism for transferring the mafic microlites to the andesite. This is supported by the wide size distribution of mafic material, from macroscopic inclusions down to crystal clusters and isolated crystals, including the strongly reacted plagioclase, orthopyroxene and hornblende crystals which had started out in the andesite. Mechanical disaggregation of inclusions was also envisaged at Tatara – San Pedro volcano, Chile (Feeley & Dungan 1996).

However, the timing and mechanism of disaggregation is unclear. Possible mechanisms include mechanical abrasion of the chilled margins (Feeley & Dungan 1996), wholesale breaking of the inclusions (Martin et al. 2006), or plastic deformation (Blake & Fink 2000). Disaggregation could take place in the magma chamber, during ascent in the conduit, or during emplacement of the dome rocks. The viscosity of the host andesite is estimated to be ~ 7×10^6 Pa s in the magma chamber, rising to approximately 10^{13}-10^{14} Pa s at the surface due to degassing and decompression crystallisation (Sparks et al. 2000). The ellipsoidal shape of some of the larger inclusions (Murphy et al. 2000) indicates that some plastic deformation took place during quenching. However, plastic deformation will effectively cease once a significant chilled margin is formed (Blake & Fink 2000). This will likely happen quickly, given the large temperature contrast between the two magmas, and this is indicated by theoretical constraints (Plechov et al. 2008b) which show that thermal equilibration of enclaves with resident magma occurs within hours to days. Therefore most of the disaggregation must have occurred after this initial stage of magma mingling.

Once the inclusions are strongly crystalline, they will undergo brittle deformation (Sparks et al. 2000) and may not transfer much heat to the host andesite in doing so. Brittle deformation was inferred at Nea Kameni, Santorini, from small fractures and bent crystals in mafic inclusions, the most angular of the inclusions commonly being found in the centre of inclusion clusters (Martin et al. 2006). The degree of deformation is related to the shear stress experienced by the enclave (Blake & Fink 2000), and will therefore increase with host magma viscosity, and with eruption rate. Since the viscosity of the andesite increases by several orders of magnitude during ascent, due largely to decompression crystallisation (Sparks et al. 2000), it seems likely that the majority of deformation and break-up of the inclusions occurred during ascent in the conduit. The presence of mafic-derived microlites in pumiceous material (MVO1523 and MVO1524) precludes transfer of material during dome emplacement.

The rapid re-equilibration times of titanomagnetite (Hammond & Taylor 1982; Venezky & Rutherford 1999) can provide clues to the timing of inclusion disaggregation. The oxide microlites are more Mg-rich than microphenocrysts from the andesite. The grainsize of the microlites analysed is typically 20 μm; grains of this size should re-equilibrate in approximately 50 days at 825 °C, 30 days at 850 °C, or only 11 days at 900 °C (Venezky & Rutherford 1999). The pre-eruptive temperature of the andesite was ~850 °C, possibly rising to ~900 °C during ascent due to the release of latent heat of crystallisation (Couch et al. 2003a; Blundy et al. 2006). This suggests that the time between disaggregation and eruption was in the range 10-30 days, and therefore that disaggregation probably occurred during ascent. This suggests ascent rates, from ~6 km to the surface, of 8-25 m/h. These rates are very similar to estimates of ascent rate for Mount Unzen, Japan (Venezky & Rutherford 1999) as well as for Soufrière Hills using different methods (e.g. Rutherford & Devine 2003).

Implications

The presence of mafic microlites in the groundmass of the Soufrière Hills andesite means that the proportion of mafic material in the system is greater than previously thought. It provides an explanation for the presence of ubiquitous clinopyroxene in some phase equilibrium studies (Couch et al. 2003a), where none is observed in the andesite. In terms of the “reactive magma” concept put forward by Pichavant et al. (2007), the bulk groundmass cannot be regarded as a good starting material for phase equilibrium experiments, because a significant fraction of the microlites are not part of the reactive magma, but are incorporated from an external source, the mafic inclusions.

CONCLUSIONS

The groundmass of the andesite magma at Soufrière Hills volcano, Montserrat contains microlites that originated in quenched mafic inclusions. Many of the microlites have different compositions from the andesite phenocrysts, but are chemically indistinguishable from the compositions of crystals found in basaltic andesite inclusions. The basaltic andesite initially had a temperature of ~1050-1100 °C and quenched rapidly to form mafic inclusions. Some phenocrysts from the andesite were incorporated into the inclusions during this time, resulting in the formation of sieved plagioclase textures, clinopyroxene overgrowths on orthopyroxene and quartz, and breakdown of hornblende. Following cooling and vesiculation of the mafic magma, mass transfer occurred by brittle disaggregation of the inclusions. Plagioclase, orthopyroxene, clinopyroxene and titanomagnetite microlites were transferred from the inclusions to the andesite. Disaggregation would have required high shear stress and probably occurred during flow in the conduit. The discovery of mafic microlites in the andesite means that groundmass material is an inappropriate starting composition for experimental phase petrology. Care should also be taken when using groundmass textures to calculate crystal size distributions, or infer growth or ascent rates.

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Figure 1. Back-scattered SEM images and photomicrographs of mineral textures in the Soufrière Hills magma. a) Hornblende phenocryst with narrow, fine-grained decompression breakdown rim (arrow). The interior of the crystal is partially replaced by black opacite. Field of view 2.3 mm. b) Hornblende phenocryst with thick thermal breakdown rim, characterised

by coarse, clinopyroxene-rich reaction products, and alignment of individual grains with the c-axis of the hornblende. Field of view 2.3 mm. c) Margin of orthopyroxene phenocryst with reversely zoned rim. This crystal has a rim with two distinct reversely zoned sections (black arrows). d) Vesicular mafic inclusion containing pyroxene (px), plagioclase (pl) and oxides (ox). e) Crystal cluster comprising vesicular (ves) mafic material, plagioclase, clinopyroxene, and yellow pargasitic hornblende (hb). Field of view ~1.1 mm. f) Crystal clot with equant grains of orthopyroxene, plagioclase and oxides as well as vesicular glass. Crystal clots are texturally distinct from mafic inclusions and crystal clusters, and probably represent cognate material. g) Sieved plagioclase showing core, 'inner rim' and 'outer rim' referred to in text. h) Typical andesite groundmass texture, comprising crystals of plagioclase (mid-grey), pyroxene (light grey), and oxide (white) with vesicles (black) in greyish glass.

Figure 2. FeO and MgO contents of plagioclase, sorted by textural characteristics. Sieved plagioclase (c and d) are significantly enriched in Fe and Mg compared with unaltered cores and other phenocrysts (a and b). Plagioclase microlites and plagioclase in mafic inclusions (a and b) are also strongly enriched in Fe and Mg, and are chemically indistinguishable from one another, and from the sieved plagioclase.

Figure 3. Hornblende compositions in the Soufrière Hills magma. a) Al^T correlates well with $(Na+K)^A$. Mafic hornblende is easily distinguished from phenocrysts in the andesite. Small grains and microlites of hornblende overlap in composition with the mafic material. b) For phenocrysts, Mg^{vi} correlates negatively with Al^T while for mafic hornblende and microlites, there is a weak positive correlation.

Figure 4. Orthopyroxene compositions in the Soufrière Hills magma. Phenocrysts are relatively homogeneous in composition. Distinctly zoned rims on phenocrysts have higher Mg, Ca and Al, and lower Mn. Microlites and mafic inclusions have more Mg, Ca, Al rich compositions compared with the phenocrysts.

Figure 5. Clinopyroxene compositions in the Soufrière Hills magma. Microphenocrysts, microlites, mafic inclusion clinopyroxene and overgrowth rims on orthopyroxene phenocrysts are all indistinguishable in composition, and cover a wide range of Mg, Al and Ti compositions.

Figure 6. Titanomagnetite compositions. Microlites and mafic inclusion titanomagnetite are significantly enriched in Ti compared with microphenocrysts.

Figure 7. Fe and Mg partitioning in plagioclase. Grey circles are plagioclase compositional data (all textural types). Curves indicate FeO and MgO contents of plagioclase, calculated from experimental partitioning data (Bindeman et al.1998), at constant temperature (labelled) and constant melt composition, with varying X_{An}. Solid curves: 1.7 wt% FeO or 0.4 wt% MgO in the melt. Dashed curve: 2.5 wt% FeO or 0.8 wt% MgO in the melt. Black diamonds are experimental X_{An} from Couch et al.(2003a) with FeO_{pl} and MgO_{pl} calculated using their experimental T and $FeO_{(m)}$ or $MgO_{(m)}$ and partitioning data from Bindeman et al.(1998). This takes into account small changes in melt composition during crystallisation (see text for details).

Figure 8. X_{An} *vs* wt% FeO for selected plagioclase phenocryst zoning traverses. Location of each traverse is shown by the arrow or bar in the accompanying BSE images (MVO1350_34p4 and MVO1350_31) or photomicrographs. Scale bar represents 100 μm.

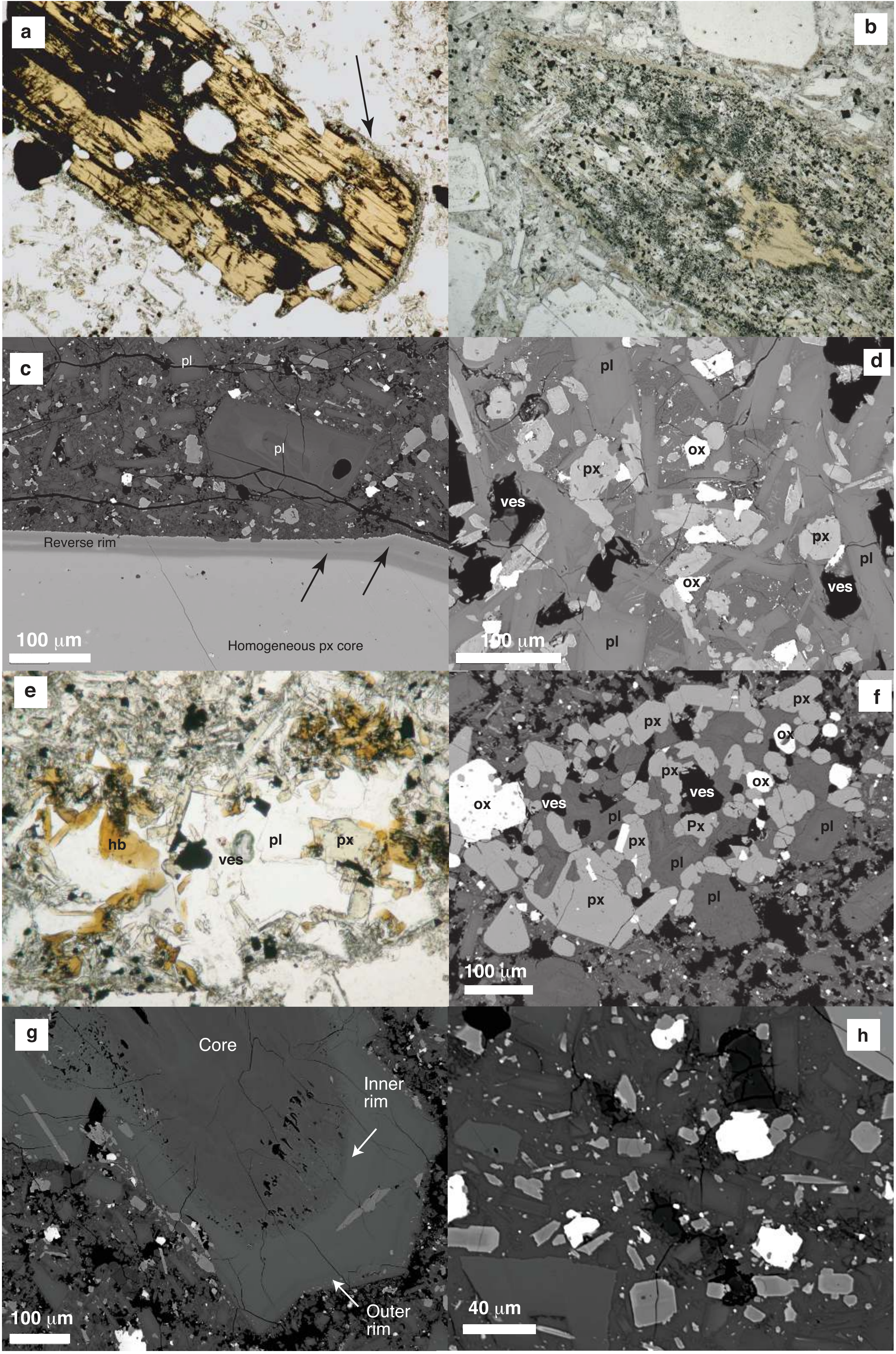
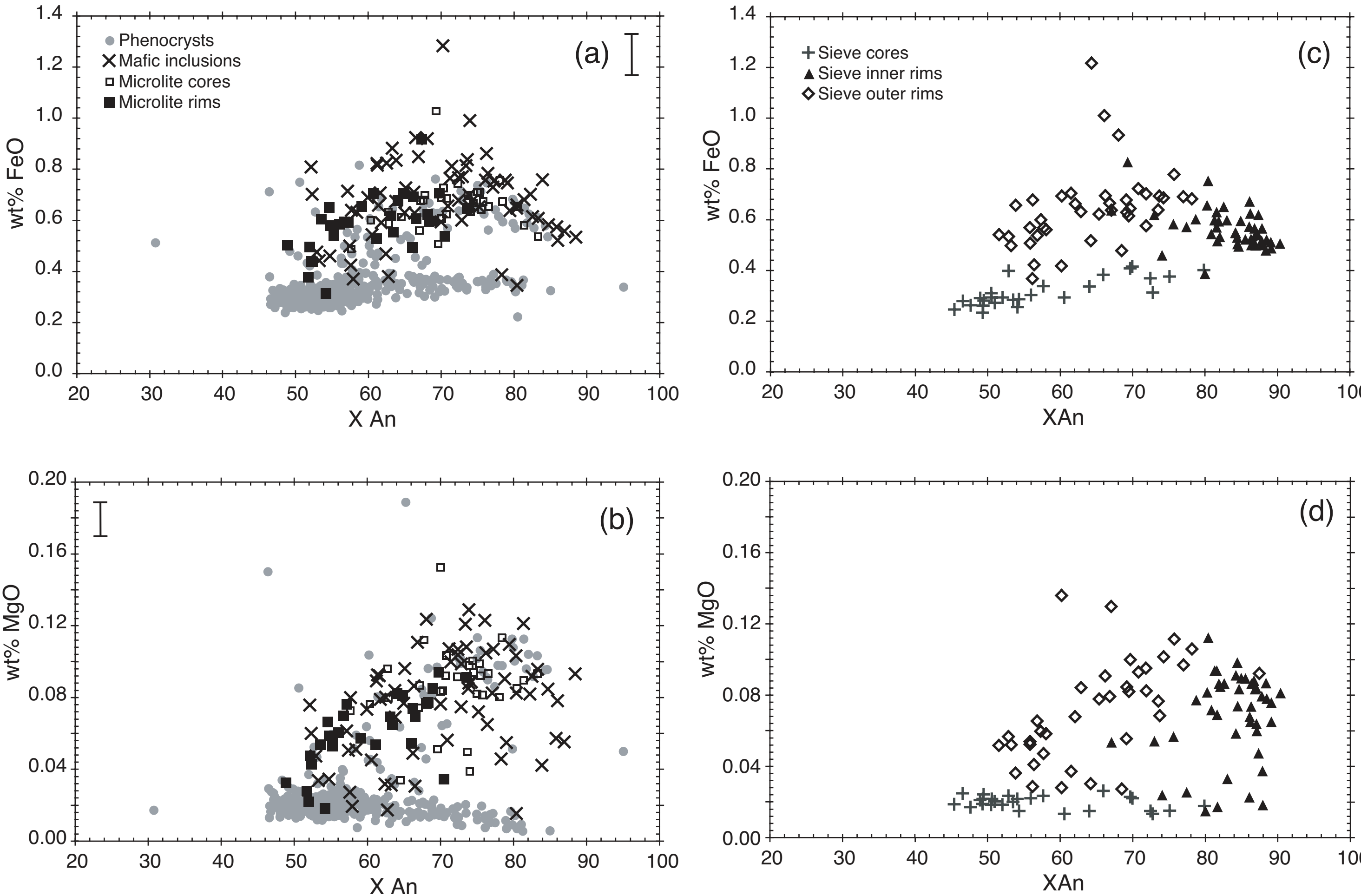
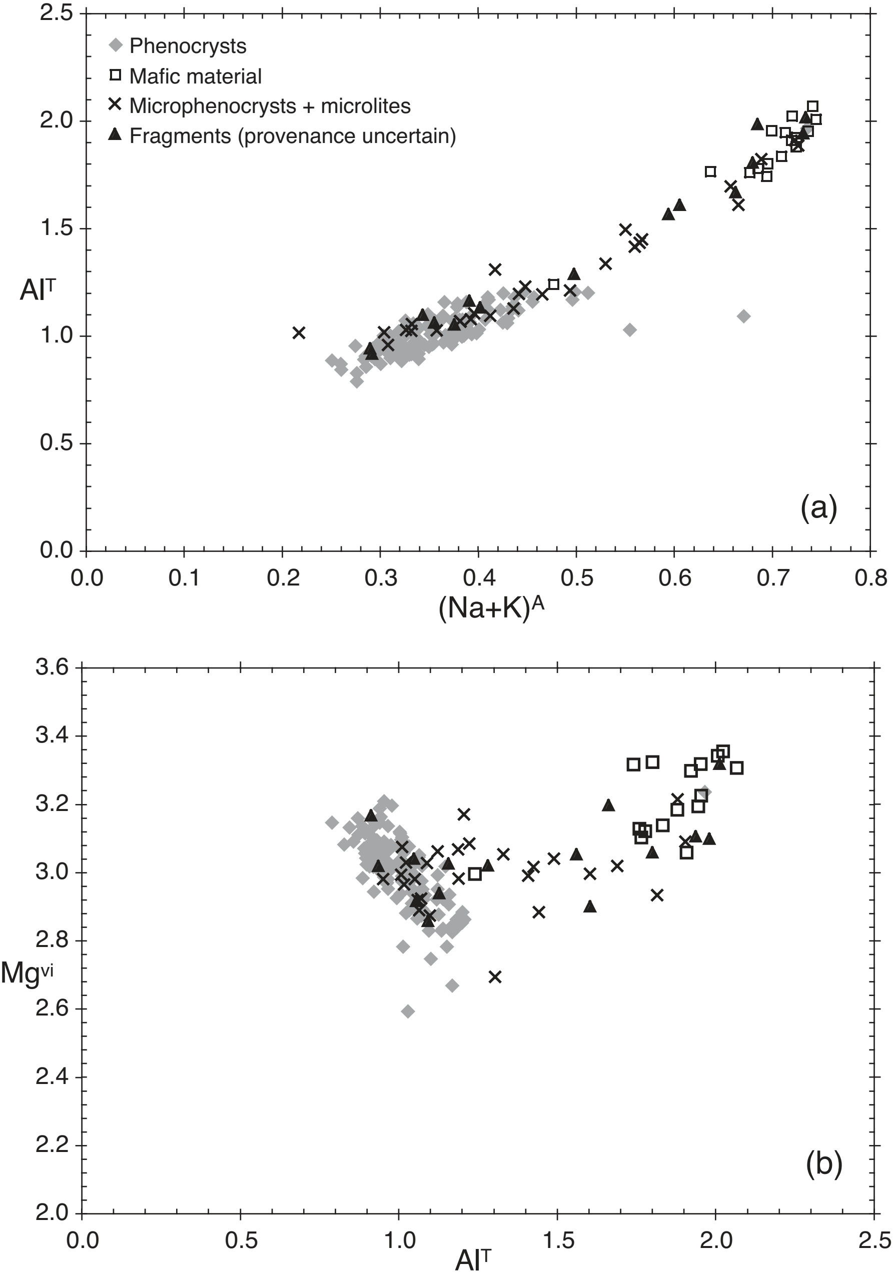

a
b
c
pl
pl
Reverse rim
Homogeneous px core
100 μm
d
pl
ox
px
ves
px
pl
ox
ves
pl
100 μm
e
hb
ves
pl
px
f
px
px
ox
px
ves
ox
ox
ves
pl
Px
px
pl
pl
pl
px
100 μm
g
Core
Inner
rim
Outer
rim
100 μm
h
40 μm

Figure 1



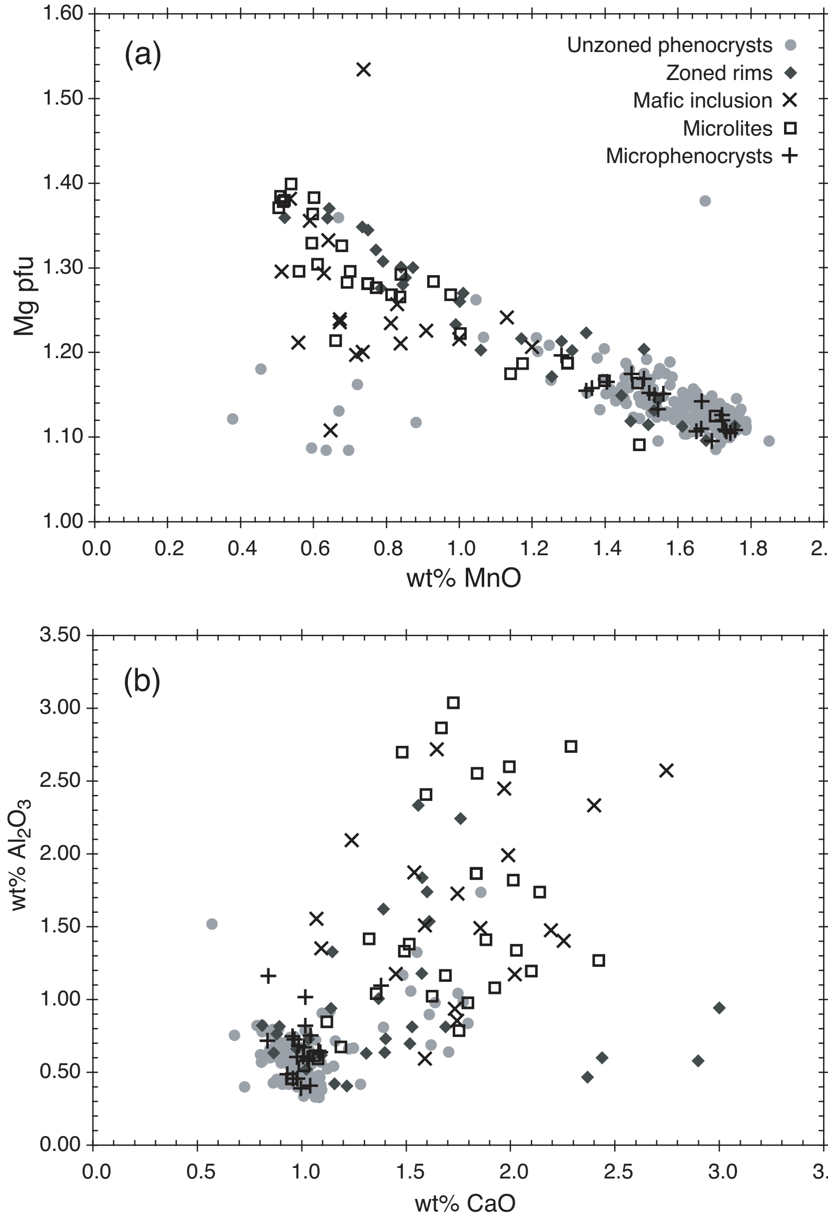
(a)
Phenocrysts
Mafic inclusions
Microlite cores
Microlite rims
wt% FeO
X An
(b)
wt% MgO
X An
(c)
Sieve cores
Sieve inner rims
Sieve outer rims
wt% FeO
XAn
(d)
wt% MgO
XAn

Figure 2

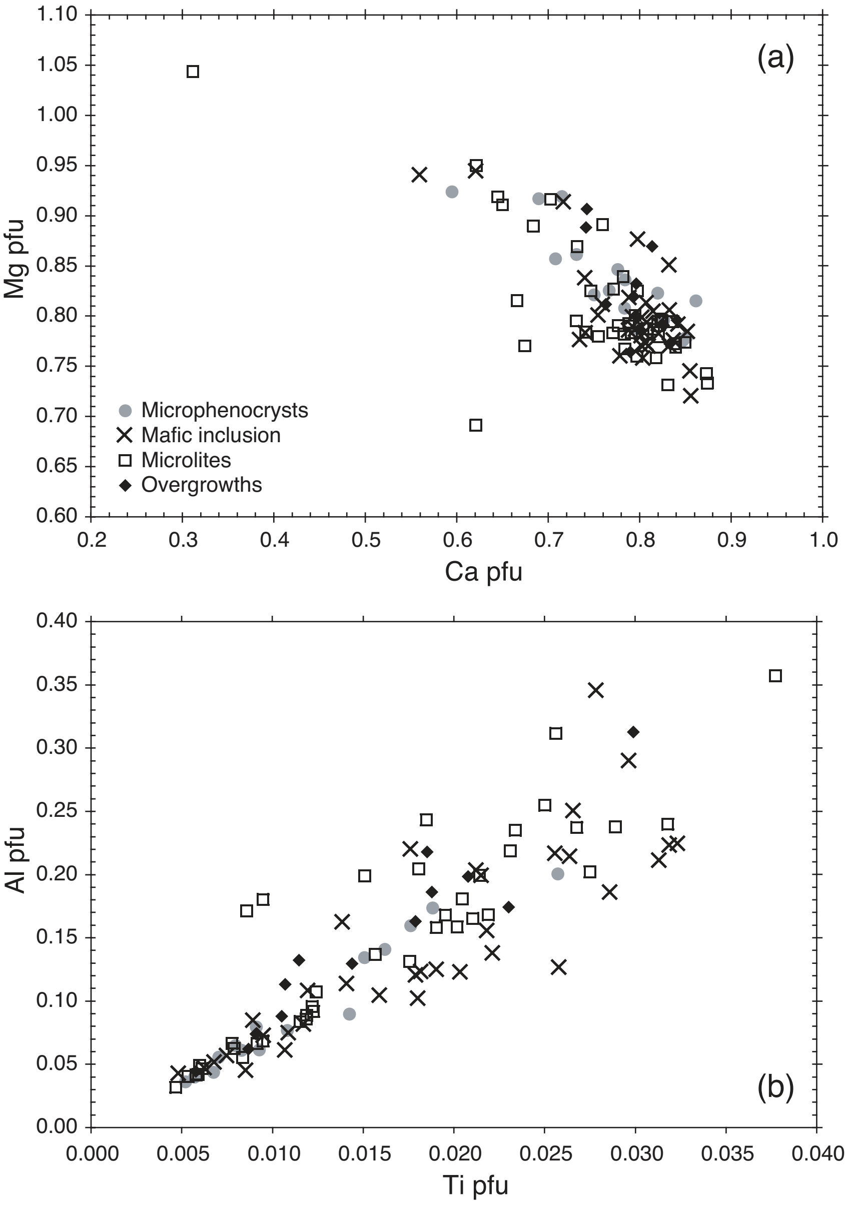


Phenocrysts
Mafic material
Microphenocrysts + microlites
Fragments (provenance uncertain)
Al^T
(Na+K)^A
(a)
Mg^vi
Al^T
(b)

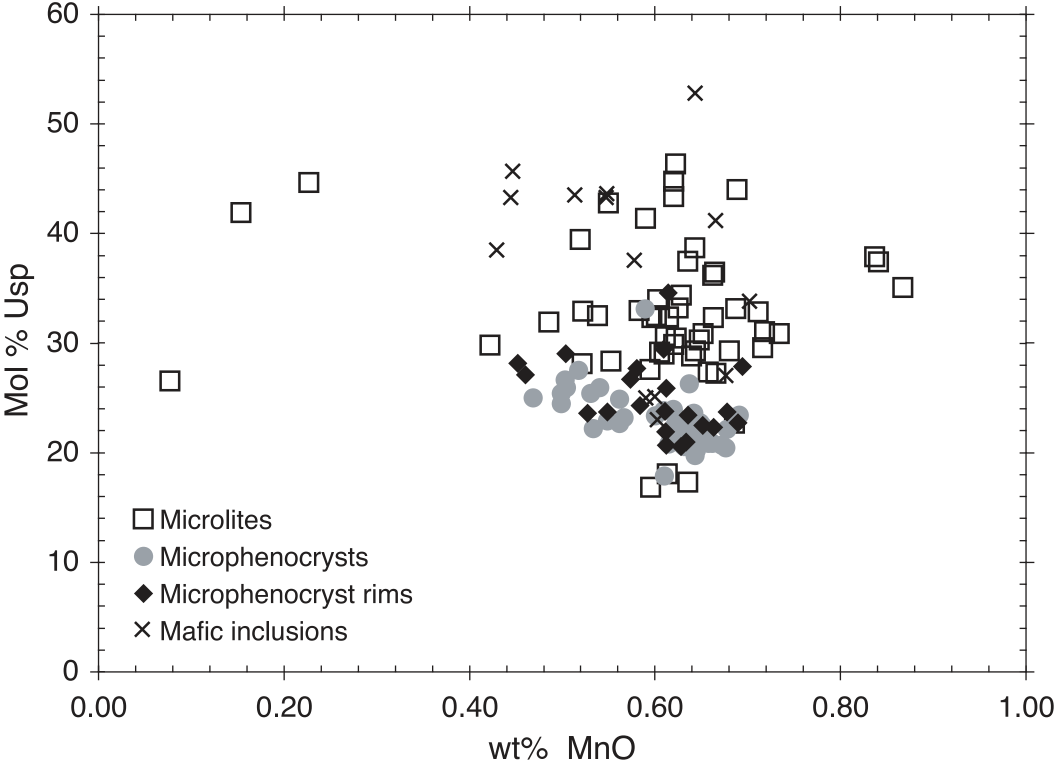
Figure 3.



(a)
Unzoned phenocrysts
Zoned rims
Mafic inclusion
Microlites
Microphenocrysts
Mg pfu
wt% MnO
(b)
wt% Al_2O_3
wt% CaO

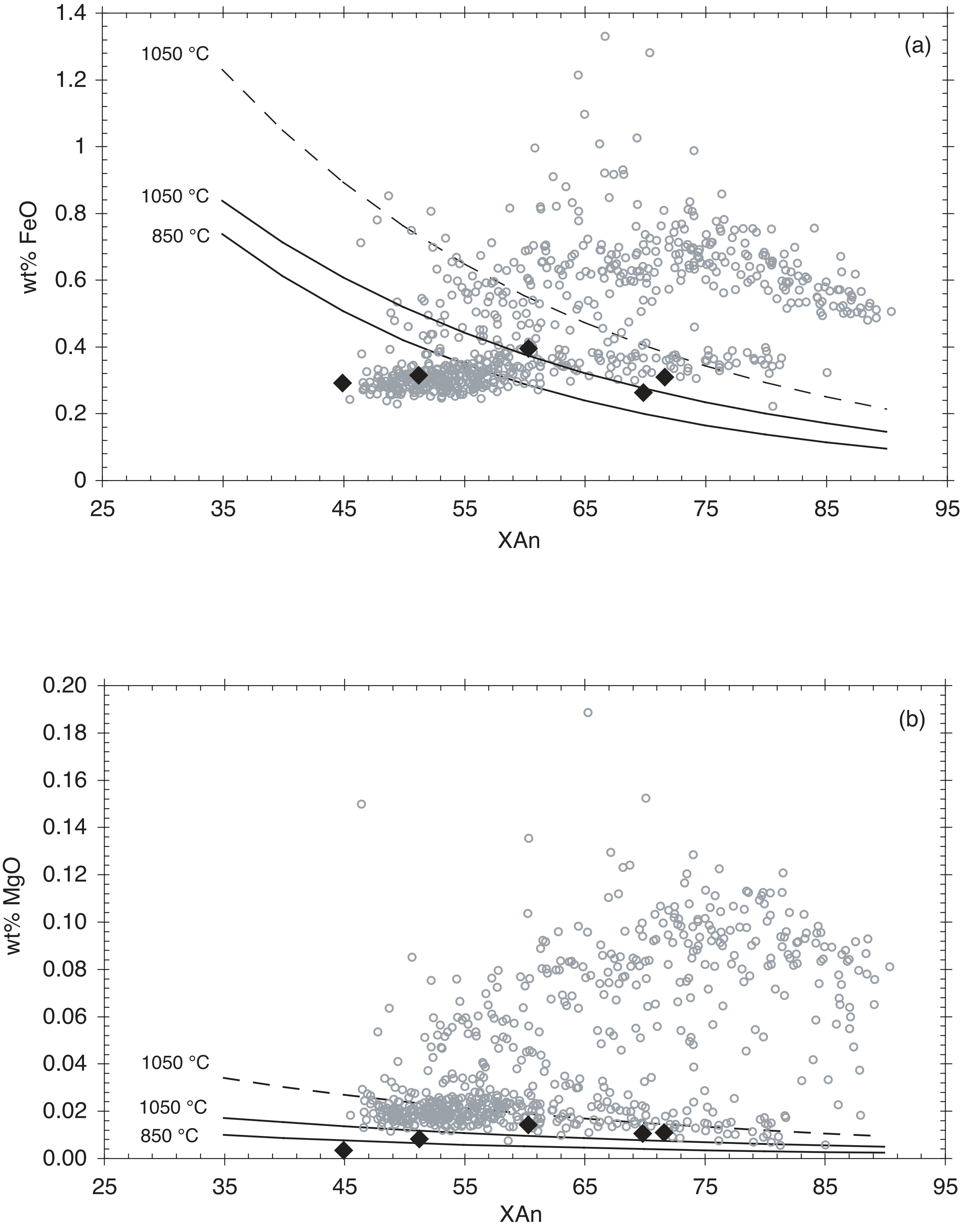


(a)
Mg pfu
Ca pfu
Microphenocrysts
Mafic inclusion
Microlites
Overgrowths
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
(b)
Al pfu
Ti pfu
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040



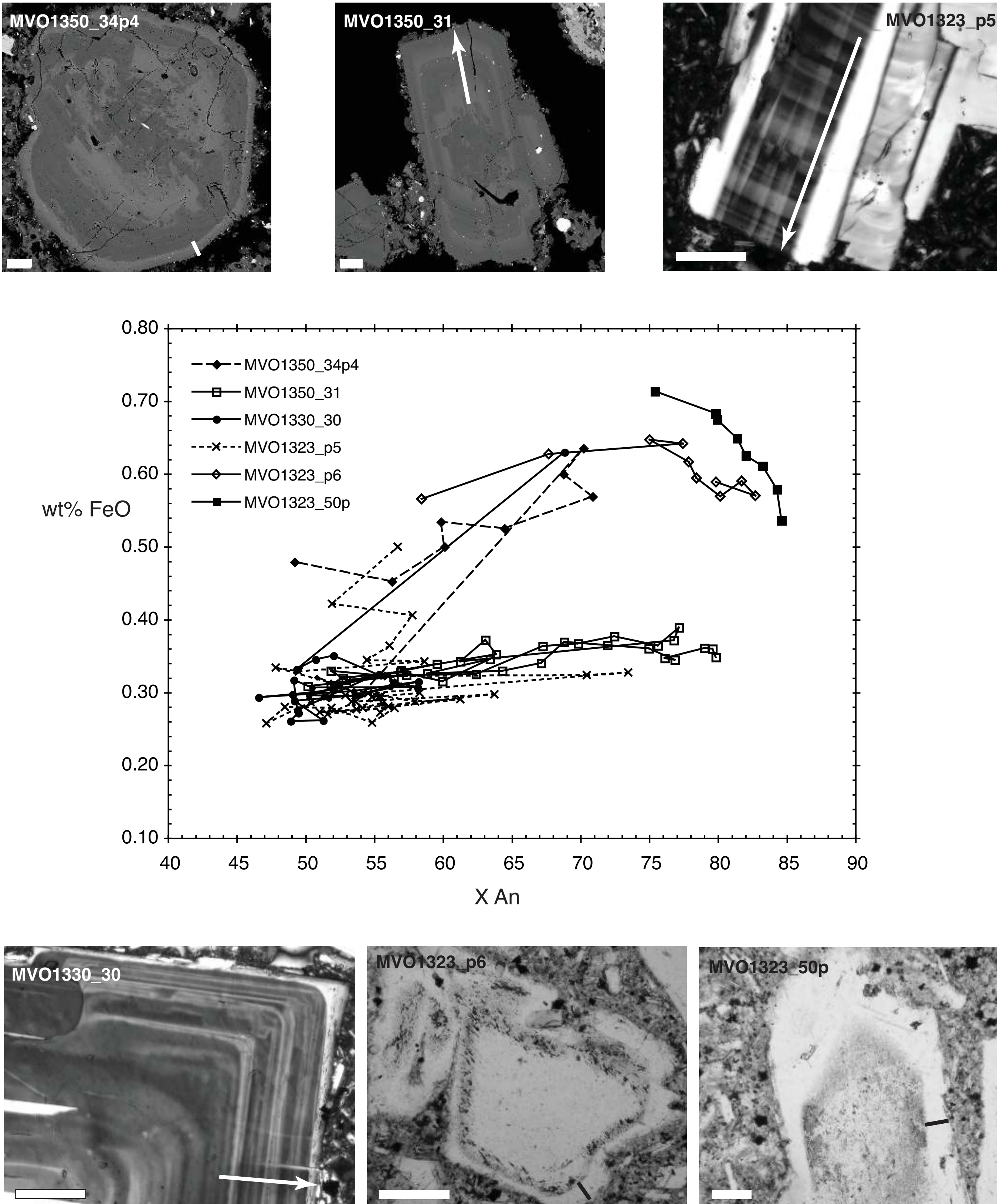
60
50
40
30
20
10
0
Mol % Usp
0.00
0.20
0.40
0.60
0.80
1.00
wt% MnO
Microlites
Microphenocrysts
Microphenocryst rims
Mafic inclusions

Figure 6



(a)
1050 °C
1050 °C
850 °C
wt% FeO
XAn
1.4
1.2
1
0.8
0.6
0.4
0.2
0
25
35
45
55
65
75
85
95
(b)
1050 °C
1050 °C
850 °C
wt% MgO
XAn
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00

Figure 8



MVO1350_34p4
MVO1350_31
MVO1323_p5
MVO1350_34p4
MVO1350_31
MVO1330_30
MVO1323_p5
MVO1323_p6
MVO1323_50p
wt% FeO
0.80
0.70
0.60
0.50
0.40
0.30
0.20
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40
45
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70
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80
85
90
X An
MVO1330_30
MVO1323_p6
MVO1323_50p