Basalt-inherited microlites in silicic magmas: Evidence from Mount Pelée (Martinique, French West Indies)

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ABSTRACT

During magma ascent in the volcanic conduit, the decompression of a silicic melt may result in the crystallization of morphologically and compositionally specific crystals, designated microlites. Hence, microlites have been considered as probes of mechanisms and time scales of magma ascent. Some microlites, however, appear to be in strong thermodynamic disequilibrium with their surrounding melt. We present here an experimental data set revealing that these microlites actually grew prior to ascent during mafic recharge of the magma chamber. Therefore, these microlites have no genetic relation to decompression-induced crystallization processes. Their presence may affect the rheological properties of the melt, as well as crystal growth mechanisms and kinetics during magma ascent.

Keywords: microlite, basalt, rhyolite melt, magma mixing.

INTRODUCTION

Island-arc silicic volcanism displays a wide range of eruptions, from effusive dome extrusions to explosive surges or Plinian events. Effusive and explosive behavior may occur during the same eruptive event, dramatically complicating risk evaluation for human life, property, and environment. Crucial questions that have been the focus of many recent studies concern the forecasting of either type of eruptive behavior, and the identification of the causes of the transition between effusive and explosive eruptions. One fruitful approach has been to couple natural observations on either active or well-characterized volcanoes with experimental and/or numerical methods.

Andesite to dacite magmas (SiO_2 = 58–64 wt%) that commonly erupt at island-arc volcanoes such as Mount Pelée (Martinique) or Soufrière Hills (Montserrat) in the Lesser Antilles carry two main types of crystals, phenocrysts and microlites. Phenocrysts, which may form relatively large, generally equant crystals (up to 1 cm), crystallize at low degrees of undercooling in the magma storage zone (or chamber) at depth. Although phenocrysts may be chemically zoned, as a result of compositional and thermal fluctuations during the lifetime of the magma chamber, their rim compositions are usually in thermodynamic equilibrium with a rhyolitic matrix melt (SiO_2 > 72 wt%). Microlites are small crystal phases (mostly <100 μm long) with specific morphologies ranging from equant, to skeletal, to dendritic (Lofgren, 1974) that result from degassing-induced crystallization at large degrees of undercooling during magma ascent in the volcanic conduit and dome emplacement. Thus, microlites carry potentially important information on ascent rates and the physical regime in the conduit. Microlite-free pumices from explosive Plinian events result from high magma ascent rates, with little or no gas loss through the conduit walls (closed-system degassing), whereas microlite-rich dense fragments from domes and pyroclastic flows have had slow magma ascent rates coupled with volatile loss (open-system degassing; Eichelberger et al., 1986; Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994). A number of recent experimental studies have focused on mechanisms and kinetics of microlite growth in order to quantify magma ascent rates during volcanic eruptions (Geschwind and Rutherford, 1995; Hammer and Rutherford, 2002; Martel and Schmidt, 2003; Couch et al., 2003a).

Our new data on Mount Pelée eruption products suggest that these concepts of microlite crystallization need to be reassessed.

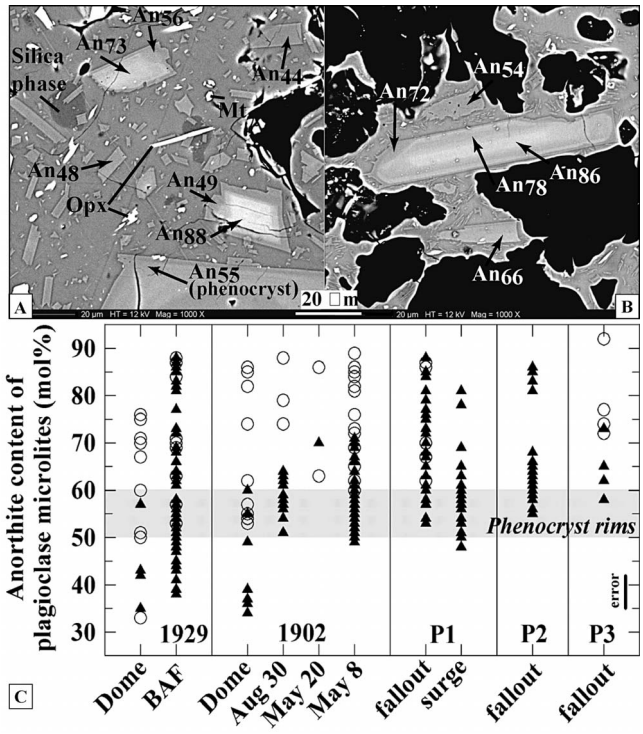

Figure 1. Textures and compositions of natural microlites from 1929, 1902, P1 (650 yr B.P.), P2 (1670 yr B.P.), and P3 (2010 yr B.P.) eruption products of Mount Pelée. A: Scanning electron microscope (SEM) image of dense juvenile fragment representative of 1929 block-and-ash flow (BAF) deposits. An—anorthite molar content of plagioclase; Opx—orthopyroxene; Mt—magnetite. B: SEM image of typical pumice from last Plinian fallout deposit (P1). C: An contents of 296 natural plagioclase microlites (analytical methods and analyses are given in the Appendix and in Tables DR1 and DR2 [see footnote 1]). Open circles—microlite areas of 4–500 μm²; filled triangles—microlite areas of 500–4500 μm². Gray band gives compositional range of plagioclase phenocryst rims in 1929, 1902, and P1 products (Martel et al., 1998).

MICROLITE COMPOSITIONS IN RECENT MOUNT PELÉE ANDESITES

Microlites (as long as 100 μm) identified in the rhyolitic matrix glass of recent Mount Pelée andesites include plagioclase, orthopyroxene, and magnetite phases; plagioclase is the most abundant. Plagioclase microlites are characterized by a large range of anorthite (An) contents. In particular, Ca-rich plagioclase microlites with An contents as high as 80–90 mol% are found both in explosive and effusive eruption products (Fig. 1; see GSA

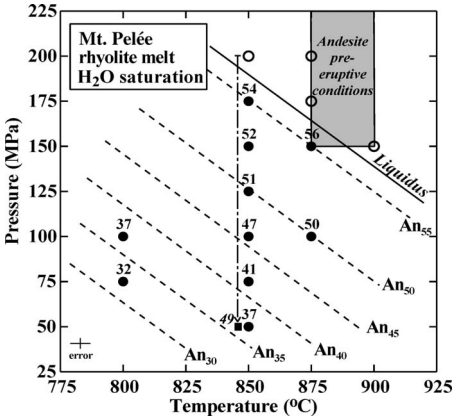

Figure 2. Phase diagram of Mount Pelée rhyolite matrix melt (75 wt% SiO_2, CaO/Na_2O = 0.6; Martel et al., 2000) at pressures ≤200 MPa and H_2O saturation (analytical methods and data are given in the Appendix and in Tables DR1 and DR2 [see footnote 1]). Circles—equilibrium experiments; filled square—continuous decompression experiment from 200 to 50 MPa in 2 days. Open symbols—plagioclase-free charges; filled symbols—plagioclase-bearing charges. Data points are labeled with plagioclase An content (in mol%). Gray field corresponds to pre-eruptive conditions for recent Mount Pelée andesite (200 ± 50 MPa, 875–900 °C, 6 ± 0.5 wt% melt H_2O; Martel et al., 1998).

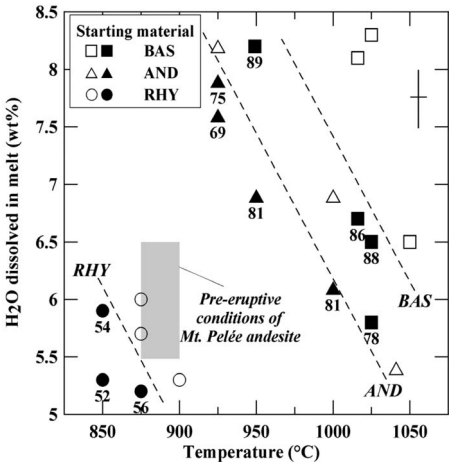

Figure 3. Maximum An content of plagioclase in crystallization experiments on three starting compositions representative of natural melts at Mount Pelée. BAS—basaltic andesite (400 MPa, Pichavant et al., 2002; 200 MPa, this study); AND—andesite (200–400 MPa; Martel et al., 1999); RHY—rhyolite (150–200 MPa, this study). Open symbols—plagioclase-free charges; filled symbols—plagioclase-bearing charges. Data points are labeled with plagioclase An content (in mol%). Dashed lines represent plagioclase out curves for three starting compositions. Gray field corresponds to pre-eruptive conditions for recent Mount Pelée andesite (875–900 °C, 6 ± 0.5 wt% melt H_2O; Martel et al., 1998).

Data Repository Table DR1[1]). The occurrence of these calcic plagioclase microlites is problematic: only plagioclase microlites with compositions less calcic than the phenocryst rims, i.e., with An <50–60, would be expected to crystallize, because microlites mark a more advanced stage of crystallization of the rhyolitic matrix melt than phenocryst rims. Equilibrium experiments simulating microlite crystallization from a water-saturated rhyolitic melt at low pressures compatible with shallow magma ascent only yield compositions less calcic than the phenocryst rims (Fig. 2; Table DR2 [see footnote 1]). This confirms the interpretation that the crystallization of microlites with An contents <50–60 is related to processes of magma ascent in the conduit or dome emplacement, but leaves the presence of more calcic microlite compositions unexplained.

ORIGIN OF CALCIC PLAGIOCLASE MICROLITES

To account for these Ca-rich plagioclase microlites, several possible mechanisms need to be explored. These microlites might have crystallized from a rhyolitic melt, but at temperatures higher than the pre-eruptive one (Couch et al., 2001). Furthermore, recent studies have considered the possibility that massive degassing-induced crystallization leads to a significant temperature elevation in the conduit due to latent heat effects (Couch et al., 2003b; Devine et al., 2003). Our experimental results on the Mount Pelée rhyolitic matrix melt composition (75 wt% SiO_2; CaO/Na_2O = 0.6) show that crystallization of plagioclase ($An_{55–60}$) imposes an upper limit on temperature, 850 °C at 200 MPa and >850 °C for pressures <200 MPa (Fig. 2). However, plagioclase An isopleths are parallel to the liquidus, and compositions more calcic than $An_{55–60}$ are not obtained at >875 °C and <200 MPa (Fig. 2). Plagioclase crystals grown in decompression experiments differ from those in equilibrium experiments because of kinetic effects, but they remain less calcic than the near-liquidus compositions (Fig. 2; Hammer and Rutherford, 2002; Martel and Schmidt, 2003; Couch et al., 2003a). This suggests that the Ca-rich microlites have crystallized from a melt more calcic than the rhyolitic matrix melt (i.e., with a higher CaO/Na_2O).

Experiments performed with a melt of Mount Pelée andesite bulk composition (SiO_2 = 61 wt%, CaO/Na_2O = 1.7; Martel et al., 1999) yield plagioclase compositions up to ~An_{80}, the most An rich ($An_{81 ± 2}$) being obtained at 1000 °C and 6–7 wt% H_2O dissolved in the melt (Fig. 3). These experimental plagioclases are significantly more calcic than either the phenocryst rims or the plagioclase microlites crystallized from the rhyolitic matrix melt, but are not quite as calcic as the most An-rich (An_{92}) microlites observed. Experiments starting with a basaltic andesite melt representative of the bulk composition of mafic magmas at Mount Pelée (SiO_2 = 53 wt%, CaO/Na_2O = 3.4; Pichavant et al., 2002) crystallize a plagioclase composition of $An_{88 ± 2}$ at 1025 °C and ~6.5 wt% H_2O dissolved in the melt (Fig. 3), in the range of the most Ca-rich natural microlites. At lower temperatures and similar H_2O contents, less calcic compositions are obtained as the equilibrium melt composition becomes more evolved. Therefore, a parental mafic melt (basaltic to basaltic andesite) is required to account for the most calcic plagioclase microlites observed in the eruption products.

MICROLITE CRYSTALLIZATION AT MOUNT PELÉE

The interpretation of plagioclase microlites at Mount Pelée thus needs to distinguish two cases, depending on microlite An contents. Microlites with An contents lower than phenocryst rims can crystallize from a water-saturated rhyolitic melt at low pressures either in the conduit or in the dome, according to our data. This population is best represented in dome and block-and-ash flows from the 1902 and 1929 eruptions, but is almost lacking in Plinian eruption products (Fig. 1C), probably because ascent rates were too fast to allow significant crystallization in the conduit. For the other population, with An contents higher than the phenocryst rims, the crystals must have grown from melts more calcic than rhyolite, i.e., in andesitic to basaltic melts. In particular, crystallization from a mafic melt with water content as high as in the experiments (6.5–8.5 wt%) is needed to explain the calcic end of this microlite population. These melts probably represent injections into the andesite body during episodes of recharge and mixing of the magma reservoir. Magma mixing is an effective mechanism at Mount Pelée, as evidenced by the presence of enclaves and banded rocks in the early products of the 1902 and 1929 eruptions (Gourgaud et al., 1989; Fichaut et al., 1989). However, nearly all the plagioclase phenocrysts from the andesitic magma lack sieve textures and reverse zoning (Gourgaud et al., 1989; Pichavant et al., 2002) that are typical indicators of magma mixing processes (Tsuchiyama, 1985; Browne et al., 2006b). The crystallization of the highly calcic plagioclases in the conduit can be ruled out

[1]GSA Data Repository item 2006204, Appendix (experimental and analytical methods), Table DR1 (composition and the size of 296 natural plagioclase microlites of Mount Pelée), and Table DR2 (*P-T* conditions and the plagioclase and glass compositions of the experimental charges), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

because an H_2O-rich melt is required (Sisson and Grove, 1993a; Pichavant et al., 2002). The mafic melt has a liquidus temperature (T) of 1050 °C (Pichavant et al., 2002), so the thermal contrast at the contact with the andesitic body (T = 875–900 °C; Martel et al., 1998) would generate degrees of undercooling up to 150 °C, appropriate for microlite crystallization. The entire compositional range within this microlite group (from An_{90} to $An_{50–60}$; Fig. 1C) can be explained by assuming some variation in the composition of the recharge melts (i.e., basaltic to andesitic). Alternatively, the chemical zonation observed in some of these high-Ca microlites (Figs. 1A, 1B; Table DR1 [see footnote 1]) suggests the possibility of either multistage growth or partial re-equilibration between early-formed crystals and the (rhyolitic) matrix melt.

The crystallization of An-rich microlites is thus viewed as the result of discrete mafic melt intrusions in an andesitic magma. Studies of mafic enclaves have shown that the main thermal and mechanical consequences of mafic-silicic magma interaction include rapid cooling and crystallization of the mafic magma and local heating of the contact silicic magma (Pallister et al., 1996; Eichelberger et al., 2006). Protracted crystallization of the mafic magma drives the matrix melt toward a rhyolitic composition (Fichaut et al., 1989; Gourgaud et al., 1989; Eichelberger et al., 2000). The viscosities of the residual liquids of the respective magmas thus become similar, which promotes their mixing and the incorporation of microlites grown in the mafic magma into the andesite. If an eruption follows mafic injection, further crystallization from the (rhyolite) matrix melt may occur in the conduit, provided that ascent rates are not too fast, giving rise to a second generation of microlite compositions (An < 50) that may form either new crystals and/or rims around the high-Ca microlites. This dual model of microlite genesis thus accounts for the entire compositional range of plagioclase microlites observed at Mount Pelée.

APPLICATION TO OTHER VOLCANIC SYSTEMS

The presence of microlites inherited from the crystallization of a mafic magma is probably not unique to Mount Pelée. At Soufrière Hills, Montserrat, plagioclase microlites and phenocryst overgrowth rims with compositions up to An_{79} are present in the still-erupting andesite (Couch et al., 2001, 2003b). These plagioclase compositions, which are more calcic than the phenocryst cores, have been interpreted as products of reheating of the andesite body from 830 to ~950 °C, following a convective self-mixing process (Couch et al., 2001, 2003b). The magnitude of this reheating event has been reevaluated, and evidence has been presented for significant mass transfer from mafic magmas to the erupting andesite body (Rutherford and Devine, 2003). Therefore, although the convective self-mixing model first recognized the necessity of specific growth conditions for the calcic plagioclase microlites and overgrowths (at high temperature in this case), the recent data on Soufrière Hills are more consistent with a model of crystallization of these Ca-rich plagioclases from mafic magmas injected into the andesite body, according to a mechanism comparable to the one presented here for Mount Pelée.

At Mount Unzen, Japan, magma mixing is a major process (Nakamura, 1995; Browne et al., 2006a, 2006b). Pargasite (low-Si, high-Al amphibole) microphenocrysts (100–300 μm long and 5–50 μm wide) have been identified in the groundmass of the dacitic lava from the 1991–1995 eruption (Sato et al., 1999). Pargasitic amphibole and calcic plagioclase are two essential phases from the crystallization of hydrous basaltic melts (Pichavant et al., 2002), and the presence of these pargasite microcrystals probably results from a magma interaction and recharge mechanism analogous to the one invoked here to explain the calcic plagioclase microlites. Blade-shaped crystals of pargasitic amphibole also occur together with high An plagioclase at Soufrière Hills, Montserrat, and these have been interpreted as products of mingling and hybridization between mafic magmas and preexisting andesite (Rutherford and Devine, 2003). The fact that amphibole is not stable at low pressures constrains the magma mixing and interaction to occur at depth (Rutherford and Hill, 1993; Rutherford and Devine, 2003).

VOLCANOLOGIC AND PETROLOGIC IMPLICATIONS

A silicic magma reservoir carrying microlites inherited from a mafic magma has significant consequences for our understanding of mechanisms of magma ascent. Numerical and experimental models of conduit-flow often assume microlite-free ascent conditions, with groundmass crystallization taking place only in the volcanic conduit depending on the ascent (decompression) rate (Hammer and Rutherford, 2002; Martel and Schmidt, 2003; Couch et al., 2003a; Melnik et al., 2005). The presence of a significant amount of microlites (mostly plagioclases, but possibly pyroxenes, amphiboles, or oxides) inherited from mafic melts may affect the rheology of the ascending melt (Roscoe, 1952). In addition, the presence of the basalt-inherited microlites complicates the use of microlite crystals to quantify magma ascent rates and degassing processes. Comparison between crystals grown experimentally under controlled pressure (P)-T-time conditions and natural microlites should be made with caution. Several stages of growth (in the reservoir, conduit, and dome), each under specific P-T-time conditions, can be distinguished in some plagioclase microlites of Mount Pelée, as indicated by their textures and compositional variations within single crystals (Figs. 1A, 1B). It becomes necessary to attribute an origin (either mafic recharge or magma ascent and dome emplacement) to microlite crystals individually before their morphological (equant, skeletal, dendritic) and compositional characteristics can be applied to delimit P-T-time crystallization conditions, degree of undercooling, and importance of H_2O loss. Experimental phase equilibrium data provide a mean to infer whether groundmass plagioclase microlites are in equilibrium with their matrix glass, provided the meltwater content at the time of crystallization is known (Fig. 4). For water pressures ≤200 MPa, distribution coefficients of CaO and Na_2O between plagioclase and melt barely exceed 5 in island-arc magmatic systems (Sisson and Grove, 1993b; Martel et al., 1999; Pichavant et al., 2002), which provides an upper limit of ~An_{70} for plagioclase to be in equilibrium with the matrix glasses analyzed in recent Mount Pelée products (CaO/Na_2O = 0.1–0.8; Fig. 4). This implies that any microlite more calcic than ~An_{70} must have crystallized at equilibrium with melts with CaO/

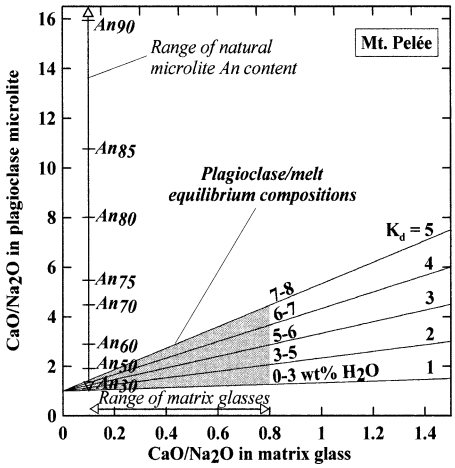

Figure 4. Distribution of CaO and Na_2O between plagioclase microlites and matrix glasses from Mount Pelée. Range of natural microlite compositions is taken from Figure 1C; CaO/Na_2O ratios in matrix glasses range from 0.1 to 0.8 (Martel et al., 2000). Ca-Na distribution coefficients between plagioclase and glass ($K_d = [CaO/Na_2O]_{plag}/[CaO/Na_2O]_{glass}$) and their dependence with melt H_2O content are from Sisson and Grove (1993b), Martel et al. (1999), Pichavant et al. (2002), Martel and Schmidt (2003), and this study. Gray area represents range of plagioclase compositions in equilibrium with matrix melt. Compositions outside this field cannot have crystallized at equilibrium with matrix melts found at Mount Pelée.

Na_2O higher than observed in the Mount Pelée matrix glasses. Such a test of equilibrium between the plagioclase microlites and their matrix glass may be applied to other volcanic rocks.

Another major implication concerns mafic-silicic magma interaction processes. These processes are documented mainly by studies of medium-scale heterogeneities (mafic enclaves, banded rocks) or, at smaller scales, by studies of phase assemblages (cognate phenocrysts, xenocrysts) and glass compositions (Pallister et al., 1996; Izbekov et al., 2002; Browne et al., 2006a). The study of microlites adds to these different tools, in providing a window at the 1–100 μm scale into mafic-silicic magma interaction processes. For successive eruptions of a given volcano, potential applications include delimiting the composition of recharge mafic magmas and the proportions of magmas involved in the mixing events through the determination of the amount of basalt-inherited microlites present, with perspectives on the temporal evolution of the deep feeding system. The fact that rhyolitic melts of different origins are effectively homogenized (as marked by the spatial juxtaposition of high-Ca and low-Ca microlites) could be used to define the fluid dynamics and time scales of the mixing events. This is critical because the flux of mafic magma controls the magnitude of reservoir overpressures, which act as an eruption trigger, and the ascent rate in the conduit (Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994).

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