

Shallow magma-mingling-driven Strombolian eruptions at Mt. Yasur volcano, Vanuatu

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[1] Mt. Yasur volcano (Vanuatu) has been increasingly recognized for its high-frequency Strombolian eruptions. Strombolian activity is often regarded as a product of the rapid ascent of gas slugs originating from a deep magma, which mingle with a batch of shallow magma upon eruption. Heterogeneous crystal distribution as well as bimodal bubble-size distributions, in the eruptive products, generally supports this view. Here, the Strombolian activity at Mt. Yasur is analyzed. A rheological investigation indicates that the basaltic-andesitic eruptive products contain an apparently homogeneous glass phase and yet, exhibit evidence of a distinct range of glass transition temperatures with multiple peaks occurring in individual samples. Such anomalous behavior is proposed to result from the mingling of magmas with contrasting oxidation states. The unstable nature of the measured glass transition behavior leads us to the inference that mingling is located in the shallow parts of the eruptive conduits, partly driven by rejuvenation of material slumped from the crater walls into an open conduit system. The dynamics of this process may expose the periodicity of the eruptions themselves. **Citation:** Kremers, S., Y. Lavallée, J. Hanson, K.-U. Hess, M. O. Chevrel, J. Wassermann, and D. B. Dingwell (2012), Shallow magma-mingling-driven Strombolian eruptions at Mt. Yasur volcano, Vanuatu, *Geophys. Res. Lett.*, 39, L21304, doi:10.1029/2012GL053312.

1. Introduction

[2] Volcanic activity at Mt. Yasur (Tanna island, Vanuatu) has been characterized by regular Strombolian eruptions for the last 300 years [Simkin *et al.*, 1981]. Currently, this activity takes place at three vents with highly varying recurrence rates [Oppenheimer *et al.*, 2006]. Strombolian activity, as epitomized by Stromboli volcano (Italy), has been described as resulting from the ascent of gas slugs – that is, decimeter- to meter-size bubbles that have decoupled from the melt phase. These gas slugs burst at the free surface of the magma column [Walker, 1973; Blackburn *et al.*, 1976; Wassermann, 1997; Chouet *et al.*, 2003; Houghton and Gonnermann, 2008] due to stresses generating strain rates

exceeding the relaxational strain rates of the bubble wall magma [Taddeucci *et al.*, 2006]. Except for brief shifts in activity to larger explosions, termed paroxysmal eruptions, the activity at Stromboli appears to recur at regular intervals, suggestive of a continuum process in an open system [Métrich *et al.*, 2010]. The surface activity is inferred to reflect the ascent of magma batches at various rates, driven by the relative buoyancy of bubbles with contrasting sizes [Vergnolle, 1996; James *et al.*, 2008]. This is a process that presumably leads inevitably to physical mingling in the conduit [Lautze and Houghton, 2005]. The mingled eruptive products of Stromboli exhibit homogeneous bulk chemical composition, yet variable crystallinities and bimodal bubble-size distributions [Lautze and Houghton, 2007, 2008]. Recent microanalytical studies on volatile concentrations in crystal-rich and crystal-free areas of erupted products have led to the idea that incipient filter-pressing melt segregation, driven by fluidization of interstitial melt due to the incompatibility of volatiles during crystallization at shallow levels, may take place during fragmentation [Schipper *et al.*, 2010]. The common bimodality of the mingled products begs the question of the potential rheological importance of shallow magma mingling/mixing in driving Strombolian activity.

[3] The rheology of magmas – their ability to flow, to exsolve volatiles, to trap bubbles, to degas and to fragment – is a central control on the eruption dynamics [Dingwell, 1996]. The rheology of magmas depends critically on the viscosity of the melt, which in turn depends on chemical composition [e.g., Hui and Zhang, 2007; Giordano *et al.*, 2008], temperature [e.g., Hess and Dingwell, 1996], crystal content [Caricchi *et al.*, 2007; Cordonnier *et al.*, 2009; Ishibashi, 2009; Lavallée *et al.*, 2007; Lejeune and Richet, 1995], bubble content [e.g., Lejeune *et al.*, 1999; Manga *et al.*, 1998; Llewellyn and Manga, 2005] and to a very minor extent, pressure [e.g. Liebske *et al.*, 2003].

[4] Magma viscosities can now be reasonably well approximated using empirical models [e.g., Giordano *et al.*, 2008; Hui and Zhang, 2007]. In iron-rich magma (such as those involved in Strombolian eruptions), iron may play a dual role depending on the oxidation state; as trivalent or divalent cations as well as occupying multiple coordination states in both valencies [e.g., Mysen *et al.*, 1984; Bouhifd *et al.*, 2004]. Viscosity determination of sub-liquidus, iron-rich melt is challenging but can be undertaken, in principle, using calorimetric technique where different cooling/heating rates can probe a range of viscosities in the glass transition interval provided that no chemical changes take place due to crystallization or devolatilization [e.g., Gottsmann and Dingwell, 2000].

[5] Previous geochemical analyses of Strombolian products have revealed the general homogeneity of their bulk chemistry evolved from more primitive, volatile-rich parental magma which do not erupt alone without dragging a substantial

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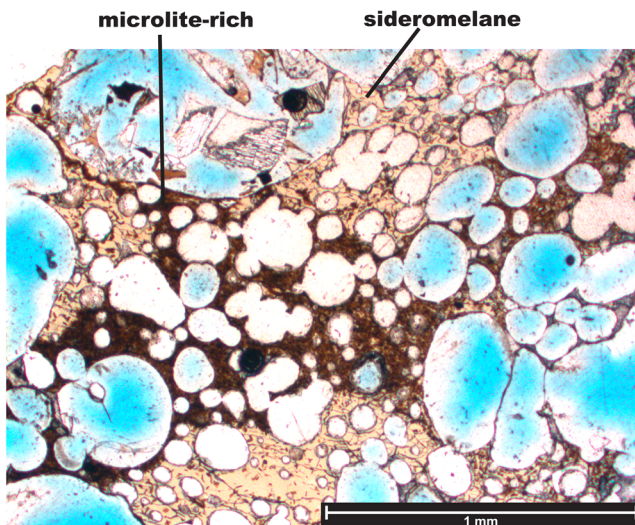


Figure 1. Microphotograph of contact between sideromelane and microlite-rich areas in sample Van A1.

amount of evolved, volatile-poor, crystal-rich magma from the upper conduit [Métrich *et al.*, 2001]. In such scenarios in which magma mingling/mixing takes place at shallow depths, just prior to eruption, the extent of homogenization of subtle differences in oxidation state may influence the bulk viscosity and thus, the eruptive rheology.

[6] Below, we describe the Strombolian activity at Mt. Yasur volcano as well as petrological and rheological analyses of the eruptive products. These observations demonstrate the importance of shallow mingling during such activity. We propose a correlation between chemical mixing and rheological homogenization processes and the recurrence rate and size of explosions.

2. Strombolian Activity at Yasur Volcano

[7] Volcanic activity at Mt. Yasur can be traced to the late Pliocene from a series of major volcanic episodes [Carney and Macfarlane, 1979; Chen *et al.*, 1995]. The most recent episode of activity formed the Siwi Group in the easternmost part of the island, and is characterized by predominantly basaltic to basaltic-andesitic deposits [Robin *et al.*, 1994; Bani and Lardy, 2007]. Present activity at the Yasur cinder cone consists of Strombolian to Vulcanian activity [Carney and Macfarlane, 1979; Bani and Lardy, 2007], produced from three small active craters (denoted as A, B and C from south to north, respectively) excavated within a larger 400-m diameter crater [Oppenheimer *et al.*, 2006] – a feature commonly observed at other Strombolian systems [Cole *et al.*, 2005].

[8] At the time of a geophysical monitoring and sample collection field campaign in August–September 2008, all three craters showed very different styles of activity. Crater A, the most active vent, had an eruption recurrence periodicity of less than one minute. Crater B showed very irregular ash venting, with variable periodicity ranging between minutes and days, while crater C produced the strongest eruptions on a longer recurrence timescale of approximately ten minutes. From our observation site we noted a considerable amount of material recycling from tephra deposited inside the

vent, in addition to inward slumping of tephra off the scree slope of the inner crater wall A.

3. Strombolian Products

[9] For the present study, the eruptive products of craters A and C were sampled. From crater A we collected one juvenile bomb (Van A1), which was torn from the wall of a bursting bubble and impacted the ground in a deformable, viscous state, and one exotic bomb (Van A2), which appears denser (than the juvenile bomb), nearly spherical in shape and undeformed by ground impact. From crater C, one juvenile bomb (Van C), representing the wall of a bursting bubble and impacting the ground in a deformable viscous state was collected (see auxiliary material).¹ The bombs Van A1 and Van C are uniformly black with abundant white millimeter-size crystals of plagioclase. The bubble shapes vary from sub-spherical to spherical and the content within a bomb grades strongly from a highly porous core to a denser glassy rim. The bomb Van A2 is light to dark-grey, almost fully crystalline and interpreted as exotic material that fell back from the crater wall into the conduit and was re-expelled during subsequent explosions. The bubbles of Van A2 show highly irregular shapes.

[10] Petrographic analysis reveals differences between these samples. First, both juvenile bombs host bimodal textures; that is, they contain regions of microlite-free glass (sideromelane) and regions of microlite-rich groundmass. The contact between each region is often sharp, though occasionally diffused contacts were noted (Figure 1). The sideromelane regions show more fluidal structures – demonstrated by the deformation and collapse structures of some bubbles – than the microlite-rich regions. The edges of these deformed bubbles are commonly oxidized to a dark brown color. The microlites present in the microlite-rich regions (and sometimes in the sideromelane regions near the edge of a transition) often show a spherulitic texture suggesting crystallization of the magma under disequilibrium conditions. Sample Van A1 (from high-recurrence rate eruptive crater A) has abundant sinuous interfaces and appears heavily mingled in contrast to sample Van C (from the Crater C). In exotic sample Van A2, almost no regions of sideromelane are observed; instead, the sample is nearly entirely crystallized.

[11] Analysis of the bubbles reveals a contrasting size distribution between the sideromelane and the crystal-rich area. Sideromelane areas are rich in small ($<1 \times 10^{-3}$ mm) vesicles whereas microlite-rich areas contain larger ($>4 \times 10^{-2}$ mm) vesicles (Figure 2). This bimodal distribution is in good agreement with the results of Lautze and Houghton [2005] on lapilli from Stromboli volcano (Italy). The regular spherical shape of the vesicles in the sideromelane areas suggest a rapid cooling shortly after expansion, whereas the irregular shapes in the microlite-rich area indicate a complex deformation overprint, probably including coalescence and shearing.

[12] Bulk rock chemistry analysis using X-ray fluorescence revealed the homogeneity of the chemical composition of the eruptive products (Table 1); an observation akin to those of previous studies on Strombolian products [Lautze and Houghton, 2005, 2008]. Electron probe microanalysis of the interstitial glass reveals a more evolved composition

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL053312.

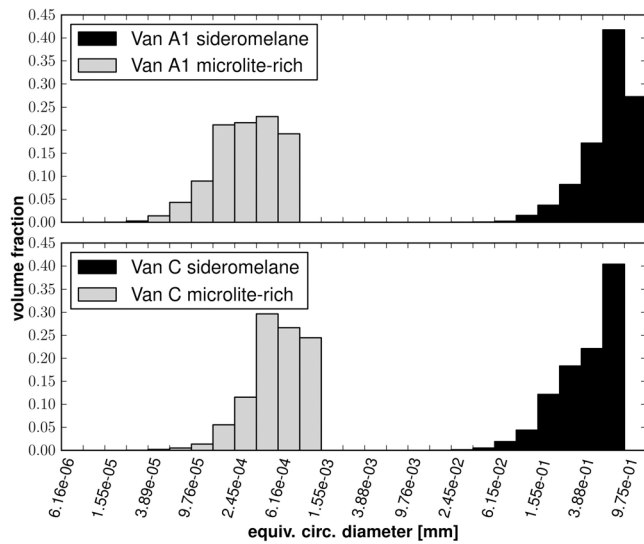


Figure 2. Bubble-size distributions using the equivalent circular bubble diameter for the sample (top) Van A1 and (bottom) VAN C. Distinct peaks evidence the sideromelane and the microlite-rich groundmass. Bin values are scaled following *Sahagian and Proussevitch* [1998] using a geometric scale of $10^{-0.1}$.

than the bulk; yet, there appears to be no chemical distinction (within the standard deviation of the measurements) between the glass in the sideromelane- and microlite-rich areas (Table 2). The crystalline phases were found to be mostly plagioclase (labradorite; see auxiliary material) with some pyroxene (augite).

[13] Thermal analyses were performed to characterize the stability of the eruptive products as well as the physico-chemical character of the glass phase. Thermogravimetric measurements show no mass loss (within the detection limit of the method – 0.1 wt.%) during heating to 1000°C, which is used to infer the absence of residual water in the glass and the crystalline phases (see auxiliary material). Complementary analysis of the heat capacity (C_p) reveals intricacies in the glass transition temperature (T_g) locked in during quenching of the products. Here, instead of showing a single, clear peak at the glass transition, the C_p curves of samples Van A1 and Van C (produced during the burst of lava bubbles) reach several successive plateaus at around 650–800°C. For the sample Van A1 the plateau further displays the extraordinary presence of two distinct peaks at 690 and 800°C, whereas sample Van C reveals C_p peaks at 690 and 735°C (Figure 3a). In contrast, sample Van A2, which contains a minor amount of glass, did not produce a clear C_p peak.

4. Shallow Magma Mixing

[14] The general bimodality of crystallinity and vesicularity of the eruptive products may indicate magma mingling,

although localized second boiling may also promote such features [e.g., *Westrich et al.*, 1988] – yet, the overall similarity in glass chemistry, despite a range in crystallinities, and the occurrence of a wide C_p plateau containing a double peak poses a geochemical paradox. A glass usually displays a sharp C_p peak at the glass transition, because a small volume of sample (e.g., a few mm^3) is generally chemically homogeneous and it is expected to cool at a relatively constant rate, locking in a certain structural state. Chemically, the glass phase inside the sideromelane- and microlite-rich areas appears identical and volatile-free. The postulated “double” glass transition signature may result from the rheological influence of iron oxidation state [*Liebske et al.*, 2003; *Bouhifd et al.*, 2004], if the oxidation states of magmas from different depths mingling with each other is variable.

[15] We tested this hypothesis through heat capacity measurements on crystal-free glasses with different oxidation states (made from remelted samples; see auxiliary material), which showed distinct C_p peaks, with a temperature range comparable to that measured in samples Van A1 and Van C (Figure 3b). During repeated measurements on the reduced glass, a shift in the T_g peak to higher temperatures with the tendency to oxidize, as seen by wet chemistry measurements (Figure 3b), showed the relatively unstable nature of reduced basaltic glass. This prevents us from providing an accurate viscosity estimate at T_g [e.g., *Gottsmann and Dingwell*, 2000]. It can however be inferred that the highly oxidized interstitial melt in sample Van A was more viscous than that in sample Van C. Rheologically, the comparison between glasses with different oxidation states and natural heterogeneous samples suggests that mingling indeed took place and most likely occurred over a very short period of time (seconds to a few minutes at the most) due to the unstable nature of the glass transition of reduced samples. Such an interpretation is in agreement with mingling occurring in the shallow parts of the conduit at the point where rapidly ascending magma interacts with shallow crystallized magma or recycled rocks (slumped from the crater into the conduit) shortly before being re-erupted.

[16] The residence of partially crystallized magma in the shallow reservoir would provide the time for the oxidation of an otherwise relatively reduced magma ascending from depth. Our observation of contrasting eruption recurrence timescales at the different vents therefore provides a measure of the oxidation level reached by the shallow magma. In our thermal analysis of the heat capacity, about 50 samples were analyzed; yet, all samples from crater C, which produced strong Strombolian eruption at a periodicity of ~ 10 minutes, were characterized by a broad C_p plateau with double peaks at the lower end of the plateau. On the other hand the eruptive products from Crater A, which were produced by frequent, but weaker eruptions, were characterized by very contrasting double glass transition peaks. This heat capacity signature distinction between eruptive products results from mingling at different recurrence timescales, which may reflect the energy driving

Table 1. XRF Analysis of Bulk Rock Compositions of All Sampled Eruptive Products

| Sample | SiO ₂ | TiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | MnO | MgO | CaO | Na ₂ O | P ₂ O ₅ | K ₂ O | Total |
|--------|------------------|------------------|--------------------------------|--------------------------------|------|------|------|-------------------|-------------------------------|------------------|--------|
| Van A1 | 55.52 | 0.72 | 18.17 | 8.30 | 0.15 | 2.88 | 7.60 | 3.86 | 0.40 | 2.51 | 99.45 |
| Van A2 | 55.49 | 0.68 | 18.67 | 7.81 | 0.14 | 2.62 | 7.60 | 3.93 | 0.39 | 2.46 | 99.95 |
| Van C | 55.81 | 0.73 | 18.10 | 8.42 | 0.15 | 2.90 | 7.54 | 3.87 | 0.40 | 2.57 | 100.36 |

Table 2. Microprobe Analysis Results of Sideromelane (Glassy) and Microlite-Rich Groundmass^a

| Groundmass | Label | SiO ₂ | TiO ₂ | Al ₂ O ₃ | FeO | MnO | MgO | CaO | Na ₂ O | P ₂ O ₅ | K ₂ O | Total |
|---------------------------------|-----------|------------------|------------------|--------------------------------|------|------|------|------|-------------------|-------------------------------|------------------|-------|
| Sideromelane <i>N</i> = 79 | Mean | 60.85 | 0.96 | 14.98 | 7.64 | 0.19 | 2.01 | 4.76 | 3.81 | 0.74 | 4.07 | 100.0 |
| | Std. dev. | 2.01 | 0.11 | 0.87 | 1.52 | 0.10 | 0.89 | 1.33 | 0.51 | 0.20 | 0.80 | 0.0 |
| Microlite-rich <i>N</i> = 44 | Mean | 59.58 | 0.95 | 14.74 | 8.44 | 0.20 | 2.64 | 5.62 | 3.46 | 0.61 | 3.76 | 100.0 |
| | Std. dev. | 1.85 | 0.19 | 1.46 | 1.68 | 0.09 | 1.10 | 1.87 | 0.48 | 0.16 | 0.97 | 0.0 |

^a*N* gives the number of measurements. Shown are mean and standard deviation.

these eruptions as well as the importance of residence time at shallow depths, as this likely dictates the crystallinity of the magma and its degree of oxidation. In essence, the frequent recurrence of weak and short events may favor longer residency of most of the shallow magma thereby inducing crystallization as well as the oxidation of iron, which would increase the range of oxidation states locked in at the glass transition and broaden the temperature range of the Cp plateau. In contrast, less frequent and stronger events may incorporate a larger volume of more shallow material thereby shortening the overall residency of magma in the shallow

conduit which would minimize the presence of iron in the oxidized trivalent state and thus favor Cp peaks at the reduced end of the Cp spectrum. The picture illustrated by the combined rheological, petrological and geochemical analyses present the complex, but rapid interplay of multiple magmas mixing upon eruptions.

5. Conclusion

[17] Strombolian eruptive products at Mt. Yasur were petrographically, geochemically and rheologically characterized to constrain the occurrence of magma mingling in the shallow

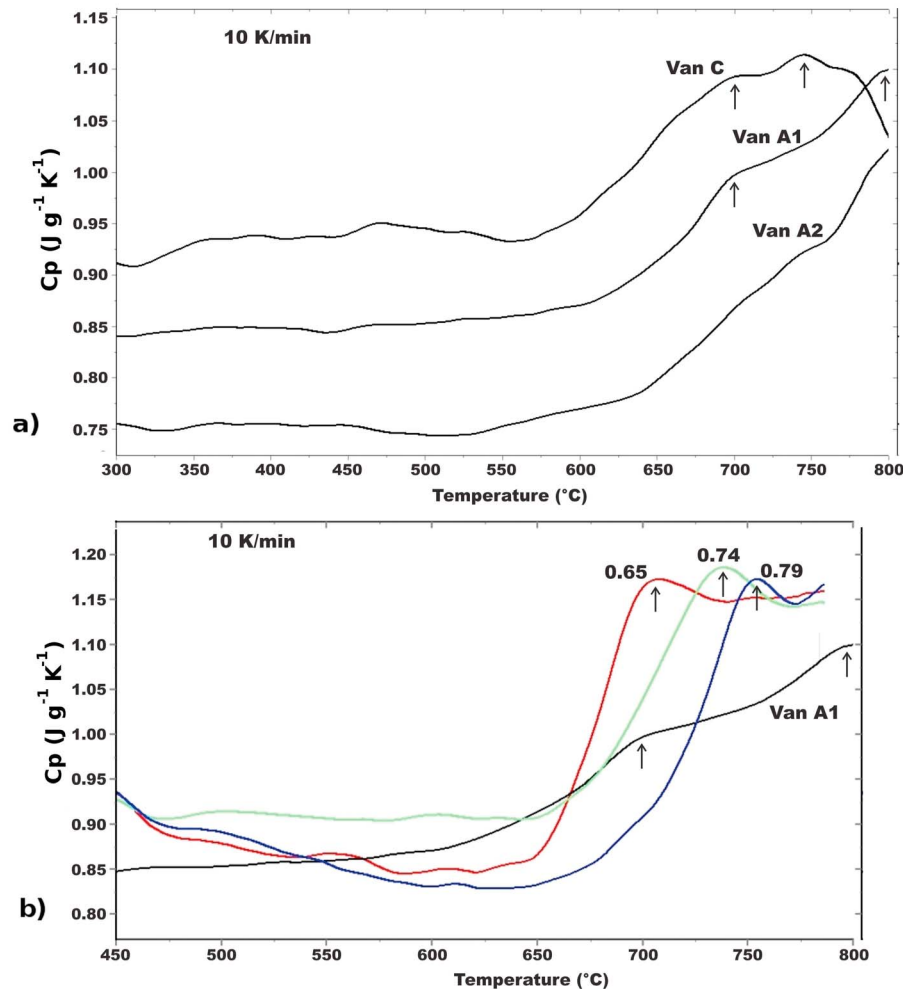


Figure 3. Calorimetric analysis (under 10 K/min). (a) Results of all three samples: Van A1 shows two distinct Tg peaks at 690 and 780°C, Van C shows a broad plateau between 600–780°C and Van A2 shows no distinct peak. (b) Results of natural (black, sample Van A1) samples versus oxidized (blue), reduced (red) and partially reoxidized (green) synthesized samples. The peaks of the reduced and oxidized samples vary by 60°C, whereas the partially reoxidized sample lies in between – a range comparable with the multiple peaks of the natural rocks. The values indicate Fe³⁺/Fe^{tot} ratio measured with wet chemistry.

magma conduit. The tephra are basaltic trachyandesites, which show regions with contrasting crystallinity and bubble-size distributions. Thermal analysis of these juvenile products revealed the presence of a glass phase exhibiting a broad heat capacity plateau between 650 and 800°C, further typified by multiple glass transition peaks. The multiple peaks can be explained by the bimodal oxidation state of iron in an otherwise, chemically homogeneous magma. This anomalous nature of the measured glass transitions and the efficiency of oxidation of reduced iron in liquids are used to infer that mingling is rapid and thus accommodated in the shallow parts of eruptive conduits, perhaps due to rejuvenation of material slumped from the crater walls into an open conduit system.

6. Methods

[18] Samples erupted from different eruptive vents were petrographically described and the bubble size distribution was analyzed according to the method by *Sahagian and Proussevitch* [1998]. The geochemical composition of the bulk rock as well as the interstitial glass was measured via inductively coupled plasma optical emission spectrometry and an electron probe micro-analyzer as well as wet chemistry. The interstitial glass rheology was determined using thermogravimetry to assess the volatile content of the material and differential scanning calorimetry to assess the temperature at which interstitial glasses undergo the glass transition. For further information see the auxiliary material.

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