Explosive to effusive transition during the largest volcanic eruption of the 20th century (Novarupta 1912, Alaska)

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ABSTRACT

Silicic volcanic eruptions commonly show abrupt shifts between powerful and dangerous (Plinian) explosive episodes and gentle effusion of lava. Whether the onset of magma permeability and ensuing gas loss controls these transitions has been a subject of debate. We measured porosities and permeabilities in samples from the A.D. 1912 eruption of Novarupta volcano, Alaska, and analyzed them within the context of a well-constrained eruptive sequence that encompasses sustained explosive and effusive activity. For the explosive samples, we find that the degree of vesicle interconnectivity, measured as the ratio of connected to total porosity, decreases with phenocryst content and with increasing eruption intensity. Permeabilities of explosive samples show a weak dependence on porosity. Dome samples are not significantly different in permeability, but are of lower porosity, which together with abundant flattened vesicles is consistent with bubble collapse by permeable outgassing. Quantitative analysis indicates that outgassing alone was insufficient to affect the transition to effusive activity. Rather, the change from explosive to effusive activity was probably a consequence of high versus low magma ascent rates.

INTRODUCTION

The degassing of magma is of critical importance for determining the style and intensity of volcanic eruptions (Jaupart and Allegre, 1991; Woods and Koyaguchi, 1994; Dingwell, 1996). The exsolution of magmatic volatiles into bubbles provides magma buoyancy and drives the ascent of the magma through the conduit. Exsolution of dissolved water also increases magma viscosity, which resists bubble growth. Consequently, during magma ascent the pressure inside bubbles decreases more slowly than the pressure outside, resulting in overpressure of the exsolved volatiles and explosive magma fragmentation, once a critical overpressure, ΔP_f, has been reached (Mueller et al., 2008).

An important discovery is that magmatic gases can flow through vesicular magma and escape (Eichelberger et al., 1986), once bubbles coalesce to form persistent interconnected networks. This process, herein referred to as permeable outgassing, may reduce the pressure of magmatic gases and, hence, the potential for sustained explosive fragmentation. The question as to what extent permeable outgassing modulates volcanic eruptions, in particular the transition between sustained explosive and effusive activity, remains a subject of debate (Jaupart and Allegre, 1991;Woods and Koyaguchi, 1994; Dingwell, 1996; Melnik and Sparks, 1999; Castro and Gardner, 2008).

THE 1912 ERUPTION OF NOVARUPTA, ALASKA

To address this question, we characterized the porosities and permeabilities of samples from a single eruption, the A.D. 1912 eruption of Novarupta in Alaska (Fierstein and Hildreth, 1992; Hildreth and Fierstein, 2000, 2012; Adams et al., 2006a, 2006b). From 6 to 8 June 1912, the explosive stage of the Novarupta eruption started with three Plinian episodes, which lasted ~60 h, albeit with two pauses in eruptive activity. Mass eruption rates for the Plinian Episodes I–III have been estimated at ~5, 1.6, and 1.1 × 10^8 kg s^{-1}, respectively. This sustained explosive activity of Episodes I–III gave way to ephemeral dome growth and Vulcanian activity of Episode IV, and subsequently to stable dome growth in Episode V, producing the current Novarupta dome.

Eruptive products consist of rhyolite and dacite, as well as andesite, which played a volumetrically negligible role (see the GSA Data Repository[1]). In Episode I, first rhyolite was erupted, followed by rhyolite and dacite erupting simultaneously, together with minor andesite. Episodes II, III, and IV were dominantly dacite, and Episode V was again rhyolite. Both rhyolite and dacite consist of rhyolitic melt, and the contrast in bulk chemistry is due to the higher phenocryst content of the dacitic magma (Coombs and Gardner, 2001; Hammer et al., 2002), which increases the viscosity of the dacitic magma by about one order of magnitude relative to the rhyolite (Mader et al., 2013).

PERMEABLE OUTGASSING

Permeable flow of gases, once coalescing bubbles have formed an interconnected pathway, is thought to occur above a critical porosity, ϕ_c, which can range from ~30% to 70% (Klug and Cashman, 1996). Above ϕ_c, permeability is thought to increase with porosity to some power, n, as bubbles continue to nucleate, grow, and coalesce. Although theoretical values of n fall near 2 (Blower, 2001), in nature they appear to be greater (Rust and Cashman, 2011). One hypothesis is that if the rate at which bubbles coalesce is much smaller than the rate at which the magma decompresses, and new bubbles nucleate and grow, ϕ_c and n will increase, because coalescence is kinetically limited (Takeuchi et al., 2009).

METHODOLOGY

Sample Analysis

We measured porosities and permeabilities in representative samples from all five episodes of the Novarupta eruption (see the Data Repository). We excluded any dense samples from Episodes IV and V that showed pervasive fine cracking, because these microcracks have an uncertain origin and would bias permeability measurements. Measured permeabilities are therefore solely due to interconnected vesicles formed by bubble coalescence.

Numerical Modeling

To assess the possible conditions of magma ascent, fragmentation, and permeable outgassing, we performed numerical modeling of integrated magma ascent and bubble growth for Episodes I–III, as well as for hypothetical scenarios at lower discharge rates (see the Data Repository). The models constitute isothermal, one-dimensional conduit flow of the ascending magma, coupled with diffusive bubble growth for both H_2O and CO_2 (Gonnermann and Houghton, 2012). Among other parameters, the model calculates gas pressure within bubbles, which together with ϕ and k_1 (where k_1 is Darcian permeability; see details in the Data Repository) allows for the prediction of magma fragmentation.

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[1]GSA Data Repository item 2014261, sample information, methodology for porosity and permeability measurements, and details on the numerical modeling, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY Data Repository item 2014261 | doi:10.1130/G35593.1

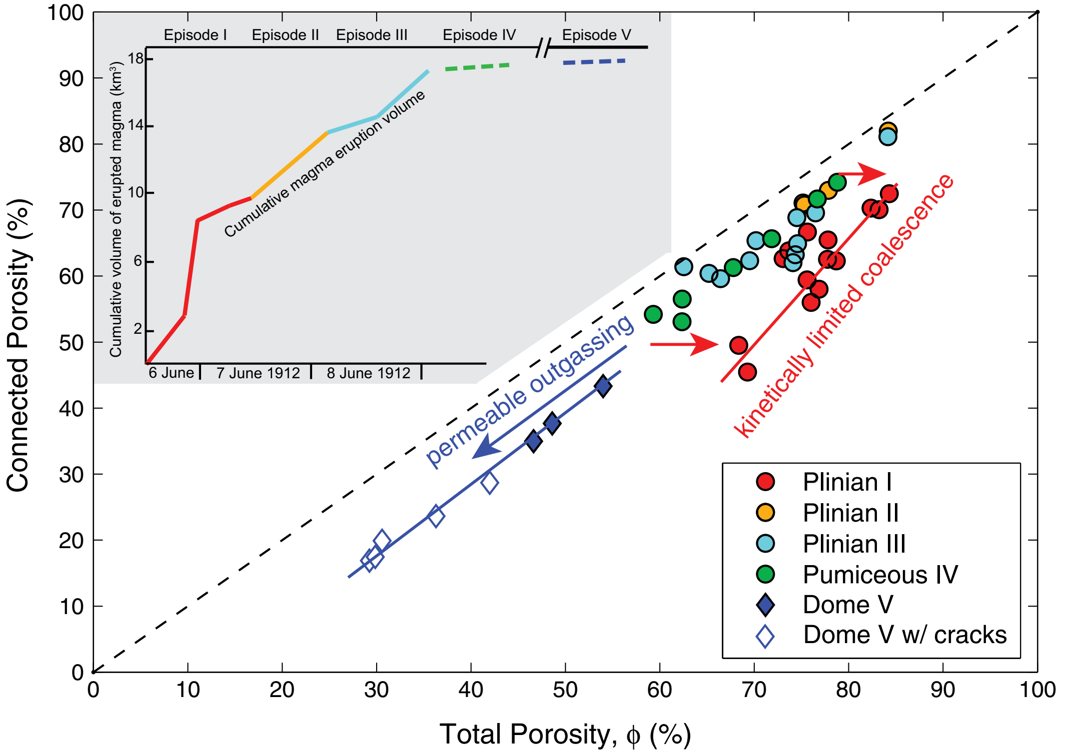

Figure 1. Connected porosity as function of total porosity, with cumulative volume of erupted magma (inset, as dense rock equivalent; Hildreth and Fierstein, 2012). Red and blue lines are drawn to guide the eye. Episode I samples have distinctly lower ratios of connected to total porosity than samples of other episodes, which may be a consequence of kinetically limited coalescence (i.e., bubble nucleation and growth outpace rate at which bubbles coalesce).

RESULTS

Porosity

Sample porosities range approximately between 30% and 60% for Episode V and 60%–85% for Episodes I–IV (Fig. 1). All samples have connected porosity that is lower than total porosity by ~10%–20% (i.e., not all vesicles are interconnected). Episode I samples have a distinctly lower ratio of connected to total porosity than all other samples. Given the high eruption rates of Episode I, this may be due to less time for bubble coalescence relative to the other episodes, although Episode I samples are also of substantially lower phenocryst content (1%–3%) than those from Episodes II–IV (30%–50%), which may also affect bubble coalescence (Takeuchi et al., 2009; Rust and Cashman, 2011). The trend in connected versus total porosity for the dome samples of Episode V is similar to that for Episodes II–IV, but at distinctly lower total porosities (Fig. 1). This, together with the flattened vesicle shapes of Episode V samples, is consistent with bubble collapse and loss of porosity during permeable outgassing (Eichelberger et al., 1986; Westrich and Eichelberger, 1994).

Permeability

Permeabilities (Fig. 2) approximately follow the relation $k_1 = r^2(\phi - \phi_c)^n$ (Blower, 2001), where $r = 3 \times 10^{-5}$ m is the approximate median vesicle radius in the Novarupta samples (Adams et al., 2006b). A range in values of ϕ_c and n can match the data, with Episode III and IV samples having on average higher values of k_1 at any given ϕ than Episode I and II samples. Feasible values of ϕ_c and n that fit the data of Episodes I–IV are $\phi_c \geq 0.5$ and $n \geq 3.5$, whereas permeabilities of Episode V dome samples are not significantly lower, but shifted toward lower values of ϕ and ϕ_c. This is consistent with permeable outgassing (Eichelberger et al., 1986; Westrich and Eichelberger, 1994), but makes it unclear to what extent permeability prior to outgassing may have been higher.

Overpressure, Fragmentation, and Permeable Outgassing

Explosive magma fragmentation is thought to be a consequence of gas overpressure, estimated as $\Delta P_f = (8.21 \times 10^5\ \mathrm{MPa\ m^{-1}}\sqrt{k_1} + 1.54\ \mathrm{MPa})/\phi$ (Mueller et al., 2008), and found to range between 1 and 5 MPa. For the erupting magma to have reached ΔP_f, the characteristic viscous time, τ_{vis} is $\sim\eta/\Delta P_f$, and the characteristic permeable time, τ_k is $\sim L^2\mu/k_1\Delta P_f$, both had to exceed the characteristic decompression time, $\tau_{dec} \sim \Delta P/\dot{P}$. Here η is melt viscosity, $L \sim 100$ m is the characteristic path length of permeable gas flow, $\mu \sim 10^{-5}$ Pa·s is the viscosity of the vapor phase (Rust and Cashman, 2011), and $\dot{P}$ is the decompression rate. The condition $\tau_{vis} \geq \tau_{dec}$ implies that there is insufficient time for bubble growth during decompression, resulting in the build-up of overpressure. At the same time, $\tau_k \geq \tau_{dec}$ indicates that there is insufficient time for permeable outgassing, providing an upper bound, $k \leq L^2\mu/\eta$, at which permeability does not prevent the build-up of overpressure. Because the fall deposits from Episodes I–III lack textural evidence for pervasive shear fragmentation, the shortest pathway for permeable outgassing is radially toward the conduit margins, where flow fracturing may provide enhanced permeability (Stasiuk et al., 1993; Gonnermann and Manga, 2003; Tuffen et al., 2003).

At magmatic temperatures (850 °C; see the Data Repository) and pressures similar to ΔP_f, the water content of the Novarupta rhyolitic melt was ~1 wt% (Liu et al., 2005), resulting in a viscosity η of $\sim 10^7$ Pa·s (Hui and Zhang, 2007), and in the presence of up to 50 wt% phenocrysts, $\eta \sim 10^8$ Pa·s for the Novarupta dacite (Mader et al., 2013). Thus, the condition $\tau_k \geq \tau_{dec}$ implies that $k_1 \leq 10^{-8}$ m^2 for permeable outgassing to have been insignificant during Episodes I–III, which is the case for all samples. It is also consistent with the relatively modest predicted increase in fragmentation pressure due to measured permeabilities (Mueller et al., 2008). If the magma had been pervasively flow fractured, at an average fracture spacing of $L \ll 100$ m, gas should have escaped into highly permeable fractures at sufficient rates to have resulted in the transition from explosive to effusive eruptive activity. However, like Plinian deposits of other rhyolitic eruptions (Castro et al., 2012, 2013), Episode I–III deposits lack evidence for pervasive shear fracturing. Therefore, a decrease in decompression rates to $\tau_{vis} \gg \tau_{dec}$ and/or $\tau_k \gg \tau_{dec}$ is the most feasible explanation for the cessation of sustained explosive magma fragmentation at Novarupta. All else being equal, for this to be the case, the characteristic decompression rate, $\dot{P}$, must have been less than $(\Delta P_f)^2/\eta \sim 10^6$ Pa·s^{-1}. Numerical modeling substantiates these results (Fig. 3) and illustrates that Episode I–III mag-

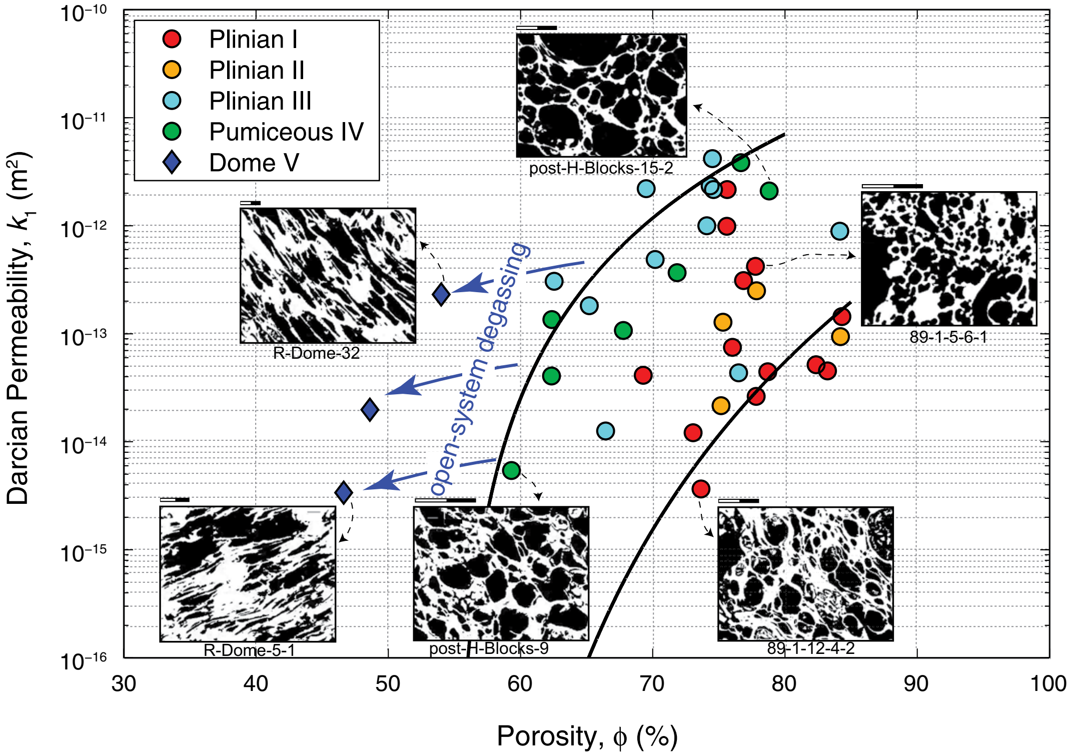

Figure 2. Darcian permeability, k_1, as function of total porosity, ϕ. Insets are scanning electron microscopy images of selected samples, with values shown on graph; black is vesicles, and white is matrix glass. Scale bar for each image is 100 μm. Black curves are $k_1 - \phi$ relations following Blower's (2001) model with n = 4, ϕ_c = 0.65 (right), and n = 3.5, ϕ_c = 0.55 (left).

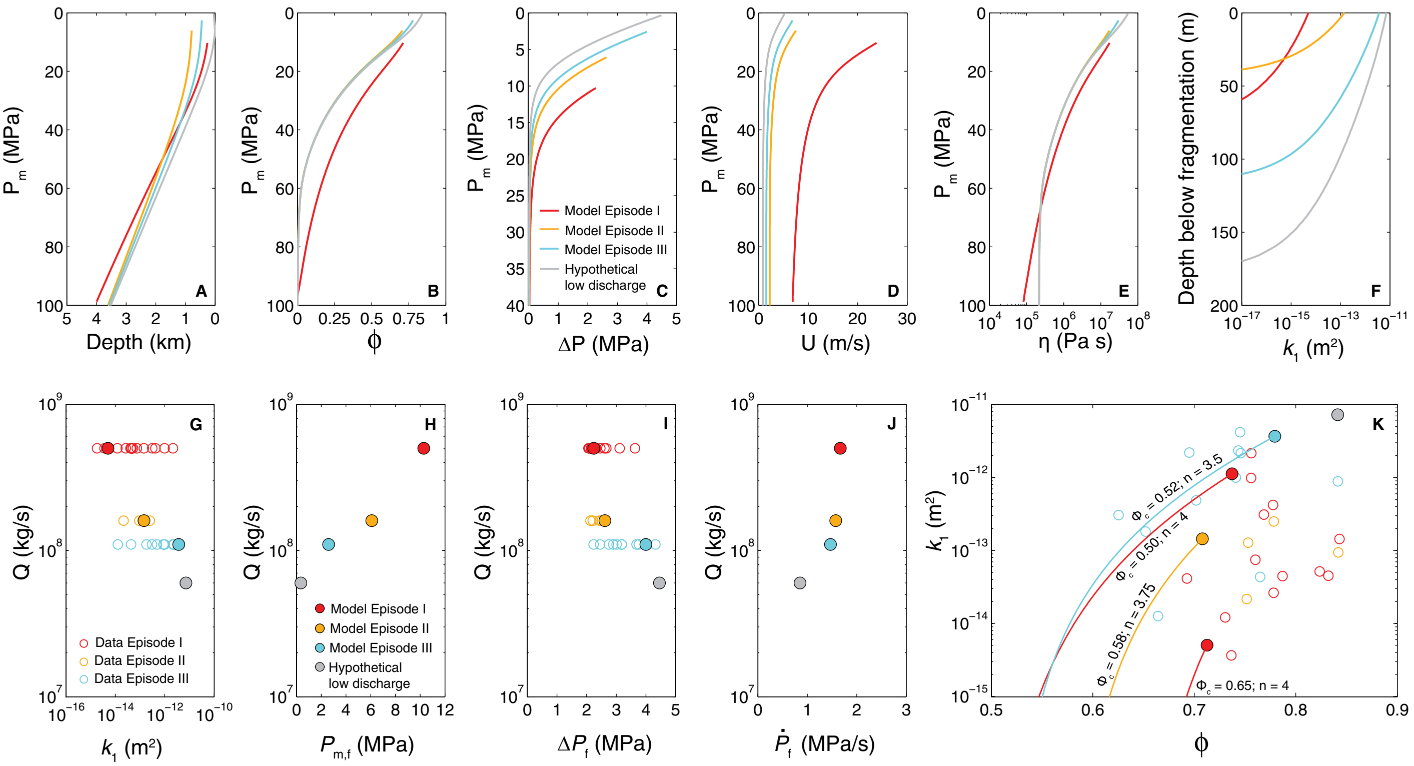

Figure 3. Results from numerical model up to the depth of fragmentation (see the Data Repository [see footnote 1]). A–E: Ambient pressure P_m as a function of depth (A), porosity, ϕ (B), gas overpressure, ΔP (C), ascent velocity, U (D), and magma viscosity, η (E). F: Depth below fragmentation as a function of Darcian permeability, k_1. G–J: Discharge rate, Q, as a function of Darcian permeability, k_1 (G), ambient pressure at fragmentation, $P_{m,f}$ (H), gas pressure at fragmentation, ΔP_f (I), and decompression rate at fragmentation, $\dot{P}_f$ (J). K: k_1 as a function of ϕ. Open circles in G–K are estimated or measured values for the Novarupta samples; filled circles are model predictions. Lines in K are for assumed permeabilities of $k_1 = r^2(\phi - \phi_c)^n$ with ϕ and bubble radius r calculated by the model. Note that models provide reasonable fit to observations. Furthermore, at decompression rates of <1 MPa·s^{-1} (the hypothetical low-discharge case), the model predicts that the fragmentation depth has moved to the surface. Further decrease in decompression rate would not result in sufficient overpressure for fragmentation.

mas may have become permeable at a few hundred meters or less below the fragmentation depth.

A potential caveat to this assertion is the possibility of permeable outgassing near the conduit walls, as a consequence of shear fragmentation (Gonnermann and Manga, 2003; Tuffen et al., 2003) and/or high permeability of the conduit wall rock (Stasiuk et al., 1993; Jaupart, 1998). Such outgassing has been suggested, based on an increase in the proportion of dense clasts near the top of the Episode III fall deposits, and may have produced a low-porosity and high-viscosity magma annulus toward the end of Episode III (Adams et al., 2006a). This would have resulted in an increase in viscous stresses and a decrease in discharge rate. Alternatively, or perhaps concurrently, a decrease in reservoir pressure would have also resulted in a decrease in eruption rate (e.g., Jaupart and Allegre, 1991), albeit modulated by caldera collapse during Episodes I and III (Hildreth, 1991; Fierstein and Hildreth, 1992).

CONCLUSIONS

Nothing inherent in the characteristics of samples from the 1912 Novarupta Plinian Episodes I–III indicates that permeable outgassing by itself resulted in the transition from sustained explosive to effusive activity. Moreover, there is no indication that Episode V lava required significantly different conditions for fragmentation than prior explosive episodes; it simply did not attain those conditions. The most viable explanation for the change from very powerful explosive activity to quiescent lava effusion during Episode V is a decrease in magma ascent rate and, hence, decompression rate. We thus find that magma permeability was not a sufficient condition for the transition from explosive to effusive activity. Instead, a decrease in magma ascent rate and decompression rate was necessary to end the explosive activity. Once the eruption changed to effusive, there was always sufficient time during ascent for permeable outgassing and loss of porosity.

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