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Mid-ocean-ridge rhyolite (MORR) eruptions on the East Pacific Rise lack the fizz to pop

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ABSTRACT

Eruptions on the Alarcon Rise segment of the northern East Pacific Rise (23.55°N, 108.42°W) at 2500–2200 m below sea level (mbsl) produced the most compositionally diverse volcanic suite found along the submarine mid-ocean-ridge (MOR) system, offering an opportunity to compare mafic through silicic eruption styles at the same abyssal depth. Eruption styles that formed evolved volcanic rocks on the submarine MOR have not been studied in detail. The prevalence of lava flows along the MOR indicates that most eruptions are nonexplosive, but some volcaniclastic characteristics suggest that explosive styles also occur. Higher viscosities in intermediate ($10^{3–5}$ Pa·s) versus mafic (10^1 Pa·s) lavas on Alarcon Rise correspond with larger, more brecciated pillows, while highly viscous rhyolite lavas ($10^{6–7}$ Pa·s) formed rugged domes mostly composed of autoclastic breccia. Although high H_2O contents (1.5–2.1 wt%), abundant volcaniclasts, and vesicularities up to 53% in rhyolite might imply eruption explosivity, limited fine-grained ash production and dispersal indicate an effusive origin. Higher viscosities of MOR rhyolite (MORR) magma and small eruption volumes, compared to MOR basalt (MORB), limit bubble coalescence and rapid magma ascent, two likely prerequisites for deep-marine eruption explosivity. This idea is supported by widespread dispersal of basaltic ash, but very limited production and dispersal of silicic ash on Alarcon Rise.

INTRODUCTION

To date, active eruptions have not been directly observed on submarine mid-ocean ridges (MORs), making it difficult to address the origins, processes, and products of explosive volcanism under high ambient pressure. Our knowledge of MOR eruption styles has therefore relied on ophiolites, bathymetric maps, seafloor samples, submersible observations, analog experiments, and numerical models (Gregg and Fink, 2000; Head and Wilson, 2003; Portner et al., 2010; Rubin et al., 2012). Most MOR basalt (MORB) eruptions form effusive flows of pillow, lobate, and sheet lavas (e.g., Chadwick et al., 2013), but detailed analysis of volcaniclastic material from MORs and seamounts, and video observations from volcanic arcs suggest that explosive, and perhaps implosive, eruptions occur 4200–500 m below sea level (mbsl; Batiza et al., 1984; Davis and Clague, 2006; Sohn et al., 2008; Deardorff et al., 2011; Resing et al., 2011; Portner et al., 2015; Carey et al., 2018). The style of these volcaniclast-producing eruptions is the subject of ongoing debate due to limited steam expansion and volatile exsolution in magma under high pressure (Schipper and White, 2010; Rotella et al., 2013). If deep-marine volcanism can be explosive despite these limitations, understanding the dynamics of magma ascent and volatile degassing may influence models of eruptions at atmospheric pressure (Cashman and Sparks, 2013).

Here, we determine the eruption styles of the only known deep-marine mid-ocean-ridge rhyolite (MORR) and the accompanying intermediate to mafic volcanic suite to evaluate the potential for explosivity of increasingly siliceous magmas at typical MOR depth. Eruption of H_2O-rich rhyolitic magmas along volcanic arcs at depths up to 1300 mbsl are thought to be effusive, explosive, or hybrid in nature, and their origins and products are actively debated (Allen et al., 2010; Rotella et al., 2013; Carey et al., 2018). On land, siliceous eruptions are generally more explosive, making the Alarcon suite ideal for studying potential eruption explosivity under the much higher pressures on the seafloor. Prior studies have focused on the petrogenesis of andesitic to dacitic lavas on the MOR (e.g., Wanless et al., 2010), but their eruption styles remain undescribed.

Rhyolite, dacite, andesite, basaltic andesite, and basalt eruptions between 2480 and 2290 mbsl cover ~3.5 km^2 of the Alarcon Rise in the Gulf of California (23.55°N, 108.42°W), making it the only known location where such a diverse range of MOR lava compositions occurs. Autonomous underwater vehicle (AUV) and remotely operated vehicle (ROV) dives to this area by the Monterey Bay Aquarium Research Institute (MBARI, California, USA) in 2012 and 2015 mapped bathymetry at 1 m resolution, recorded ~50 h of video footage, and collected 143 lava and 77 sediment samples (Clague et al. 2018). New data presented here include measurements of lava flow morphology, volcaniclast grain-size distribution (GSD) and componentry, volatile content, crystallinity, vesicularity, and viscosity.

GEOLOGIC SETTING

Alarcon Rise is the northernmost spreading segment of the East Pacific Rise where the Gulf of California opens to the Pacific Ocean (Fig. 1A, inset). The Alarcon Rise is 47 km long, and its northern terminus with the Pescadero transform is 8 km from the Mexican continental shelf. Studies of rhyolite to basalt geochemistry indicate that the compositional range was produced by crystal fractionation and end-member mixing of partial melts from a depleted MORB mantle (Castillo et al., 2002; Clague et al., 2018). Here, we focused on the evolved volcanic suite in the northern third of the Alarcon Rise between 23.58°N and 23.53°N (Figs. 1A and 1B).

METHODS

Elongate pillow-lava diameters from 5 to 35 pillows/flow were measured using ROV lasers.

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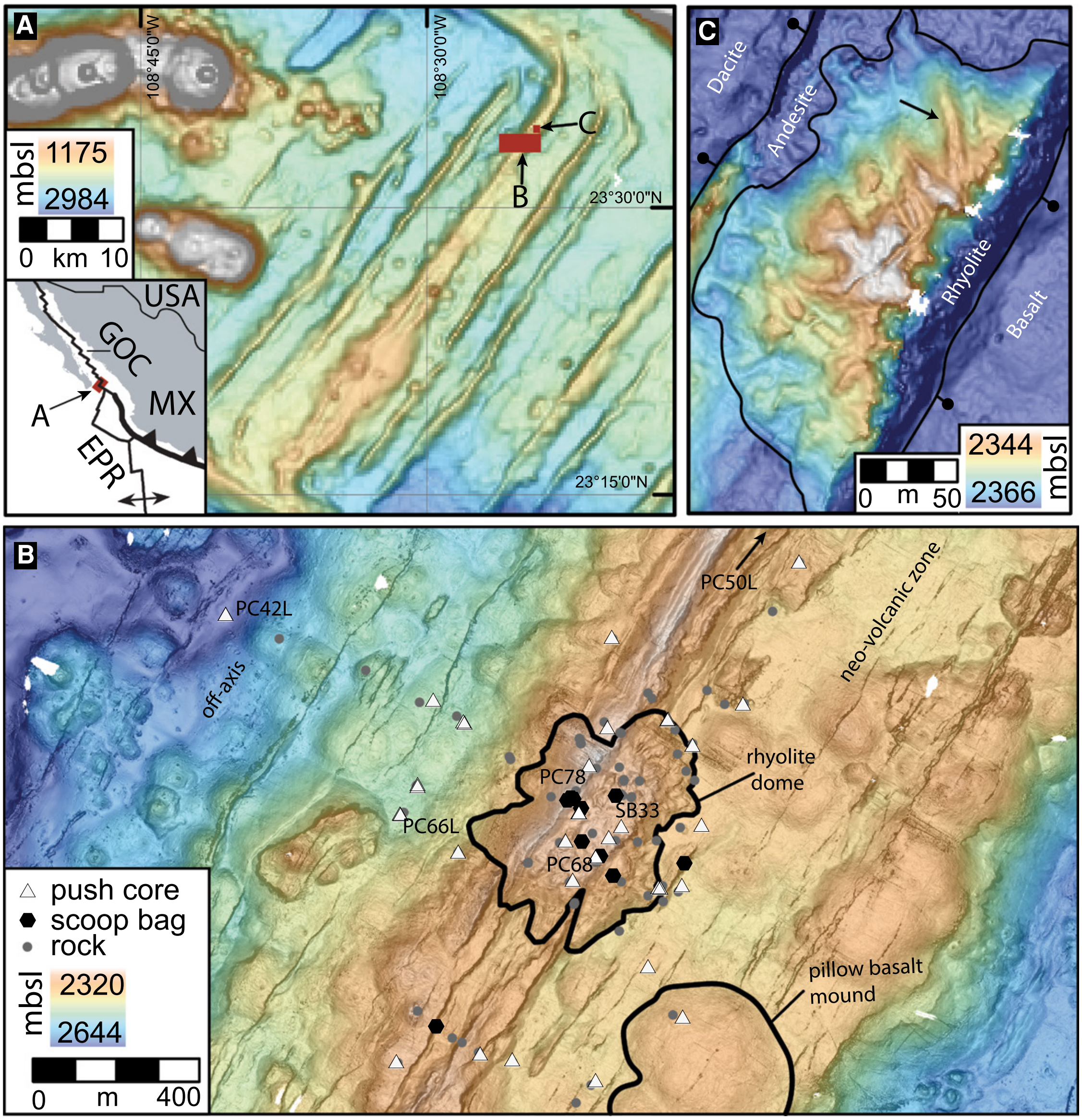

Figure 1. (A) Alarcon Rise (Gulf of California; 23.55°N, 108.42°W) spreading segment showing locations of panels B and C. Inset shows field site in Gulf of California (GOC). EPR—East Pacific Rise; USA—United States; MX—Mexico; mbsl—m below sea level. (B) Central rhyolite dome showing sample locations. Sample D742-PC50L is located 2.6 km north of the map. (C) Northern rhyolite dome with corrugated ridges (arrow) and adjacent intermediate to mafic flows.

Bathymetric slope and flow volumes were calculated from 1-m-resolution AUV data using ArcGIS software (Yeo et al., 2013; Clague et al., 2018). Rock and clastic samples were collected by ROV for volatile and textural analysis.

Clastic samples were collected using scoop bags and 25–150 cm push cores (Fig. 1B). Cores were split into 2 cm intervals, and representative subsamples were processed for GSD and componentry. Grain size was measured in ¼ϕ intervals by wet-sieving (>1 mm) and laser diffraction (<1 mm; Malvern Mastersizer 2000G). The 250–500 µm fraction was point counted ($n = 500$) for glass color and microlite content to determine mafic, intermediate, and silicic compositions. Point count results were supported by scanning electron microscope–energy-dispersive X-ray (SEM-EDX) spectra from 15 unknown grains/sample and internal electron microprobe standards (Clague et al., 2018).

Dissolved volatile contents were measured on doubly polished glass chips using a Nicolet iN10 MX Fourier transform infrared (FTIR) spectrometer at the U.S. Geological Survey in Menlo Park, California. Five to three spots per chip were analyzed using transmission FTIR spectroscopy. Measurements were collected from 50 150-µm-size spots for 256 scans. Volatile contents were quantified using the Beer-Lambert law, where peak heights and chip thicknesses were measured using a flexi-curve method and micrometer. Detection limits were ~10 ppm CO_2 and 0.05 wt% H_2O. Uncertainties were calculated from published extinction coefficient (ε) errors and are similar to sample 1σ (Table S1 in the Supplemental Material[1]).

Magma temperatures for rhyolites and dacites were calculated using Fe-Ti oxide chemistry (Ghiorso and Evans, 2008) and used for melt viscosity (η_m) calculations (Giordano et al., 2008). Effective magma viscosities (η_{eff}) were corrected for bubble and microlite contents: $\eta_{eff} = (1 + \phi_{void})\eta_m(1 - 1.35\phi_{solid})^{-2.5}$. Crystal volume ($\phi_{solid}$) was quantified from representative two-dimensional (2-D) images of polarized and reflected photomicrographs (Higgins, 2000). Vesicle contents (ϕ_{void}) were calculated from bulk density measurements (Houghton and Wilson, 1989) and SEM images of 1–4-cm-size lapilli and rock thin sections.

RESULTS

Eruption Products

Eruptions of all lava compositions on the northern Alarcon Rise formed pillows (Figs. 2A–2C), but only mafic-intermediate lavas exhibit hummocky mound morphologies (Fig. 1B). Pillow diameters increase with lower slope angles and higher silica contents (Fig. 2D). The latter values extend the observations of Gregg and

[1]Supplemental Material. Table S1 (chemical and physical characteristics of Alarcon Rise lava suite). Please visit https://doi.org/10.1130/GEOL.S.13182977 to access the supplemental material, and contact editing@geosociety.org with any questions.

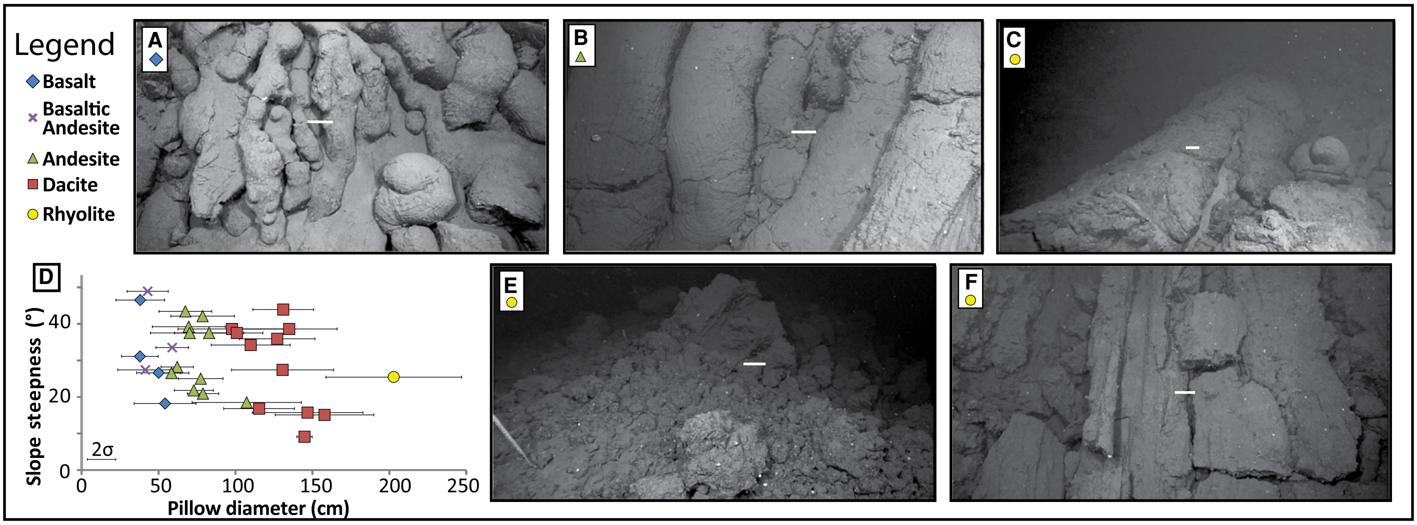

Figure 2. **(A) Pillowed basalt lava, 51.1 wt% SiO_2, 34° slope; (B) andesite lava, 61.8 wt% SiO_2, 30° slope; and (C) rhyolite lava, 70.6 wt% SiO_2, 27° slope. (D) Pillow diameter vs. substrate slope angle. (E) Brecciated rhyolite. (F) Corrugated rhyolite. Scale bars in remotely operated vehicle (ROV) photos are 32 cm across.**

Fink (2000) to more silicic submarine lavas and reflect increasing viscosities from 10^1 Pa·s for basalt to 10^{3-4} Pa·s for andesite and 10^{6-7} Pa·s for rhyolite (Table S1). Eruptions of rhyolite, up to 77 wt% SiO_2, formed lava domes that are mostly composed of breccia (Fig. 2E). Coherent rhyolite is rare and is made up of >2 m diameter pillows (Fig. 2C) or distinctive corrugated ridges (Figs. 1C and 2F). Silicic and intermediate lavas have rougher bathymetric signatures (Figs. 1B and 1C; Maschmeyer et al., 2019) and smaller maximum flow volumes up to 2.4×10^6 m^3 and 5.0×10^6 m^3, respectively, compared to mafic lavas (32×10^6 m^3).

Breccias are unimodal, genetically associated with all underlying lava compositions, and most abundant with more siliceous flows. Approximate deposit thicknesses are <1 m around pillows and >>1 m on rhyolite domes. Rhyolite breccias are too coarse for accurate GSD measurements, but video observations indicated that primary modes are 30–80 cm (Fig. 2E). Rare pumiceous lapilli tuff is comparatively finer grained.

Tuffaceous mud (TM) fills in depressions on all lavas flows and contains a bimodal GSD of ash (125–500 μm) and hemipelagic mud (1–10 μm; Fig. 3A, i–ii). The ash component contains variable proportions of mafic, intermediate, and silicic shards (Fig. 3B). Point counts of TM indicated that ash in most (75%) proximal cores collected on the rhyolite dome is mafic, with a minor proportion of felsic shards (blue points in Fig. 3C). Cores taken in marginal locations (<200 m from rhyolite), but on older crust, contained subequal proportions of mafic to intermediate ash (red points in Fig. 3C), along with a very minor proportion of fluidal rhyolitic ash (Fig. 3D). Distal cores recovered off-axis and in the neovolcanic zone lacked volcanic ash (Fig. 3A, iii) but locally contained rare unimodal ash laminations (Fig. 3A, iv). Rhyolitic ash was mostly restricted to proximal breccias and pumiceous lapilli tuff (purple and yellow points in Fig. 3C).

Textures and Volatile Contents

Vesicularity increases from <2% in basalt to 5%–14% in andesite-dacite (Table S1). Rhyolite

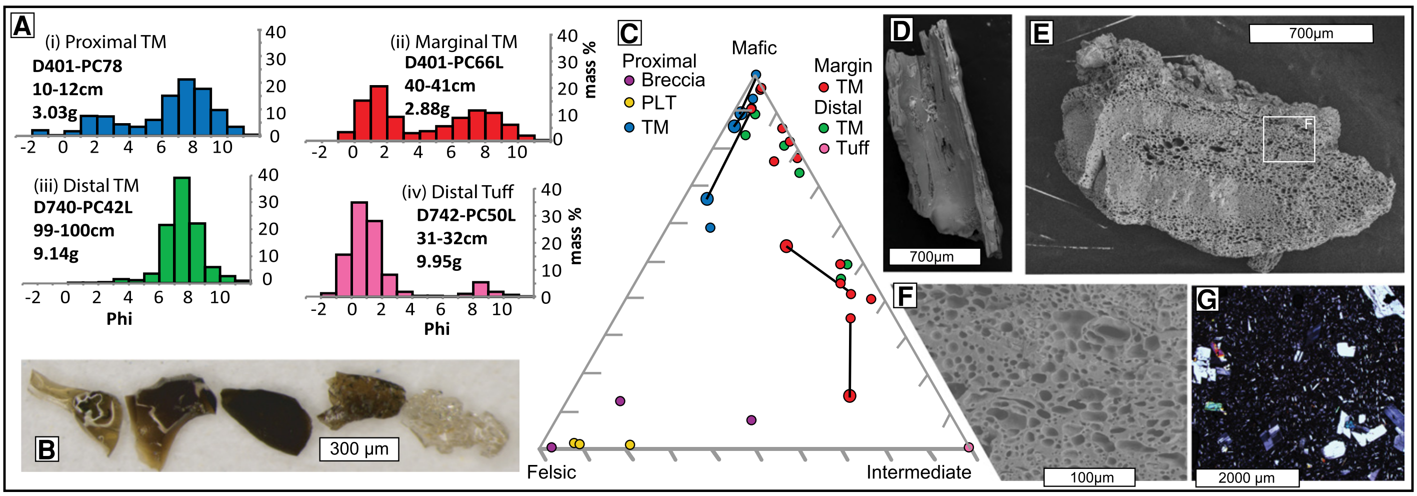

Figure 3. **Grain-size distributions and componentry of representative samples collected from (i) proximal (0 m), (ii) marginal (<50 m), and (iii) distal (100–1000 m) sites around central rhyolite dome. (A) Grain-size plots from representative tuffaceous mud (TM) samples (see Fig. 1A). (B) Real color image of, from left to right, basalt, andesite, basaltic andesite, dacite, and rhyolite glass shards. (C) Ash componentry from 250–500 μm fraction of breccia, pumiceous lapilli tuff (PLT), TM, and tuff. Larger circles represent 500–1000 μm fractions. (D) Fluidal rhyolite ash. (E–F) Pumiceous rhyolite with 43.9 bulk vol% vesicles. (G) Cross-polarized photomicrograph of rhyolite with plagioclase (white/gray) and pyroxene (color) crystals.**

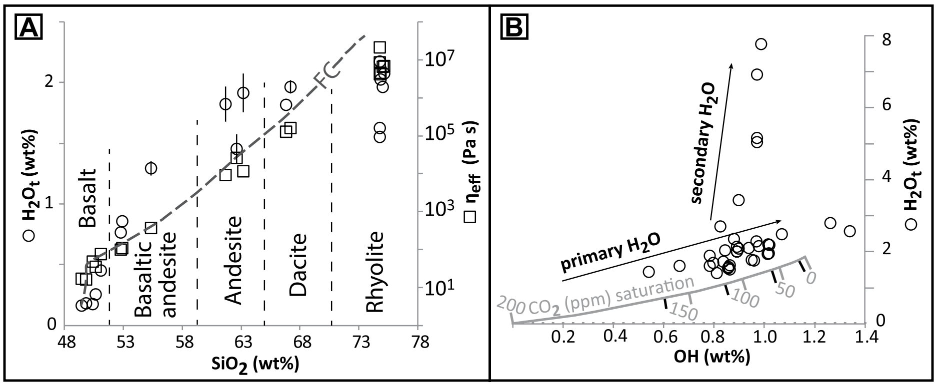

Figure 4. Volatile data. Plotted symbol diameters are greater than analytical uncertainty, unless indicated otherwise with error bar. (A) Total water (H_2O_t; circles) and effective viscosity (η_{eff}; squares) for all lava compositions. H_2O_t is an average of 3–6 spot analyses. Fractional crystallization (FC) model is from Clague et al. (2018). (B) Hydroxyl (OH^{-1}) speciation in rhyolites (*n* = 7 samples) showing primary (magmatic) and secondary (hydration) H_2O_t trends. Volatile saturation curve (Newman and Lowenstern, 2002) for 24.9 MPa (gray) and 23.2 MPa (black) depicts idealized OH^{-1} fraction at given CO_2 compositions.

vesicularity varies from 7% to 25%, locally up to 53% in rare pumiceous lapilli (Fig. 3E). Vesicles are mostly isolated with limited connectivity (Fig. 3F). Crystal content generally increases with silica content, except for a few phyric basalts and basaltic andesites. Rhyolites contain 16%–28% plagioclase, olivine, and pyroxene phenocrysts (250–1500 µm; Table S1). Most microlites (10–100 µm) are plagioclase (Fig. 3G).

Water contents in volcanic glass increase from 0.15%–0.45% in basalt to 1.5%–2.2% in andesite-dacite-rhyolite, consistent with higher vesicularities in more siliceous samples (Table S1). Fractional crystallization modeling also suggests that the most silicic magmas degassed the highest amount of H_2O (Fig. 4A). Some pumiceous rhyolites have unusually high water contents (>2.5 wt%) and high H_2Om:OH ratios (>>2) that indicate secondary hydration (Fig. 4B). CO_2 contents vary from 20 to 150 ppm in basalt (Table S1) to <10 ppm (below detection limit) in glasses more evolved than basalt. Average volatile contents for each lava composition are consistent with volatile solubility limits at eruption depth pressures (23.2–24.9 MPa; Newman and Lowenstern, 2002).

MORR ERUPTION STYLE

Intermediate to silicic lava domes are often associated with hazardous explosive eruptions on land. Subaerial explosive episodes, including vigorous Vulcanian and even Plinian eruptions, generally occur during dome collapse and core depressurization, where much of the potential energy is stored (Fink and Kieffer, 1993; Voight and Elsworth, 2000). This process produces a notable proportion of pyroclastic ash.

The presence of <10% intermediate through silicic ash in sediment cores on and around Alarcon Rise lava domes suggests that explosive fragmentation and ash dispersal of eruptions more evolved than basalt were minor. This observation is surprising considering the highly vesiculated and volatile-saturated nature of the more siliceous lavas. Estimates of maximum ash dispersal distances from explosive submarine eruptions are not well constrained, but modeling and early investigations indicate 1–5 km (Clague et al., 2009; Barreyre et al., 2011), i.e., much greater than that observed for Alarcon's rhyolitic ash. Moreover, high hydrostatic pressure at the depth of Alarcon Rise limits the potential for explosive fragmentation by seawater/steam expansion, which would otherwise generate a diagnostic very fine-grained ash signature (Zimanowski and Büttner, 2003).

Very coarse-grained breccias on and around the Alarcon Rise rhyolite domes indicate a nonexplosive autoclastic origin. This process is common during the brittle disaggregation of growing subaerial lava domes (Fink and Manley, 1987; Wadge et al., 2009). Compared to subaerial settings, higher cooling rates on the seafloor may increase the proportion of brittle fragmentation processes and the development of thicker breccia carapaces (Allen et al., 2010). A completely effusive origin for Alarcon rhyolite clastic deposits is further supported by higher proportions of breccia with larger, more siliceous pillow lavas.

Compared to subaerial eruptions, the high hydrostatic pressure along the MOR increases volatile solubility, which reduces bubble exsolution and magma viscosity. Volatile-rich Alarcon rhyolites had effective viscosities (4×10^6 to 2×10^7 Pa·s) that are two to three orders of magnitude less than what they would be if they had erupted at sea level. Such lower viscosities for MORR may have contributed to the formation of unique corrugated ridges, which are not observed on subaerial domes. The lower viscosity of MORR facilitated faster ascent through the crust, limiting the ability to attain significant overpressures needed for explosivity. Yet, MORR viscosities are still much higher than MORB (Fig. 3A), which limits the ability for exsolved volatiles in MORR to coalesce and generate Strombolian-style bursts, the most likely explosive eruption style at abyssal depths (Head and Wilson, 2003; Clague et al., 2009).

Due to limited bubble exsolution and coalescence imposed by higher pressures on the MOR, very high volatile contents alone would be needed to cause explosivity in MORR. The low vesicle connectivity in Alarcon MORR implies volatile exsolution under closed system conditions with no permeable outgassing, and it permits application of the ideal gas law to quantify the total exsolved volatile content of pumice (2.21 wt% H_2O; with negligible CO_2). Recombining this quantity with the currently dissolved volatile content, we find that the most vesiculated Alarcon MORR would have had a maximum of 4.14 wt% H_2O prior to bubble exsolution. This estimate is less than the minimum needed (4.9 wt% H_2O; after Head and Wilson, 2003) to achieve explosive fragmentation by magma film collapse (>60%–75% vesicles; Cashman and Sparks, 2013) at ~2300 mbsl. In addition, this minimum volatile content is unlikely for MORB-fractionated rhyolite.

Despite overwhelming evidence for significant degassing (pumice) and magma fragmentation (breccia), eruptions of intermediate through silicic magmas on Alarcon Rise were entirely effusive. In contrast, fluidal mafic ash deposited on the rhyolite dome was sourced from vents that were 80 m deeper and >250 m away (Fig. 1B), suggesting explosive MORB fragmentation and distal transport. These observations, combined with relatively lower initial volatile contents of MORB, indicate that MOR eruption explosivity may be restricted to lower-viscosity mafic magmas that permit volatile decoupling and coalescence (Head and Wilson, 2003). In addition, the smaller eruption volumes of MORR, compared to MORB, reflect more confined conduit geometries and slower ascent rates (Wilson and Head, 1981), inhibiting their ability to generate high enough overpressures to erupt explosively (Allen et al. 2010). The results presented here illustrate the essential need to (1) refine models of subaqueous ash generation and dispersal, and (2) assess the role of magma ascent and volatile behavior during submarine eruptions.

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