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The petrogenesis of plagioclase-phyric basalts at mid-ocean ridges

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[1] Plagioclase ultraphyric basalts (PUBs) have been sampled along most mid-ocean ridges with ultraslow to intermediate spreading rates. Over the past 40 years, the prevalent models for their origin assume positive buoyancy of plagioclase in basaltic liquids resulting in selective concentration of plagioclase phenocrysts by floatation. However, when the global population of PUB lavas is examined, this hypothesis becomes less compelling. PUB host lavas demonstrate a large range of compositions and densities, similar to aphyric glasses from the same ridge segments. Most importantly, the majority of PUB host liquids are less dense than their phenocryst cargo, meaning that plagioclase floatation within a magma chamber cannot be the driving force for phenocryst enrichment. Furthermore, PUB lavas have never been sampled on axis at fast-spreading centers or from locations with noted contemporaneous axial magma chambers, where PUBs should be abundant if plagioclase is buoyant in mid-ocean ridge basalt (MORB). Instead, we argue that the high modal abundance of plagioclase results from interaction between magma and preexisting zones of crystal cumulates within the lower crust, possibly followed by loss of olivine during magma ascent. PUBs erupt when the magma maintains an ascent velocity greater than the settling rate of the plagioclase phenocrysts, which precludes long crustal residence times for these magmas. In addition to being a proxy for lower spreading rates, our findings also suggest that PUB eruption can also be used as a proxy for the absence of a magma chamber or transport through a conduit system that bypassed an axial chamber.

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1. Introduction

[2] Basalts containing abundant plagioclase phenocrysts are a common occurrence at mid-ocean ridges with ultraslow to intermediate spreading rates and in off-axis seamounts [*Batiza et al.*, 1977; *Flower*, 1980; *Bryan et al.*, 1981; *Cullen et al.*, 1989; *Hansen and Gronvold*, 2000; *Hellevang and Pedersen*, 2008]. These basalts are noteworthy due to both their high phenocryst content (>10%)

and high relative proportion of plagioclase compared to olivine. Previous examination of the phenocryst cargo of mid-ocean ridge basalts (MORBs) noted that the modal proportion of plagioclase phenocrysts increases as the total phenocryst percentages increase [*Bryan*, 1983]. This is in contrast to the expected proportion of phenocrysts predicted during cotectic crystallization of plagioclase and olivine (~70/30). This high plagioclase content could be derived from the crystallization of a high alumina parental liquid [e.g., *Panjasawatwong et al*., 1995] or the physical accumulation of plagioclase in the melt [e.g., *Cullen et al*., 1989]. Because the glass compositions of PUB lavas and plagioclase-hosted melt inclusions are multiply saturated with plagioclase, spinel and olivine, PUBs are likely the result of selective plagioclase accumulation rather than extensive plagioclase crystallization [*Bryan*, 1983; *Sinton et al*., 1993; *Kohut and Nielsen*, 2003].

[3] Existing models for PUB formation propose that plagioclase accumulates in the melt by floatation in a shallow magma chamber prior to eruption [*Kushiro and Fujii*, 1977; *Flower*, 1980; *Bryan*, 1983; *Hekinian and Walker*, 1987; *Cullen et al*., 1989; *Hansen and Gronvold*, 2000; *Halldorsson et al*., 2008; *Hellevang and Pedersen*, 2008]. Due to the lower density of plagioclase compared to olivine (~2.7 and 3.2 g cm^{-3}, respectively), gravitational separation of phenocrysts could account for the selective aggregation of plagioclase. Several experimental studies have demonstrated that plagioclase has variable buoyancy in basaltic liquids at a variety of pressures. *Kushiro and Fujii* [1977] established that although An_{90} plagioclase is more dense than a Kilauea tholeiite at lower pressure, it becomes buoyant in the liquid above 6 kbar. *Campbell et al*. [1978] used a centrifuge furnace to measure the buoyancy of An_{55}, An_{76}, and An_{89} in multiple melts and found the higher anorthite compositions to be negatively buoyant in most of the liquids. *Shibata et al*. [1979] placed ~5 mm An_{70} crystals within a single starting MORB composition and observed that the plagioclase floats when held at 1228°C for 22 h at atmospheric pressure. Based on these results, many researchers have speculated that plagioclase phenocrysts in PUB are erupted preferentially due to their neutral or positive buoyancy in the host melt [*Flower*, 1980; *Kuo and Kirkpatrick*, 1982a; *Hellevang and Pedersen*, 2008]. However, most plagioclase phenocrysts in PUB are anorthitic [*Davis and Clague*, 1987; *Cullen et al*., 1989; *Natland*, 1989; *Stakes and Franklin*, 1994; *Hellevang and Pedersen*, 2008], denser, and consequently less likely to be buoyant than low An compositions, except at increased pressures. In addition, the pressures required for positive buoyancy in some experiments [e.g., *Kushiro and Fujii*, 1977] are significantly greater than the pressure range experienced in oceanic crust from slow and intermediate spreading ridges, making it less likely that plagioclase flotation occurs in crustal magma chambers. Thus far, little attention has been focused on the relevance of the plagioclase floatation hypothesis for the specific set of conditions appropriate to mid-oceanic ridge magmatism, which includes the eruption of high-anorthite plagioclase (>An80) phenocrysts likely sourced from crustal or shallow mantle pressures (<6 kbar).

[4] Understanding the petrogenesis of PUB lavas is important because the plagioclase phenocrysts within these magmas contain a wealth of unique information about crustal processes, as well as the characteristics of the primitive magma array present in the lower oceanic crust. Plagioclase crystals and plagioclase-hosted melt inclusions can extend to compositions that have not been sampled as part of the array of MORB glasses [*Sours-Page et al*., 1999; *Adams et al*., 2011; *Lange et al*., 2013] and can often record more primitive compositions than those erupted at the surface [*Sinton et al*., 1993; *Kohut and Nielsen*, 2003]. Thus, understanding how PUB lavas form provides the context for interpreting the compositions recorded in these phenocrysts. This study examines PUBs from numerous spreading centers in an attempt to identify systematic differences between the lavas that carry abundant plagioclase phenocrysts and spatially associated aphyric lavas. Using the compositional range of the host lavas, associated lavas and phenocrysts, we develop a set of constraints for the set of conditions that allow for the eruption of plagioclase ultraphyric basalts.

2. Sample Selection

[5] Data in this study were collected from several sources, including published literature reporting the occurrence of highly plagioclase-phyric basalts, the Initial Reports of the Integrated Ocean Drilling Program and the Deep Sea Drilling Program, and several repositories (Table 1). Basalts containing >10% plagioclase phenocrysts by volume are defined as highly plagioclase-phyric basalts in this study, following the classification of

Table 1. Data Sources Used in This Paper for PUB Host Glass Composition and Locations

Arctic Ridges	*Hellevang and Pederson* [2008]	Iceland	*Hansen and Gronvold* [2000]
Axial Seamount	*Eaby et al.* [1984]	Juan de Fuca Ridge	*Karsten et al.* [1990]
	Rhodes et al. [1990]		*Adams et al.* [2011]
	This study[a]		*Cousens et al.* [1995]
Blanco Fracture Zone	*Sprtel* [1997]		*Eaby et al.* [1984]
Chile Ridge	*Sherman et al.* [1997]		IODP [vol. 139, *Shipboard Scientific Party*, 1988]
Costa Rica Ridge	IODP [vol. 111, *Shipboard Scientific Party*, 1988]		*Melson and O'Hearn* [2003]
	Natland et al. [1983]		This study[a]
			Cousens et al. [1995][b]
East Pacific Rise		Mid-Atlantic Ridge	*Stakes and Franklin* [1994]
21°N	*Eissen* [1982]		
21°N	*Hekinian and Walker* [1987]		IODP [vol. 151, *Shipboard Scientific Party*, 1995a][b]
Garrett	*Hekinian et al.* [1995]		IODP [vol. 153, *Shipboard Scientific Party*, 1995b][b]
Lamont Smts.	*Allan et al.* [1989]		*Bryan et al.* [1981][b]
Siqueiros	*Natland and Melson* [1980]		*le Roex et al.* [1996][b]
Galapagos	*Christie* [2004]		
	Cullen et al., [1989]	SEIR	*Christie* [2004]
	Sinton et al. [1993]		*Priebe* [1998]
Gorda Ridge	*Davis and Clague* [1987]		*Weinsteiger* [2010]
	Davis et al. [2008]	SWIR	*Lund* [1999]
	Nielsen et al. [1995]		This study[a]

[a] Analytical methods for the glass data reported in this study are outlined in the supporting information.[1]
[b] Citations where only location information was used because glass data was not present.

plagioclase ultraphyric basalts by *Cullen et al.* [1989]. Identification of PUB lavas from literature sources has proven challenging for many reasons. Modal percentages and petrographic information are not consistently reported, and despite the common occurrence of PUB, there is no consistent terminology for describing them. While reliable modal abundance information of most samples exists, it is often contained only in the original cruise log. In addition, even when PUB lavas are sampled, they are often not chosen for further study and are often treated separately from the general interpretation for the area [e.g., *Rhodes et al.*, 1990]. The exclusion of PUB from followup studies could be due to a number of reasons, often related to the fact that these samples were previously considered anomalous [*Bryan*, 1983; *Cullen et al.*, 1989]. Further, many early studies reported only whole rock data rather than glass analyses [e.g., *Batiza et al.*, 1977], and this reinforced the "anomalous" nature of these samples because they exhibited high CaO and Al_2O_3 values that reflect the accumulation of plagioclase phenocrysts rather than the nature of the liquid that carried them.

[6] The current practice for studying MORB petrogenesis focuses on the analysis of MORB glasses, which represent the liquid at the time of eruption. This methodology has many advantages, such as avoiding the effects of alteration and phenocryst accumulation. Furthermore, many MORB lavas have glassy surfaces and are aphyric to sparsely phyric. However, overlooking the more phyric samples, such as PUB, also creates an inherent bias in data collection and interpretation. It is a generally accepted fact that MORB glasses represent the end point of a long history of crustal processes, including melt transport, mixing, and crystal fractionation, all of which can alter the chemistry of the melt [*Rubin et al.*, 2009]. Documenting the glass chemistry, modal proportions, and mineral chemistry of phyric lava provides an important complement to the advances that have been made using solely aphyric melt chemistry.

3. Characteristics of Plagioclase Ultraphyric Basalts

[7] Samples included in this study have ~10–40% plagioclase phenocrysts and include depleted normal MORB (N-MORB) and enriched MORB (E-MORB) compositions. The term "phenocryst" is used to describe large crystals and does not have a petrogenetic implication, as the large plagioclase crystals in PUBs appear out of equilibrium with the host melt in some samples [*Lange et al.*, 2013]. Small (<1 mm) olivine phenocrysts are present, up to 5 modal %. Aluminum-rich spinel is present both as a groundmass phase and as inclusions in plagioclase. Plagioclase phenocrysts are characterized by abundant melt inclusions [*Danyushevsky et al.*, 2002; *Kohut and Nielsen*, 2004; *Adams et al.*, 2011], and typically exhibit a

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[1] Additional supporting information may be found in the online version of this article.

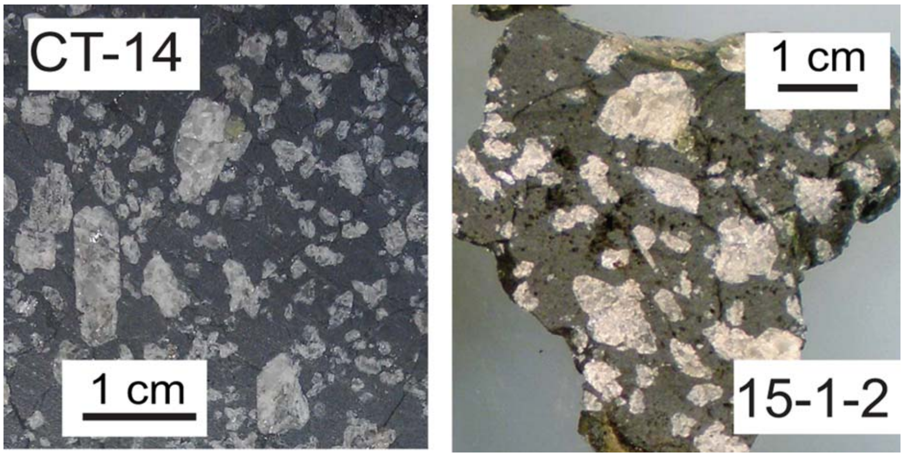


Figure 1. Two examples of plagioclase ultraphyric basalts from Juan de Fuca (CT-14) and Southwest Indian ridge (15-1-2). More sample pictures can be found in supporting information.

slightly elongate morphology ranging in size from 0.2 to 20 mm, with most falling between 1 and 10 mm (Figure 1). Plagioclase crystals exhibit resorption textures that suggest a complicated transport history, and are consistent with the observed chemical disequilibria between the plagioclase and their host lava [*Meyer and Shibata*, 1990; *Nielsen et al*., 1995; *Cordier et al*., 2007]. While some plagioclase phenocrysts in these samples contain complex compositional zoning patterns [*Kuo and Kirkpatrick*, 1982b; *Hekinian and Walker*, 1987; *Hellevang and Pedersen*, 2008], they are just as often characterized by remarkably homogeneous compositions [*Batiza et al*., 1977; *Cullen et al*., 1989; *Sinton et al*., 1993; *Sours-Page et al*., 1999; *Hansen and Gronvold*, 2000; *Adams et al*., 2011].

[8] Plagioclase compositions in PUB are also typically An-rich (An_{80}–An_{94}, Figure 2), and these compositions are not in equilibrium with any known erupted MORB liquid [*Fisk*, 1984; *Nielsen et al*., 1995]. Thus, the plagioclase phenocrysts must have crystallized from a melt with high CaO/Na_2O ratios compared to the sampled MORB array [*Panjasawatwong et al*., 1995; *Kohut and Nielsen*, 2003]. Liquids in equilibrium with high-An plagioclase reproduced from naturally occurring MORB [*Kohut and Nielsen*, 2003] are distinctly more primitive than any lava sampled from the ocean floor, with higher Al_2O_3, MgO, and CaO. To explain the documented disequilibria between the phenocrysts and their host lavas, many authors suggest mixing between primitive plagioclase-bearing liquids and a more evolved liquid [*Cullen et al*., 1989; *Meyer and Shibata*, 1990; *Stakes and Franklin*, 1994]. Moreover, PUBs often exhibit strong bimodal crystal populations [*Bryan*, 1983], which are typical of mixed magmas [*Marsh*, 1988].

4. Distribution of PUB Lavas

[9] The occurrence of PUB and the overall abundance of phenocrysts in MORB appear to be strongly dependent on spreading rate [*Flower*, 1980]. PUBs have only been found at spreading centers with intermediate to ultraslow spreading (Figure 3), and have never been found among the axial lavas at fast-spreading ridges, such as the East Pacific Rise (EPR). However, they have been found near the slower-spreading ridge offset at

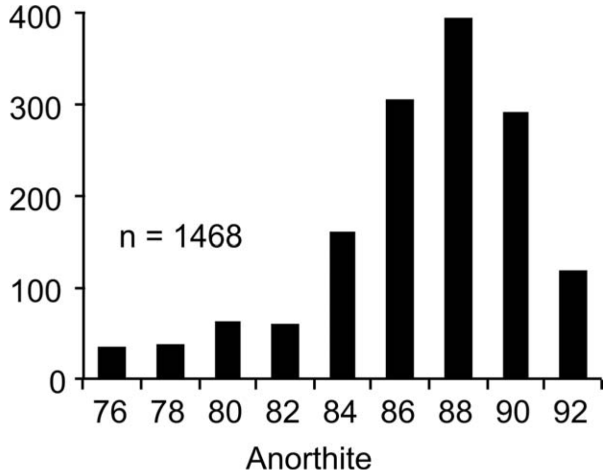


Figure 2. Distribution of plagioclase phenocryst compositions in PUBs. Data from *Adams et al*. [2011] and this study.

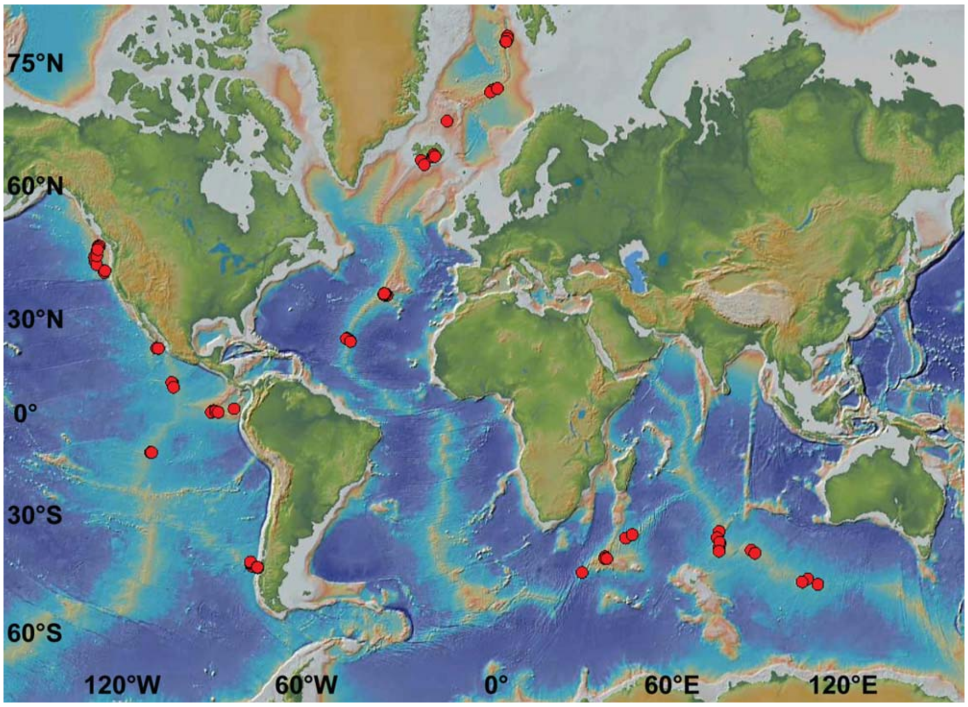


Figure 3. Location of PUBs. Map made using GeoMapApp (http://www.geomapapp.org) using the Global Multi-Resolution Topography basemap [Ryan et al., 2009].

21°N [*Hekinian and Walker*, 1987], within magmatic basins in transforms along the EPR [*Batiza et al*., 1977; *Natland and Melson*, 1980; *Hekinian et al*., 1995], and are associated with near axis seamounts [*Allan et al*., 1989; *Niu and Batiza*, 1991]. Some studies noted more primitive compositions and porphyritic lavas approaching transform boundaries and the propagating sections of rifts [*Christie and Sinton*, 1981; *Hekinian et al*., 1995], suggesting that the eruption of PUBs would more likely occur near segment ends. Hekinian et al. [1995] propose that ascent of magma through cold conduits could serve to increase crystal nucleation and increase the viscosity, promoting the extrusion of porphyritic lavas. However, when the location of PUBs is compared to their position within a ridge segment (Figure 4), there appears to be no correlation with their position relative to the end of the segment. We observe that PUBs have been sampled both in the center of segments and toward the segment ends at ridges with full spreading rates below 76 mm/yr.

5. Comparison With Aphyric Lavas

[10] If PUB host glasses are compositionally distinct from aphyric MORB in the same ridge segment, this could suggest that there are different sources or petrogenetic processes for producing aphyric versus PUB lavas. *Hellevang and Pederson* [2008] conjectured that Arctic PUB lavas originated from a separate source than neighboring aphyric lavas due to their more depleted compositions based on lower La/Sm and K_2O. Furthermore, PUB magmas were also distinctive by lower Mg#, suggesting that the PUBs experienced more fractionation than the adjacent aphyric lavas. *Hekinian et al*. [1995] observed that the porphyritic samples at the Garrett Transform had higher CaO/Al_2O_3, lower Mg#, and lower Na_2O than the sparsely phyric basalts. *Cullen et al*. [1989] noted that the PUB and aphyric lavas in the Galapagos overlap in major element concentrations; however, PUBs were slightly lower in La/Sm and Ba/Rb ratios than the aphyric basalts. Nevertheless, other studies have made the opposite claim, e.g. *Hansen and Gronvold* [2000] demonstrate that Icelandic PUB host glasses show the same range of major elements (MgO, TiO_2, FeO^*, Al_2O_3, K_2O, CaO, and Na_2O) as the aphyric lavas from the same Icelandic rifts. In order to understand the level of compositional distinction between PUB and aphyric lavas, we compared our compilation of PUB glass compositions to aphyric lavas from the same ridge segments.

[11] Examination of this data set shows no significant difference between the populations of PUB

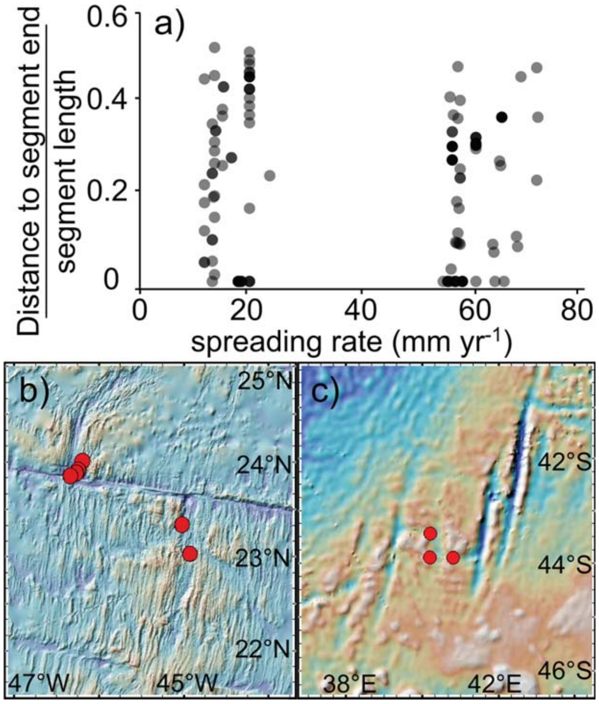


Figure 4. (a) Plot of spreading rate versus the location of the sample within a first-order segment. The distance to the end of the segment is normalized to the length of the segment, thus a sample in the center of a segment would be 0.5 and a sample at the end would be 0. PUBs appear equally likely to be found in the center as at the edge of ridge segments. The sample gap between 25 and 55 mm yr^{-1} appears to be a characteristic of MORB data, as few mid-ocean ridges exhibit those spreading rates. (b) PUB samples concentrated toward the segment end at the Mid-Atlantic Ridge. (c) PUB samples located in the center of the segment at the slow-spreading Southwest Indian Ridge. Map made using GeoMapApp (http://www.geomapapp.org) using the Global Multi-Resolution Topography basemap [Ryan et al., 2009].

host glasses with those that are aphyric (Figure 5). Both PUB host glasses and glasses from aphyric samples are characterized by MgO values that range from 4 to 10 wt % and range from N-MORB to E-MORB major element compositions. Some locations, such as Axial Seamount and Juan de Fuca (Figure 5b), appear to have PUB and aphyric lavas showing distinct compositional populations. While only comparing PUB and aphyric samples from within the same segments avoids some of the variation that can exist between first-order segments, the small number of PUB samples (four at Axial and seven at Juan de Fuca) compared to aphyric samples makes a statistical distinction impossible, as the apparent contrasting compositions could easily be a sampling bias. Even though they are distributed worldwide, the total number of PUB lavas is relatively small compared to the total number of aphyric MORB lavas. However, the similarity in ranges of major element composition observed in both types of MORB does not suggest any distinction between the petrogenesis of PUB and aphyric MORB melts.

6. Density Variation

[12] Since there appears to be no obvious chemical bias between the lavas that erupt abundant plagioclase phenocrysts and those that are aphyric, we infer that specific physical conditions are required

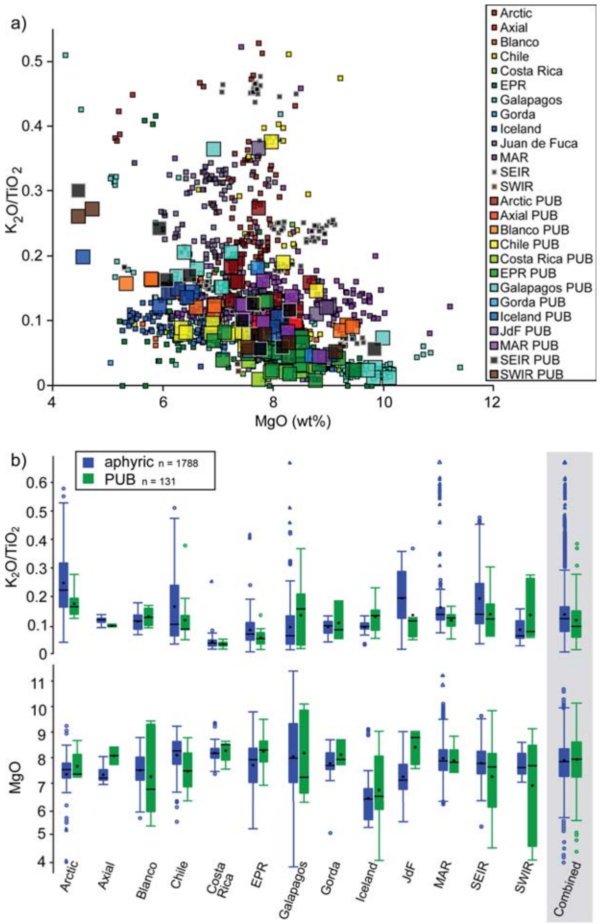


Figure 5. (a) Plot of K_2O/TiO_2 versus MgO (wt %) for PUB host glasses (larger squares) compared to aphyric glasses (smaller squares) from the same ridge segment. EPR = East Pacific Rise; JdF = Juan de Fuca; MAR = Mid-Atlantic Ridge; SEIR = Southeast Indian Ridge; SWIR = Southwest Indian Ridge. (b) Box and whisker statistical plots showing the same data separated by location. The black lines mark the median and the black spots mark the average. The "Combined" plots on the right contain the total data set from all the spreading ridges together. PUB host glasses have the same range of compositions as the aphyric lavas from the same segments.

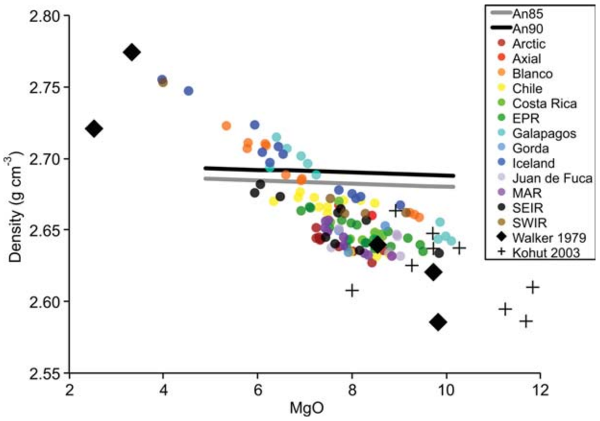


Figure 6. Plot of MgO (wt %) versus density (g cm^{-3}) of the host melt of PUB samples (circles) compared to An$_{85}$ and An$_{90}$ plagioclase (lines). Glass MgO% analyses were taken from the literature and this study. Melt densities were calculated using the *Bottinga and Weill* [1970] equation with updated thermal expansion coefficients [*Lange and Carmichael*, 1987]. Density of plagioclase was calculated by extrapolating for the standard state densities of An$_{85}$ and An$_{90}$ assuming that density varies linearly between the end members. This value was adjusted for thermal expansion using the method outlined by [*Tribaudino et al.*, 2010] and is further described in the supporting information. In order to plot the plagioclase densities, MgO melt concentrations in equilibrium with the plagioclase were estimated using the linear relationship between MgO of the host melt and equilibrium temperatures calculated using MELTS. Experimental data from *Kohut and Nielsen* [2003] and *Walker et al.* [1979] is discussed in the text.

to erupt PUBs. Recognition of the density contrast between basaltic liquids and plagioclase [*Kushiro and Fujii*, 1977; *Campbell et al.*, 1978; *Shibata et al.*, 1979; *Sparks and Huppert*, 1984] has led many investigators to cite plagioclase buoyancy as a driving force for PUB eruption [*Flower*, 1980; *Cullen et al.*, 1989; *Hellevang and Pedersen*, 2008]. A simple test of this theory is to calculate the density of the PUB host liquid and compare those densities to the density of the plagioclase phenocrysts. In this study, liquid densities were calculated using the *Bottinga and Weill* [1970] expression utilizing partial molar volume and updated thermal expansion and compressibility coefficients for major element oxides [*Lange and Carmichael*, 1987; *Lange*, 1997]. The effect of pressure on liquid density was calculated using the methods and compressibility coefficients found in *Lange and Carmichael* [1990]. Melt densities calculated by this method agree with density values calculated using the MELTS software [*Ghiorso and Sack*, 1995]. An$_{85}$ and An$_{90}$ plagioclase densities were calculated by extrapolating from end-member densities [*Deer et al.*, 1992] and correcting these values to magmatic temperatures using anorthite-dependent thermal expansion expressions [*Tribaudino et al.*, 2010]. The effects of pressure on the density of feldspar produces effects smaller than the plotted data points and is sufficiently small to be ignored for the purpose of this comparison [*Niu and Batiza*, 1991]. Comparing the calculated densities of An$_{85–90}$ plagioclase and the erupted host liquids allows us to determine under what conditions the phenocrysts would have been buoyant in these liquids.

[13] Instead of exhibiting a strong signature of negative buoyancy, the liquid fraction in PUB host lavas reported here are mostly less dense than An$_{85–90}$ plagioclase, implying that plagioclase would naturally sink in liquids of these compositions rather than float (Figure 6). The few basalts that are denser than An$_{85}$ (~15% of the total) are rather evolved with MgO $\leq$ 6 wt %, which are not common MORB compositions. Experimental liquids calculated to be in equilibrium with high-anorthite plagioclase [*Kohut and Nielsen*, 2003] are more primitive and less dense than the suite of PUB host lavas, yet are part of the compositional continuum in terms of density and MgO. Despite being in chemical equilibrium with high-An plagioclase, the liquids are substantially less dense (Figure 6). The positive density contrasts between the phenocrysts and their equilibrium liquid would imply that the phenocrysts would settle out of suspension upon formation creating cumulates containing high-An feldspar within the crust. These liquids could then continue to rise due to their low density and fractionate, ultimately forming the array of aphyric MORB sampled at the surface. This is consistent with the analysis of *Kohut and Nielsen* [2003] that those experimental liquids can be related to the array of MORB lavas by simple fractionation of plagioclase and olivine. Calculated PUB host lava densities also correspond with the experimental tholeiitic liquids of *Walker et al.* [1979], which were used to establish the changes in density that occur during fractional crystallization [*Stolper and Walker*, 1980]. The agreement between the PUB host lava and the experimental data further reinforces that the plagioclase phenocrysts belong to the array of MORB liquids and did not crystallize from atypical melts. The phenocrysts instead rarely erupt because of the high density of the anorthitic plagioclase phenocrysts.

[14] The density contrast between plagioclase and host lavas will decrease with pressure because of the relatively high compressibility of magmatic

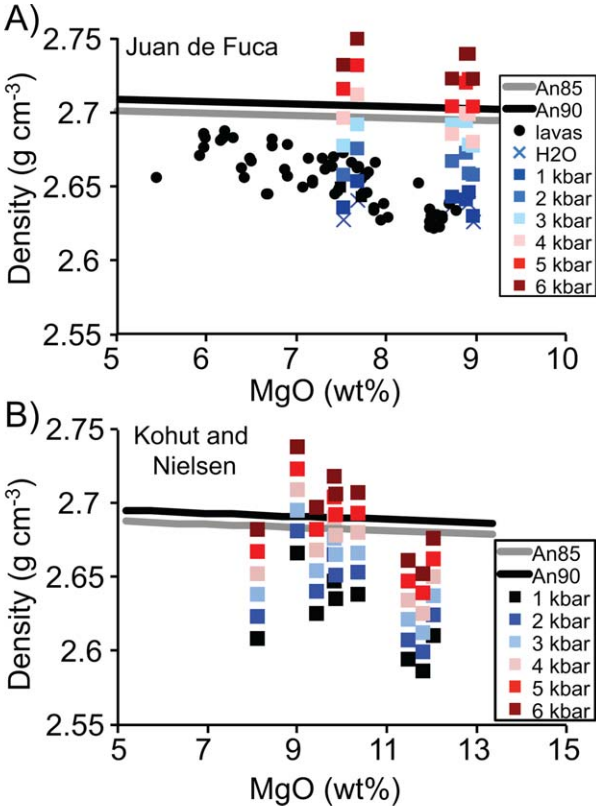


Figure 7. (a) Comparison of PUB host density and the density of aphyric lavas from the Juan de Fuca. Juan de Fuca PUB densities were calculated at increasing pressures to discern the pressure where the plagioclase phenocrysts would be neutrally buoyant. The density of the 1 kbar PUB liquids with 0.1 wt % water added is also shown to show that adding water to the melts would decrease the likelihood of plagioclase floatation. (b) Effect of increased pressure on the experimental liquids in equilibrium with high-An plagioclase [*Kohut and Nielsen*, 2003].

liquids compared to crystalline phases. Despite having limited effect on the density of plagioclase, pressure can cause appreciable increases in melt density. We examined the pressure dependence of the melt density contrast by calculating liquid densities at increased pressures for lavas at the Juan de Fuca (Figure 7a). While the effect of pressure would raise the PUB host liquid density, pressures over 3 kbar (~9 km) would be needed for high anorthite plagioclase to be neutrally buoyant within several of the host liquids. This is less than the required pressure of 6 kbar for plagioclase (An_{90}) floatation measured by *Kushiro and Fujii* [1977] at which high-An feldspar became buoyant in the Kilauea basalt. Additionally, we assessed the effect of pressure on the *Kohut and Nielsen* [2003] experimental liquids. For most of the experimental liquids in equilibrium with high-An feldspar, the melt had to be at a pressure of 4–6 kbar to be neutrally buoyant with the plagioclase phenocrysts (Figure 7b). The depth of crystallization of such anorthitic plagioclase is limited by the observation that the crust thickness in slow and intermediate spreading oceanic crust is typically 6 km or less [*Chen*, 1992], which equates to pressures of roughly 2 kbar. Pressure and anorthite content are negatively correlated, decreasing by ~1 mol % An for each 1 kbar increase in pressure [*Fram and Longhi*, 1992; *Panjasawatwong et al.*, 1995], making it unlikely that anorthite-rich crystals form in a high pressure setting.

7. Discussion

7.1. Physical Conditions Required for PUB Formation

[15] PUBs are distinguished by their high abundance of plagioclase crystals, the higher proportion of plagioclase to olivine than would be expected from cotectic crystallization, and their occurrence only at ultraslow to intermediate spreading ridges. Any model for PUB petrogenesis must take all of these observations into consideration.

[16] Plagioclase-phyric basalts are formed in other environments by eruption of less dense, lower anorthite plagioclase in an evolved, higher density liquid (as occurs in some continental basalts; e.g., Steen Mountain basalts *Johnson et al.* [1996]) or by transport of high-anorthite plagioclase floatation in an evolved, high density melt. However, our data suggest that these mechanisms do not explain the vast majority of PUB in MORB, where liquid densities are too low to support a model of plagioclase flotation (Figures 5 and 6). The popularity of the plagioclase floatation model may in part be due to the similarities with the lunar magma-ocean model for lunar anorthosites as well as commonly cited mechanisms for forming terrestrial anorthosites [*Wood et al.*, 1970; *Kushiro and Fujii*, 1977]. However, these comparisons are misleading because the composition and densities of the liquids and feldspars in these settings are dissimilar to MORB. Most terrestrial anorthosites are composed of less dense, lower anorthite plagioclase (~An_{60} compared to ~$An_{80–90}$ in PUB) or crystallized from more evolved Fe-rich, and thus denser, liquids [*Phinney et al.*, 1988]. Lunar anorthosites have high anorthite plagioclase ($An_{85–95}$) [*Wenk et al.*, 1972] but also form via flotation within dense Fe-rich melt [*Walker and Hays*,

1977; *Hess and Parmentier*, 1995], and thus the flotation model may still be viable in such a setting. However, we also note that recent advances in understanding the chronology of lunar anorthite formation have created uncertainty about the viability of the plagioclase flotation model for lunar anorthosites [*Borg et al*., 2012]. Regardless, while plagioclase floatation might be feasible in lunar and terrestrial anorthosites, our results suggest that that process is unlikely to be the mechanism for formation of PUB at mid-ocean ridges, as most plagioclase would be denser than its associated melt.

[17] We suggest that the majority of PUBs in MORB are the result of disruption of plagioclase-bearing cumulates during magma ascent within the lower oceanic crust or uppermost mantle. Cumulates that are rich in plagioclase are described in the lower crustal sections of many ophiolitic sequences [*Pallister and Hopson*, 1981; *Elthon et al*., 1982; *Kelemen et al*., 1997; *Morales et al*., 2011; *Nicolas and Boudier*, 2011]. In addition, most MORB glasses show evidence of having fractionated along an olivine-plagioclase cotectic [*Grove et al*., 1992]; however, these early stage crystals are rarely erupt at the surface, suggesting that the phenocrysts are left behind in crustal cumulate zones. Accumulation of these crystals within the crust could occur via gravitational separation, sidewall crystallization, filter pressing, flow segregation, or other mechanisms. Incorporation of these crystal cumulates into PUB is strongly supported by the observation that plagioclase phenocrysts in PUB and other MORB are often in disequilibrium with the host glass [*Meyer and Shibata*, 1990; *Sinton et al*., 1993; *Bryce and DePaolo*, 2004; *Cordier et al*., 2007; *Halldorsson et al*., 2008; *Lange et al*., 2013], suggesting they often have a xenocrystic or antecrystic relationship to the host melt. In addition, the primitive nature of liquids in equilibrium with PUB plagioclase and olivine [*Kohut and Nielsen*, 2003] also suggests that such crystal-rich cumulate zones form during the earliest stages of MORB fractionation, and are most likely to form deep within the oceanic crust or in the uppermost mantle [*Kohut and Nielsen*, 2003, 2004]. Disruption of such zones to form PUB probably occurs during subsequent magma injection events, resulting in remobilization of the crystal-rich material, producing a slurry of MORB liquid combined with the antecrystic crystal load. Incorporation of plagioclase at depths approaching 9 km would be aided by the smaller difference in density between plagioclase and melt at these higher pressures (Figure 6). However, as noted above, the equilibrium plagioclase compositions become increasingly albite rich with depth, making it unlikely that the depth of crystallization was typically greater than ~6–9 km.

[18] Melt ascent processes within the shallower crust also may play an important role in PUB formation. As melts ascend toward the surface, plagioclase becomes increasingly negatively buoyant in the liquid due to the decreasing density of the liquid phase with decompression. However, crystal fractionation may simultaneously drive the melt to a higher density [*Stolper and Walker*, 1980]. Thus, even if the plagioclase crystals are entrained in the lower crust where the crystals are closer to neutral buoyancy within a liquid, decreasing melt density with ascent may cause the crystals to settle out if the magma pools at lower pressures for an extended period—depending on the degree of simultaneous fractional crystallization. This process is probably responsible for the dearth of PUB in fast-spreading centers and other locations with established axial magma chambers. As ascending plagioclase-rich melts enter larger magma chambers, the magma stalls within the crust, bringing the ascent velocity to zero and allowing plagioclase to separate from the liquid fraction. In this way, axial magma chambers and other magma storage zones may act as a filter for PUB, and allow them to only reach the surface in intermediate and slow spreading centers and other locations where overall magma fluxes are low or where magma conduits to the surface may bypass established magma chambers. Although the high melt supply at fast-spreading ridges would provide enough momentum to carry the plagioclase phenocrysts upward through the crust, PUBs do not erupt in these locations because the axial magma chambers act like a density filter, allowing the higher density crystals to settle out and the lower density melt to be erupted.

[19] The enigma of PUB formation limited to ridges with ultraslow to intermediate spreading ridges has previously been attributed to the effects of melt supply [*Flower*, 1980; *Sinton et al*., 1993]. Although existing models for PUB formation that argue for plagioclase flotation require this accumulation to occur in crustal magma chambers, highly plagioclase-phyric lavas appear to only erupt along spreading ridges with low to intermediate magma supplies, where long-lived magma chambers are not generally found. This link between PUBs and lower magma supply can be observed within a single spreading center. For example, at the Galapagos spreading center, PUBs are more common

further from the hot spot where the magma supply rates are lower. Adversely, only aphyric lavas have been sampled closer to the Galapagos host spot, where magma supply is increased and a near-continuous axial magma chamber has been imaged [*Colman et al*., 2012]. The absence of PUBs in locations with high magma supplies and seismic reflectors suggests that although many studies have argued that PUB forms due to plagioclase flotation in axial magma chambers [*Hekinian and Walker*, 1987; *Cullen et al*., 1989; *Hansen and Gronvold*, 2000; *Halldorsson et al*., 2008; *Hellevang and Pedersen*, 2008], the presence of an axial magma chamber precludes the eruption of plagioclase ultraphyric lavas.

[20] The low proportion of olivine in PUB may also be reflective of magma ascent processes. Since both the host glass and the plagioclase-hosted melt inclusions show evidence of plagioclase and olivine fractionation [*Bryan et al*., 1981; *Sinton et al*., 1993; *Kohut and Nielsen*, 2003], olivine must have been present earlier in the system and must have been a major fractionating component. However, even though microphenocrysts of olivine are found in most PUBs, they occur in proportions far below those predicted by cotectic crystallization (often <1–2% modal). There are two options for the excess concentration of plagioclase in PUB magmas. One possibility could be that the melts are sampling noncotectic cumulates that are already enriched in plagioclase prior to being entrained by the ascending melt. These environments could be similar to the anorthosites and plagioclase-rich troctolites zones that have been identified within the oceanic crust [*Elthon*, 1987; *Hekinian et al*., 1993; *Perk et al*., 2007] and in ophiolites [*Pallister and Hopson*, 1981; *Kelemen et al*., 1997; *Morales et al*., 2011; *Nicolas and Boudier*, 2011]. Another possibility is that the density contrast between olivine and plagioclase may allow them to become segregated during transport and ascent. When olivine phenocrysts are found in PUB lavas, they are usually smaller than the plagioclase in the same sample [e.g., *Hellevang and Pedersen*, 2008]. Given the relatively high density of olivine compared to the tholeiitic host melt ($\sim$3.24 g cm^{-3} and $\sim$2.65 g cm^{-3}, respectively), olivine phenocrysts would settle out of a tholeiitic melt faster than coexisting plagioclase (see below). If the host magma is ascending fast enough to overcome the negative buoyancy of plagioclase phenocrysts but not fast enough to entrain the denser olivine, then relative olivine loss will occur. Additionally, flow segregation during melt transport has been identified as a method of crystal sorting, which could enrich plagioclase over cotectic proportions [*Brophy*, 1989, *Zellmer et al*., 2010]. Likely, both of these processes contribute to phase segregation in the crust.

7.2. Minimum Ascent Velocities

[21] Despite ruling out plagioclase buoyancy as the primary driver of PUB formation, negatively buoyant plagioclase crystals can still be erupted if the ascent velocity of the host melt exceeds the velocity at which the plagioclase crystals are sinking. In effect, we can assume that any plagioclase-phyric magma that is sampled as lava must have had an ascent velocity at least as fast as the calculated settling velocity for the plagioclase phenocrysts in that melt. Recent geochemical and geophysical advances have provided greater constraints on the time scales of melt transport through the oceanic crust. U-series disequilibria studies have allowed for the minimum transport time to be decreased from several hundred years [*Sims et al*., 2002] to the decadal scale or less [*Rubin et al*., 2005]. Modeling of diffusion profiles for trace elements in plagioclase from the Mid-Atlantic Ridge and the Costa Rica Rift suggest crystal residence times of less than 1 year between disintegration of a crystalline mush by recharge of a new magma and eruption [*Costa et al*., 2010]. Perhaps most significant, the systematics of CO_2 degassing have demonstrated that minimum ascent rates between 0.6 and 15 cm s^{-1} are necessary to maintain observed levels of CO_2 concentrations measured in MORB glasses [*Sarda and Graham*, 1990; *Soule et al*., 2012]. These ascent velocities are supported by earthquake migration rates of $\sim$30–55 cm s^{-1} that are associated with the movement of magma prior to eruption [*Dziak et al*., 2007]. The new volatile degassing and seismic data provide an estimate of magma ascent rates at mid-ocean ridges, which can be used to validate the calculated minimum ascent rates necessary to entrain negatively buoyant plagioclase.

[22] If we can estimate the settling velocity of the plagioclase phenocrysts in the melt, we can establish a minimum velocity that the magmas must maintain in order to carry the phenocrysts to eruption. A first-order estimate of this settling velocity can be calculated using Stoke's Law, which utilizes the density contrast between the melt and the phenocrysts, the size of the phenocrysts and the viscosity of the melt. Densities were calculated using the methods detailed above (Figure 6). Melt viscosity was calculated using the method of

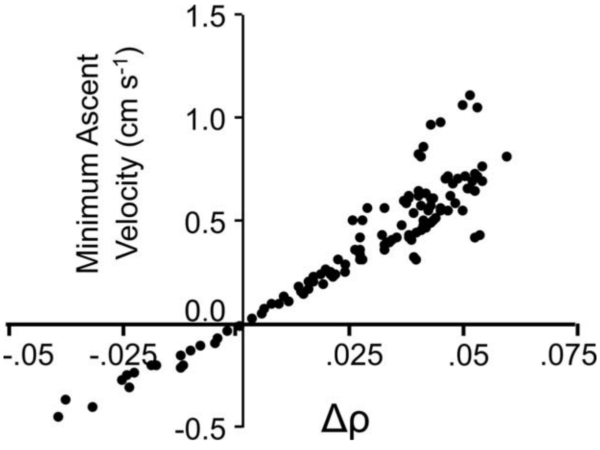


Figure 8. Plot of minimum ascent velocity necessary to entrain An_{85} plagioclase in the melt versus the density contrast between the melt and the crystals. In order for higher density plagioclase to be entrained in a less dense melt, the ascent velocity must be higher than the crystal settling velocity. These minimum ascent velocities were estimated by calculating the Stoke's settling velocity of a maximum An_{85} 1 cm crystal in the PUB host liquids from this study. The density variation ($\Delta\rho$) is the density of An_{85} at 1200°C minus the melt density calculated by the method outlined in the text. The calculated melt velocity does not include the effect of increasingly crystallinity on magma viscosity.

Giordano et al. [2008], assuming the equilibrium temperatures calculated using MELTS [*Ghiorso and Sack*, 1995]. Crystal size and crystallinity have large effects on the calculated viscosity. While the crystal size varies between samples, the plagioclase phenocrysts in PUB are usually well sorted and can include maximum phenocryst sizes in excess of 10 mm (Figure 1). As the ascent velocity must be high enough to carry even the largest crystals to the surface, we use this value as an upper limit toward calculating the minimum necessary ascent velocity for PUB eruption. Crystal settling rates calculated using Stoke's Law range from negative values for the few melts that are more dense than their plagioclase phenocrysts up to 1 cm s^{-1}, with most of the data falling between 0.5 and 1 cm s^{-1} (Figure 8). For these melts to carry their plagioclase phenocryst cargo, their ascent velocities would have to exceed these sinking rates, which extend to 1 km d^{-1}. These values fall into the range of ascent velocities expected by CO_2 concentrations in MORB [*Soule et al*., 2012].

[23] Using the minimum ascent velocities calculated from anorthitic plagioclase settling rates, Stoke's Law could be used to calculate the hydraulic equivalent olivine size that can be carried in that same liquid at that velocity. Olivine densities were estimated using extrapolation of end-member compositions to Fo_{85} and were corrected for thermal expansion [*Niu and Batiza*, 1991]. At these conditions, olivine size is limited from ~1 to 3 mm at the velocities required to carry 1 cm An_{85} phenocrysts. Olivine phenocrysts observed within PUBs are often 0.2–1 mm and show resorbed textures, which agrees with our size estimates and the expected level of disequilibria with the host lava. One possible issue with physically separating olivine from the melt is that the viscosity of magmas is highly dependent on the crystallinity. Thus, as you increase the amount of crystals in the melt, the magma becomes more viscous, which would decrease the settling velocity of olivine. However, this effect could be minimized if there is a high melt to crystal percentage during and after crystal entrainment, allowing for significantly lower viscosities where olivine can be separated from the magma. Additionally, multiple events of melt transport may aid the process of crystal sorting within the crust. Concurrently, melt transport processes within the conduits, such as grain dispersive pressure, could assist with separating plagioclase from olivine during transport [*Zellmer et al*., 2010]. The physical separation of olivine and plagioclase has previously been utilized to explain the occurrence of both plagioclase-rich and olivine-rich MORB found in oceanic settings. Both types of MORB have matrix glasses that have evolved along the olivine-plagioclase cotectic and their noncotectic proportion of phenocrysts are inferred to have been caused by separation during transit [*Natland and Dick*, 2009].

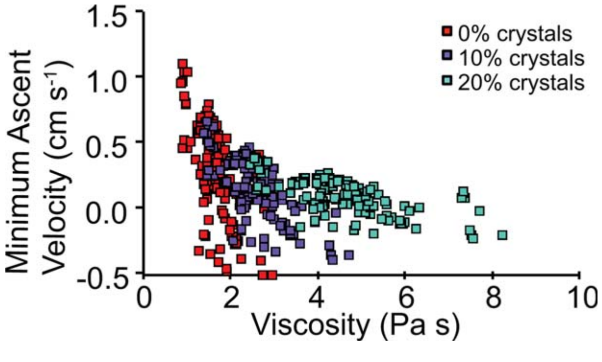
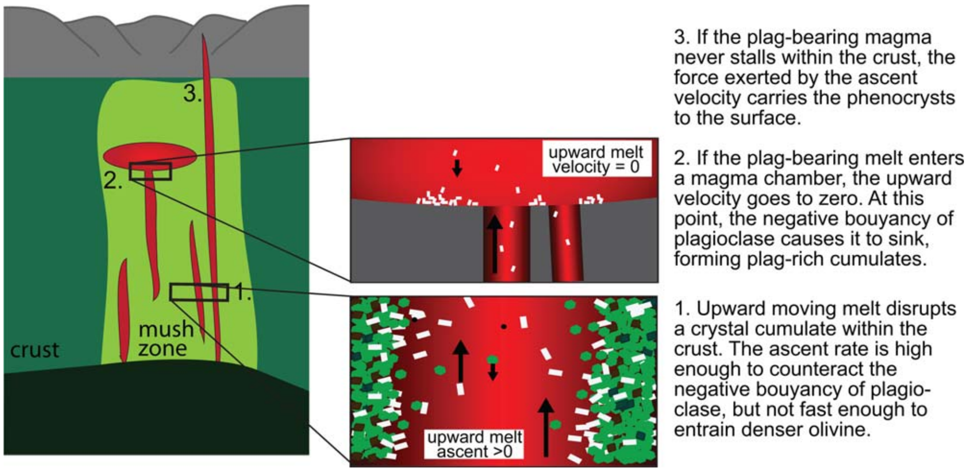


Figure 9. Effect of increasing crystallinity on the viscosity and minimum ascent velocity needed to erupt the plagioclase phyric lavas. Melt viscosity calculated using methods of *Giordano et al*. [2008]. Minimum ascent velocity is equal to the settling velocity for 1 cm An_{85} crystals in the host melt calculated using Stoke's Law, as in Figure 7.



3. If the plag-bearing magma never stalls within the crust, the force exerted by the ascent velocity carries the phenocrysts to the surface.

2. If the plag-bearing melt enters a magma chamber, the upward velocity goes to zero. At this point, the negative bouyancy of plagioclase causes it to sink, forming plag-rich cumulates.

1. Upward moving melt disrupts a crystal cumulate within the crust. The ascent rate is high enough to counteract the negative bouyancy of plagioclase, but not fast enough to entrain denser olivine.

Figure 10. Proposed model for the occurrence of PUB lavas.

[24] Although plagioclase phenocrysts can be denser than the melt, we observe that they can still be carried in that melt if it maintains expected ascent velocities. Thus, locations with long-lived magma chambers might not erupt PUBs because the melts lose their upward velocity upon entering the chamber and are unable to continue carrying the phenocrysts. As noted above, once the phenocrysts are entrained into the magma, magma viscosity will increase significantly, which will decrease the settling velocity. Increasing the crystallinity to 10% increases the viscosity by ~50% and decreases the subsequent minimum ascent velocity by ~60% (Figure 9). This decrease in settling velocity would make it easier to erupt phyric lavas once the phenocrysts are entrained. However, these crystals still have a settling time of approximately 0.5–0.8 cm s^{-1} if the magma has 10% crystallinity, which equates to a settling rate of 430–700 m d^{-1}. The plagioclase crystals would still be likely to settle out in a magma chamber if held there for an extended period.

8. Conclusions

[25] Liquids that erupt with >10% plagioclase phenocrysts do not appear to be distinctive from the array of aphyric MORB in any way besides the modal abundance of plagioclase. Because the host lavas are most often less dense than the anorthitic phenocrysts, plagioclase buoyancy cannot be used to explain the eruption of PUB magmas. In addition, if plagioclase were commonly buoyant in MORB, we would expect PUBs to be abundant in environments with long-lived axial magma chambers, where the phenocrysts would have more time to accumulate at the top of the chamber. However, the opposite is the case, as there are no known occurrences of PUB lavas erupting along on-axis at fast-spreading segments or where there was a documented axial magma chamber.

[26] Our analysis suggests that three conditions must be satisfied for PUB lavas to be erupted. First, the melt must pass through conduits in which plagioclase cumulates are present. The overabundance of plagioclase compared to plagioclase-olivine cotectic proportions may be an existing feature of the cumulates, which would be exaggerated during transport due to the high density of olivine. Second, the ascent velocity of the magma within the conduit must be greater than the settling velocity of the entrained phenocrysts (on the order of ~0.5–1 cm s^{-1}). Finally, the magma must not travel through a conduit system containing an axial magma chamber, which could halt the upward ascent of the magma and allow the denser crystals to segregate (Figure 10). Thus, PUBs only erupt when plagioclase-bearing magmas travel through conduit systems that lack or bypass a magma chamber.

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