Glass Inclusions in Mariana Arc Phenocrysts: A New Perspective on Magmatic Evolution in a Typical Intra-oceanic Arc[1]

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ABSTRACT

Major element compositions of glass inclusions in olivine and plagioclase phenocrysts from representative Mariana arc lavas show that mafic Mariana arc liquids are tholeiitic and not high-alumina, implying that the high-alumina characteristic of these lavas reflects accumulation of plagioclase. Glass inclusions also show the common occurrence of felsic melts previously unrecognized among Mariana arc lavas and indicate that felsic melts are important, if cryptic, components of this magmatic system. Primitive, mantle-derived melts have not been found. Glass inclusion data indicate that the arc magma systems sampled by erupting lavas are compositionally bimodal, with Fe-rich mafic and high-silica (66 to 76% SiO_2) modes. These observations are most simply interpreted as being due to shallow, compositionally zoned magma chambers. The restriction of felsic glass inclusions to plagioclase phenocrysts indicates that felsic melts reside in the upper part of the magma chamber, underlain by Fe-rich mafic melts. Plagioclase phenocrysts accumulate between mafic and felsic zones. Glass inclusions from plagioclase and olivine in the same sample are compositionally distinct, indicating that these minerals formed in different melts. These data indicate that Mariana arc magmas reside in strongly zoned magma chambers, and that coupled magma mixing and plagioclase accumulation are important for controlling the spectrum of lavas erupted in this typical arc.

Introduction

One of the great controversies of igneous petrology concerns the composition of convergent margin melts. This controversy is important because igneous rock compositions are the most meaningful constraint for petrogenetic models. Igneous rocks from other major tectonic settings such as hot spots and mid-ocean ridges are commonly aphyric or sparsely phyric and can generally be interpreted as approximating magmatic liquids. In these cases, knowledge of silicate melt-solid equilibrium obtained from experimental petrologic studies can be applied advantageously. This approach, however, may be inappropriate for convergent margin lavas, because they are commonly porphyritic (Ewart 1979, 1982). We often do not know whether whole-rock compositions reflect melt compositions or are mechanical mixtures of melt and phenocrysts. In the latter case, interpreting porphyritic lava chemical compositions as representing melt compositions will result in erroneous conclusions about petrogenesis. At the very least, it is more difficult to infer melt compositions from porphyritic lavas, and conclusions based on such studies are bound to be controversial. Crawford et al. (1987) provide an excellent overview of the controversy as it applies to the origin of high-Al basalt, a magmatype thought to be characteristic of island arcs (Kuno 1960). Brophy (1989*a*) concurred that crystallization and convection causes mineralogical sorting and preferential plagioclase retention to form non-liquid high-alumina basalts of accumulative origin. From the association of high-MgO, low-alumina basalt and low-MgO, high-alumina basalt within a single host lava on Kanaga Island, Brophy (1989*b*) showed that nonprimary high-alumina basalt can be produced from high-MgO, low-alumina basalt through low-pressure mafic crystal fractionation accompanied by plagioclase retention, and ruled out eclogite melting as an origin for high-alumina basalt.

A similar problem may exist for the 2500 km long arc system that extends south from Japan through the Izu, Bonin, Volcano, to Mariana seg-

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ments and is known as the IBM arc system (Taylor 1992). This arc is one of the world's most typical and best-studied examples of an intra-oceanic arc, that is, an arc built on oceanic crust. Understanding petrogenesis of IBM arc system magmas is important for our general understanding of magmagenesis at convergent margins, but questions regarding the significance of its commonly porphyritic lavas must first be resolved.

This study focuses on lavas from the Mariana arc system. Numerous petrologic studies of Mariana arc lavas have been carried out, but these are based on conventional whole-rock analyses of fresh lavas (e.g., Larson et al. 1974; Stern 1979; Chow et al. 1980; Dixon and Stern 1983; Meijer and Reagan 1983; Stern and Bibee 1984; Woodhead and Fraser 1985; Bloomer 1987; Woodhead 1988; Lin et al. 1990; Jackson 1993; Stern et al. 1993). We take a different approach in this study and report for the first time on the compositions of trapped melt preserved as glass inclusions in phenocrysts of olivine and plagioclase from the Mariana arc lavas.

Microanalysis of glass inclusions in phenocrysts is a powerful tool for estimating the compositions of melts from which the host crystals grew (Roedder 1984). Where homogeneous and glassy, they preserve original melt compositions except for possible exchange with the host or post-entrapment growth of the host phase at the melt-host interface. Where post-entrapment modifications are absent or can be accounted for, this method to determine magmatic liquid compositions has obvious advantages over traditional approaches that depend on whole-rock compositions. Numerous studies have used this approach to determine magma compositions plus magmatic volatile contents, and to document magmatic processes (crystallization, magma mixing and degassing history, liquid immiscibility, etc.) for lavas and tephra from various tectonic settings (Anderson 1976; Watson 1976; Dungan and Rhodes 1978; Hibbard 1981; Harris and Anderson 1984; Nielsen and Dungan 1985; Dunbar et al. 1989; Halsor 1989; Sullivan 1991; Dunbar and Hervig 1992; Sobolev and Shimizu 1993; Sisson and Layne 1993; Kamenetsky et al. 1995; Vogel and Aines 1996). Interestingly, relatively few of these studies focus on the significance of glass inclusions in phenocrysts from lavas of intraoceanic arcs (e.g., Falloon and Green 1986; Jackson 1993).

This study builds on our earlier study of tephra glasses recovered from DSDP cores and inferred to be erupted from the Mariana arc (Lee et al. 1995). Those data demonstrated a much greater compositional range for Mariana arc melts, from basalt to rhyolite, than recognized from whole-rock analyses. No primitive glasses were found (maximum Mg# [$100Mg/(Mg + Fe^{2+})$] = 55), and more evolved tephra glasses defined a trend of monotonously decreasing FeO* throughout the entire range of silica contents. Lee et al. (1995) noted that mafic tephra are tholeiitic and inferred that Mariana arc high-alumina basalts reflect accumulated plagioclase phenocrysts and are not liquid compositions. These results are so different from conclusions based on whole-rock analyses that independent confirmation was sought via study of glass inclusions. We report here major element compositions of glass inclusions and selected host olivine and plagioclase grains along with new major element analyses for host lavas. This is the first time such a study has been carried out on samples of the active IBM arc. We use these data to evaluate three important questions. The first is whether high-alumina lavas of the Mariana arc approximate melts or are mixtures of melt and accumulative plagioclase, as suggested by earlier studies (e.g., Crawford et al. 1987; Woodhead 1988; Jackson 1993; Lee et al. 1995). The second question concerns the discrepancy between abundant felsic tephra and rare felsic Mariana arc lava: can we identify cryptic felsic components in other magmatic components of the active Mariana arc? This is related to questions about the significance of bimodal silica distributions observed in DSDP tephra glasses (Lee et al. 1995). The third question concerns why primitive melts or magmas are rarely recognized from the Mariana arc: can we find evidence of primitive melts in glass inclusions? Finally, we use our data to evaluate the extent of magma mixing in Mariana arc magmas.

Geologic Setting and Sample Descriptions

Samples come predominantly from volcanoes of the active Mariana arc, although one sample is from Nishinoshima in the Bonin arc (figure 1). The geologic history, tectonic setting, and petrology/geochemistry of the Mariana arc have been discussed by numerous workers (e.g., Stern and Bloomer 1992; Meijer 1982; Dixon and Stern 1983; Bloomer et al. 1989*a*, 1989*b*.) Samples with suitable glass inclusions were identified by examining more than 400 thin sections of Mariana arc lavas from both islands and seamounts. Only one sample is from a subaerial volcano (Guguan, G4). Other samples were recovered by dredging during a 1985 expedition aboard the R/V T.G. Thompson (TT192) and are mainly from lava flows, sometimes pillowed, but a few were from minor volcaniclastic and scoriaceous material. The lavas studied for this report are all fresh, showing little or no alteration in thin section (except D20-12, which is slightly altered although its glass inclusions are unaffected and

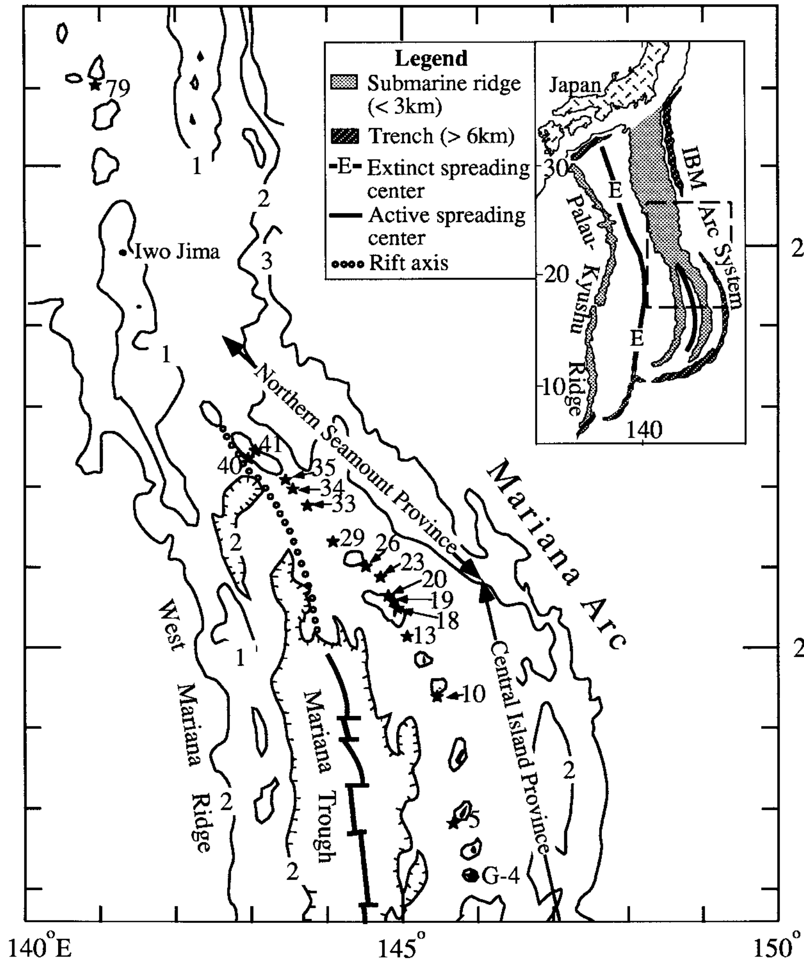


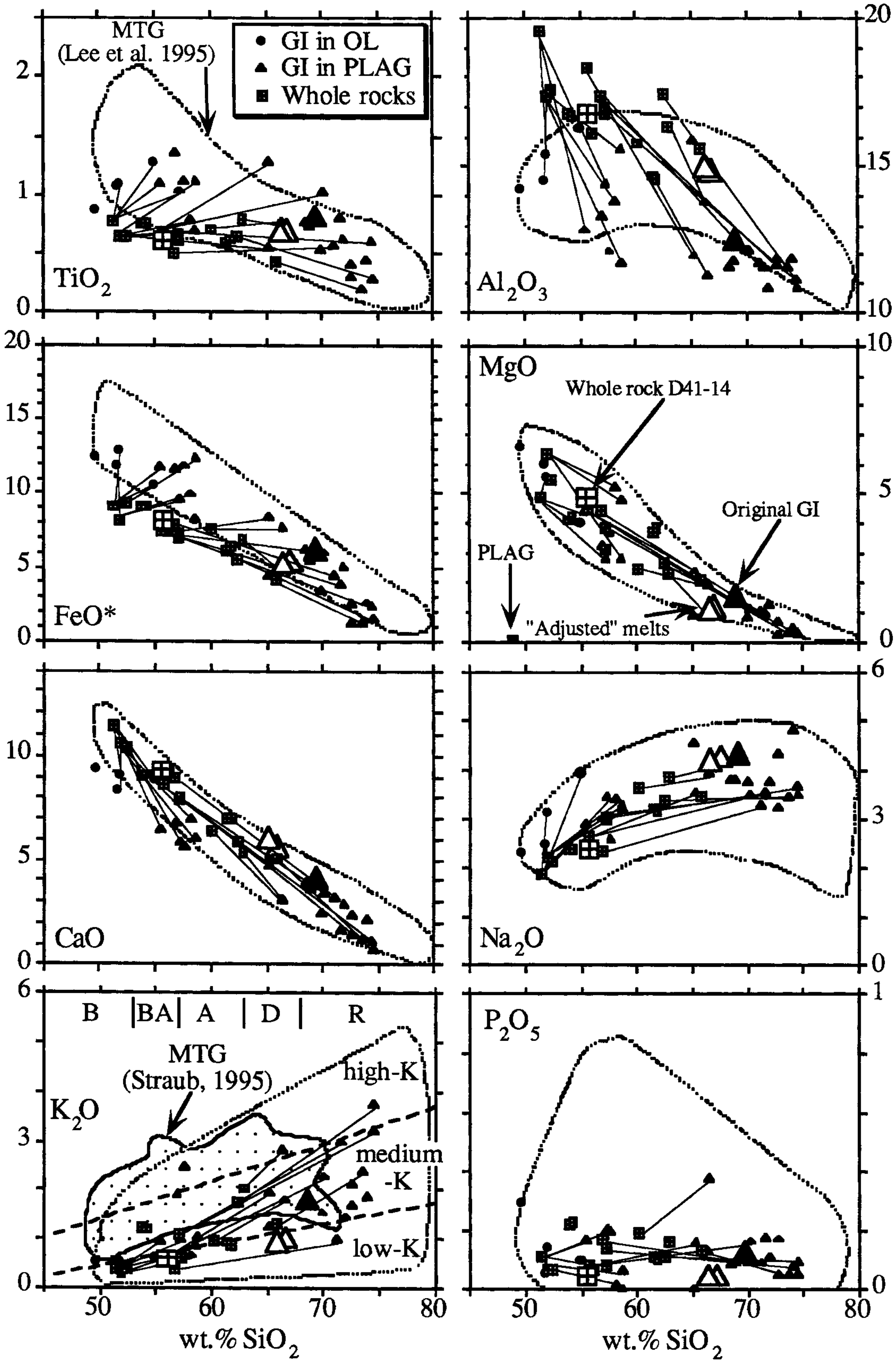
Figure 1. The generalized tectonic setting of the Mariana arc system and sample localities (stars). The position of the sample locality map in the Izu-Bonin-Mariana (IBM) arc system is shown as a dashed box in the inset map. Bathymetry is shown in 1000s of fathoms (≈1800 m; modified from Bloomer et al. 1989).

therefore used for this study) and are mainly plagioclase-clinopyroxene-olivine-magnetite ± hornblende ± orthopyroxene porphyritic, with plagioclase the dominant phenocryst phase (up to 30 modal %; Bloomer et al. 1989*a*, 1989*b*). These lavas range from 51% to 66% SiO_2 and define a low- to medium-K suite (figure 2). They belong to the subalkaline series and have transitional characteristics between tholeiitic and calc-alkaline suites (figure 3). Samples of the alkaline volcanic province in the northernmost Mariana and southern Volcano arc were specifically avoided.

Occurrence of Glass Inclusions

Olivine- and plagioclase-hosted glass inclusions are the focus of this study, although glass inclusions were also observed in pyroxenes. This is because it is relatively simple to adjust olivine-hosted inclusion compositions for post-entrapment crystallization and to estimate the maximum growth of plagioclase on the inclusion wall by evaluating electron microprobe (EMP) compositional traverses across the two phases. Most of the inclusions are of primary origin based on criteria by Roedder (1984). Textural characteristics including shape, size, and presence of exsolved fluid phase are variable. The majority of glass inclusions are round or subround, although a minor proportion of irregularly shaped ones occur, especially in plagioclase. Glass inclusions are rare in olivines and only found in microphenocrysts (0.3–1.2 mm in length), with relatively low Mg# of 69 to 76; olivine phenocrysts and megacrysts with high Mg# (e.g., > 80) are free of glass inclusions. Glass inclusions are common in plagioclase regardless of size, composition, and zoning pattern, and usually contain an exsolved fluid bubble. They are not found, however, in the normally zoned and clean plagioclase megacrysts having highly anorthitic cores ($>An_{95}$) mantled with narrow rims of rapidly decreasing An contents, which are compositionally similar to the predominant glass inclusion-bearing plagioclases ($\sim An_{70\text{-}90}$). Plagioclase containing inclusions commonly show complicated zoning, with core-rim variations of more than 15 mole % An.

Mariana glass inclusions contrast significantly with those from Fuego, Guatemala (Anderson



MTG
(Lee et al. 1995)
GI in OL
GI in PLAG
Whole rocks
TiO2
Al2O3
FeO*
MgO
Whole rock D41-14
Original GI
PLAG
"Adjusted" melts
CaO
Na2O
B
BA
A
D
R
MTG
(Straub, 1995)
high-K
medium
-K
low-K
K2O
P2O5
wt.% SiO2
wt.% SiO2

1982; Rose et al. 1974), where olivine-hosted glass inclusions of similar silica contents have more MgO and less Al_2O_3 than inclusions in the calcic cores of plagioclase phenocrysts. This was interpreted to reflect resorption of the host. Mariana glass inclusion compositions have lower MgO and higher Al_2O_3 contents in olivine-hosted glass inclusions than in plagioclase-hosted ones with a similar silica range. This suggests that the Mariana melt inclusions did not experience significant resorption of the host crystal prior to quenching.

Analytical Techniques

Major element whole-rock compositions for 11 samples reported in data table 1A (available, with tables 2A–4A, from *The Journal of Geology* free of charge upon request) were determined by X-ray fluorescence at XRAL Laboratories, Toronto, Canada. Glass and mineral analyses were accomplished with the fully automated, five-spectrometer JEOL JXA-8600 electron microprobe (EMP) at the University of Texas at Dallas. For glass inclusions, we followed the same analytical methods and data reduction for EMP described by Lee et al. (1995): accelerating voltage = 15 kV, beam current = 5 nA, beam diameter = 10–15 μm. Rhyolitic (RLS 132) and basaltic (USNM 113498/1) glass standards were used for calibration. EMP data for glass inclusions of similar composition in an individual host mineral are reported as means, along with standard deviations. Compositions listed in table 4A are not recalculated to total 100%, because summation deficits may be due to magmatic water. We used beam conditions of 20nA, 1 μm for olivine and 10nA, 5 μm for plagioclase analyses. San Carlos olivine (Fo_{90}, USNM 111312/444) and labradorite (USNM 115900) were used to calibrate mineral analyses. For compositional traverses across the boundary between glass and host plagioclase, we used focused beam (~1 μm) with the same beam current as used for glass analyses. Replicate analyses of individual standards before and during each analytical session agree within analytical precision with the reported compositions of standards.

Evaluating Post-entrapment Modification of Trapped Melts

Olivine. We assume for this study that host crystals were in equilibrium with an ambient magmatic liquid in a cooling magma chamber or conduit, from which melts were trapped by growing crystals. We assume that such inclusions may not preserve this original composition because of continued crystallization of host phase or re-equilibration with the host after entrapment (Watson 1976; Dungan and Rhodes 1978; Roedder 1984). The importance of such processes may be shown by the depletion or enrichment of specific elements in the glass inclusion. For example, host olivine-glass inclusion pairs in the Mariana arc lavas yield apparent K_Ds for Fe-Mg partitioning [$K_D = (Fe_{ol}/Mg_{ol})/(Fe_{liq}/Mg_{liq})$] ranging from 0.14 to 0.20, with an average of 0.17. Compared with a K_D of 0.30 determined experimentally for coexisting olivine and melt (Roeder and Emslie 1970), these figures indicate significant post-entrapment crystallization of olivine by trapped melt.

Meaningful interpretation of glass inclusion compositional data requires evaluation of the extent to which trapped melts were modified after entrapment. These modifications potentially reflect three processes: (1) crystallization of host mineral on the inclusion wall; (2) formation of non-host crystallites; and (3) diffusion between host and glass inclusion. The effects of the last two processes can be minimized by selecting and analyzing

Figure 2. SiO_2 variation diagrams for glass inclusions (GI). Concentrations of all oxides are given in weight %. Olivine-hosted GI (GI in OL) compositions are adjusted for post-entrapment crystallization; plagioclase-hosted GI (GI in PLAG) compositions are as analyzed. Dotted field outlines compositions of Mariana tephra glasses (MTG) from Lee et al. (1995). Also shown in K_2O versus SiO_2 diagram is the composition of MTG analyzed by Straub (1995; stippled area). Dashed lines in K_2O versus SiO_2 diagram separate the fields for low-K, medium-K, and high-K rock series. Short vertical lines separate the fields of basalt (B), basaltic andesite (BA), andesite (A), dacite (D), and rhyolite (R) (Basaltic Volcanism Study Project 1981), extended for basaltic and rhyolitic glass compositions. Compositions of 17 whole rocks coexisting with GI are also shown (table 1, Bloomer et al. 1989; R. J. Stern, unpub. data 1996). Tie lines connect whole-rock and melt inclusion compositions from the same sample. Note that only limited number of pairs are connected by tie lines for clarity. Large symbols show estimation of the maximum amount of post-entrapment crystallization of plagioclase, using D41-14 as an example. D41-14 whole rock (large square with cross), related melt inclusions adjusted (large open triangles; melt 1 to the right, melt 2 to the left), the original glass inclusion (large solid triangle) and the host plagioclase (solid rectangle) were used to carry out a lever-rule calculation in the MgO-SiO_2 system, indicating a maximum of 10–15% post-entrapment crystallization of plagioclase, as discussed in the text.

Table 1. Representative Composition of Olivine- and Plagioclase-Hosted Glass Inclusions

	OL-hosted GI (adjusted)				PLAG-hosted GI (raw)			
	Fukujin	Supply	Guguan		Guguan	Supply	Uracas	Chamorro
	35M11-3	D13-3-3	G4-5		G4a	D13-3a	D19-3-15	D23-3
SiO_2	49.0	52.5	54.9		55.5	58.6	65.2	73.7
TiO_2	.71	1.05	1.27		1.10	.70	.55	.19
Al_2O_3	14.1	14.6	16.3		12.8	15.6	15.9	11.5
FeO^*	12.5	11.4	10.5		11.8	8.22	4.36	1.17
MgO	6.72	5.90	3.98		4.40	2.80	.89	.28
CaO	8.88	8.38	8.85		6.42	6.02	5.03	1.23
Na_2O	2.57	2.70	3.95		2.88	3.29	4.55	3.47
K_2O	.67	.37	.62		.94	.88	1.25	2.38
MnO	.16	.24	.24		.08	.13	.14	.11
P_2O_5	.29	.03	.09		.17	.00	.00	.05
Total	95.6	97.2	100.7		96.1	96.3	97.9	94.1
OL[a] Mg#	76.2	75.5	69.2	Ab[e]	12.0	10.7	26.8	46.8
OL added[b]	11.5	13.5	6.2	An[e]	87.9	89.2	72.9	52.3
Melt Mg#[c]	51.6	50.7	42.9	Or[e]	.1	.1	.3	.9
				Melt Mg#[d]	42.5	40.3	28.8	32.2

Note. Major elements in weight %.
[a] Host olivine.
[b] Wt % of post entrapment crystallization of host olivine.
[c,d] Mg# of adjusted OL- and raw PLAG-GI, respectively. For calculation of Mg#, $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.9$.
[e] Composition of host plagioclases in Mol %.

the interior of large and clean glass inclusions (Anderson 1982; Halsor 1989; Sullivan 1991). We use a 10–15 μm beam diameter for EMP analysis, so we consider glass inclusions >25 μm across to be large. Most of the glass inclusions from the Mariana arc are <50 μm across, but some are greater than 100 μm across. We adjusted the effects of post-entrapment olivine crystallization by adding 1% increments of olivine in successive equilibrium with the inclusion (using K_D of 0.30 (Roeder and Emslie 1970) for Fe-Mg partitioning between olivine and melt) back into the glass composition until equilibrium was obtained with the host (fractional addition adjustment; see also Sisson and Layne 1993).

Fractional addition of olivine under a fixed common magmatic fO_2 (QFM or NNO) yields an estimate of the maximum amount of host crystallization because this assumes that the fO_2 of the surrounding magma was transmitted through the phenocryst and was imposed on the inclusion as the inclusion experienced host-phase crystallization (open-system adjustment). Otherwise, crystallization of olivine would remove Fe^{2+}, but not Fe^{3+}, and the remaining melt would become progressively more oxidized. As a result, estimates of original melt composition following fractional addition will always give the lowest alumina for the adjusted composition. Another endmember calculation is a minimum limiting adjustment obtained by adding host olivine composition until the ferric-ferrous ratio of the inclusion has reached some magmatically relevant value under fO_2-closed system (closed-system adjustment). These calculations were made using Fe^{2+}-Mg K_D of 0.3, fO_2 calculated based on Kress and Carmichael (1991) at 1000 bars pressure, and temperature from the olivine-liquid geothermometer of Sisson and Grove (1993). Calculations were ended when the inclusion fO_2 was equivalent to that of the NNO buffer. The adjusted compositions are more aluminous than the fractional addition case, but are still much less aluminous than many Mariana arc lavas. The closed system adjusted compositions show a poorer match with the tephra glass than the open-system adjusted compositions on a MgO-SiO_2 diagram, but a better match on a CaO-SiO_2 diagram. Not surprisingly, nature probably operates between the fO_2-open and fO_2-closed cases. Results from fractional addition of olivine are presented in table 2A, and representative analyses in table 1, and indicate that the maximum degree of post-entrapment crystallization in olivine-hosted inclusions ranged from about 6 to 14%, with a mean of 10%.

Plagioclase. It is difficult to correct for post-entrapment modification of melts trapped in plagioclase because there is no ready procedure for assessing equilibrium between individual glass inclusion-host plagioclase pairs. The procedure outlined for olivine cannot be used, because K_D for Ca-Na exchange between melt and plagioclase depend strongly on pressure and melt water content (Sisson and Grove 1993). We adopted two independent, empirical approaches to evaluate post-entrapment modification of trapped melts. First, we assumed that the tephra glass data (Group I) of Lee et al. (1995) define major element trends for Mariana arc magmatic liquids, including trapped melts. Comparison of glass inclusion compositions with the tephra field allows a qualitative assessment of post-entrapment crystallization by comparing such elements as Al_2O_3, CaO, FeO*, TiO_2 and MgO between the tephra glass field and glass inclusions. Glass inclusion compositions largely correspond to the field of tephra glasses (figure 2) but suggest limited post-entrapment crystallization of plagioclase by slight depletion of Al_2O_3 and CaO and enrichment of TiO_2 in some glass inclusions. Concentrations of FeO* and MgO increase in the liquid as post-entrapment crystallization proceeds, but are similar between glass inclusions and tephra glasses, suggesting that post-entrapment crystallization of host plagioclase is not extensive. An example of this type of calculation for MgO is shown in figure 2, which indicates a maximum of 10–15% post-entrapment crystallization.

In the second attempt to constrain the maximum amount of post-entrapment crystallization, we carried out EMP compositional traverses across glass inclusion–plagioclase boundaries. The results show that inclusion and plagioclase compositions are homogeneous up to <1 μm on either side of sharp and vertically dipping contact surfaces, indicating that post-entrapment crystallization in plagioclase was relatively minor. We observed a few examples of diffuse compositional boundaries up to 10 μm wide, which we interpret to reflect a shallowly dipping contact being partly penetrated by the electron beam; therefore, only nearly vertical contact surfaces should be used to assess reasonable extent of post-entrapment crystallization of plagioclase. This consideration gives a maximum zone of post-entrapment crystallization of 1 μm for most Mariana plagioclase. Based on this, we estimated a maximum volume of 15% post-entrapment growth of the host mineral for a representative glass inclusion (D41-14-PL4-G1) by assuming a prismatic (30*30*50 μm) inclusion shape. We also estimate a maximum volume of 21%, assuming a spherical geometry and minimum radius (12.5 μm) of glass inclusions we studied. We take these results to indicate that no more than 21 vol % of plagioclase crystallized after entrapment and reiterate that these are maximum estimates. These volumes were converted to weight % with consideration of density difference between melt and host plagioclase (melt density of 2.44 g/cc was calculated following Bottinga and Weill [1970] and that of 2.66 g/cc host plagioclase was from Clark [1966]) and added back to the glass composition (table 3A). Even for the maximum estimate, SiO_2 content of the glass inclusion changes only slightly, 3 wt % or less, and the inclusion composition, adjusted or not, is distinctly more siliceous than the host lava (table 3A). Other whole rock–inclusion pairs (figure 2) show significant differences in SiO_2 ranging from 3 to 17 wt %, with an average of 10 wt %.

The relatively minor changes in silica values found for adjusted vs. analyzed glass inclusions in plagioclase show that the compositions of these inclusions were only slightly affected by post-crystallization modification and mostly reflect the composition of magmatic liquids when these were trapped. We are particularly impressed by the similarity between compositions of inclusions and tephra glass and the striking differences that these have with whole-rock compositions, especially regarding TiO_2, FeO*, and Al_2O_3.

Results

Compositions of olivine-hosted glass inclusions before and after adjusting for crystallization of host olivine are listed in table 2A. Compositions of plagioclase-hosted glass inclusions are listed in table 4A (note that most of the analyses listed in table 4A are mean compositions). The compositions of host olivine and selected plagioclase are tabulated in tables 2A and 4A respectively. The data plotted in figures 2, 3, 4, and 6 correspond to adjusted (closed-system fractional addition) compositions for olivine-hosted inclusions and unadjusted compositions for plagioclase-hosted inclusions. It should be noted that analyses of different glass inclusions in a single plagioclase commonly show a significant compositional range, whereas individual olivines usually contain glass inclusions of very similar composition.

Inspection of the variation diagrams (figure 2) reveals four important points. First, trends defined by glass inclusions are similar to fields defined by tephra glasses of Lee et al. (1995) and Straub (1995). TiO_2, FeO*, MgO and CaO negatively correlate with SiO_2, behaving as compatible components. Al_2O_3 concentration decreases slightly with SiO_2. K_2O and Na_2O behave incompatibly, increasing with silica contents. This trend may result from low-pressure olivine-pyroxene-plagioclase-magnetite fractionation, as previously concluded for Mar-

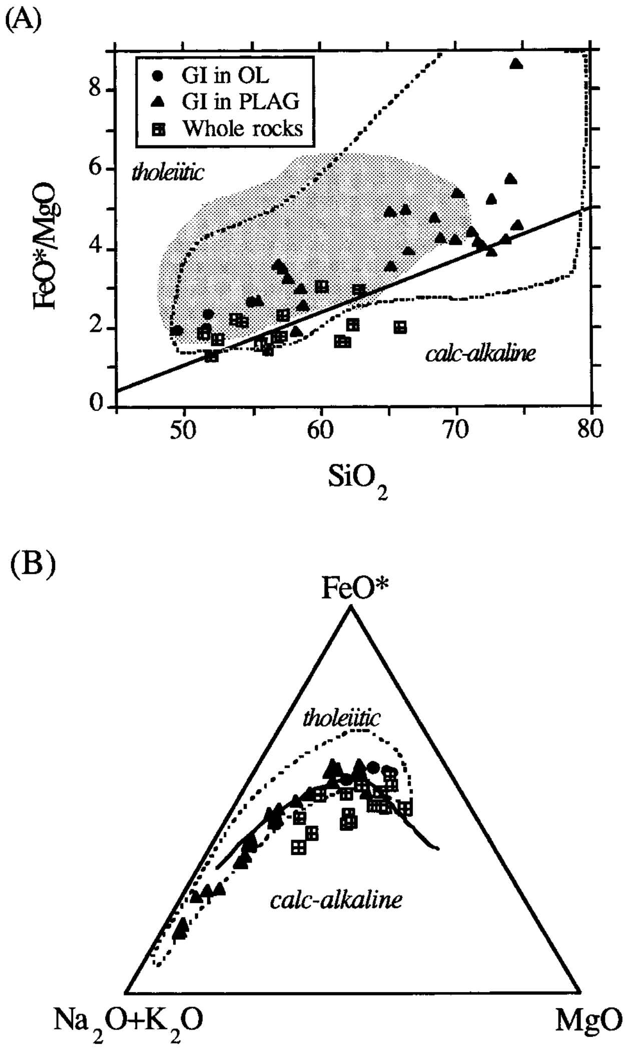


Figure 3. Plot of FeO*/MgO against SiO_2 (*A*) and AFM diagram (*B*) comparing tholeiitic versus calc-alkaline fractionation trend of glass inclusions, tephra glasses (dotted field from Lee et al. 1995; stippled field from Straub 1995), and lavas from the Mariana arc. The boundaries between tholeiitic and calc-alkaline fields in (*A*) and (*B*) are from Miyashiro (1974), and Irvine and Baragar (1971), respectively.

iana arc lavas (Stern 1979; Dixon and Batiza 1979; Woodhead 1988; Straub 1995). Second, the inclusion and tephra compositions are distinctively lower in Al_2O_3 CaO and higher in FeO* and TiO_2 than whole-rock compositions. For example, mafic glasses contain 10.5 to 13.6 wt % FeO* and 14.1 to 16.3 wt % Al_2O_3, whereas whole-rock samples have <10 wt % FeO* and typically 16 to 20 wt % Al_2O_3. The higher FeO* contents of mafic glass inclusions result in a distinctly tholeiitic trend of fractionation. In contrast, host lavas define a transitional tholeiitic to calc-alkaline trend (figure 3). Third, whereas olivine-hosted inclusions are broadly similar in composition to host lavas, plagioclase-hosted inclusions are typically much more felsic. Several of the plagioclase-hosted inclusions contain up to 17 wt % more SiO_2 than their host lavas; no more than about 3% of this difference is due to post-entrapment growth. These felsic inclusions are remarkably similar to the felsic mode of Mariana tephra glasses described by Lee et al. (1995). Finally, although the identification of primary magmatic liquids was an important motivation for this study, we did not find compositions that were in equilibrium with the mantle. The most primitive glass inclusions have an Mg# <52, far below the Mg# of 65 expected for primary mafic melts, indicating that extensive fractionation transpired before any melts were trapped.

Discussion

Magmatic Melts vs. Plagioclase Accumulative Lavas. At similar silica contents, glass inclusions have systematically lower Al_2O_3 and higher FeO* and TiO_2 contents than Mariana arc lavas, supporting the conclusion of Lee et al. (1995) that fundamental differences exist between tephra glasses and porphyritic Mariana arc lavas, and that the former more faithfully preserve melt compositions. These results were confirmed by an independent study of <400 ka tephra glasses (Straub 1995). Our adjusted analyses of olivine-hosted mafic glass inclusions are not high-alumina basalts. All basaltic glass inclusions plot in the tholeiitic field, whereas the host lavas plot in the high-alumina or calc-alkaline basalt field (figure 4). This reinforces the idea that many compositional features of Mariana arc lavas (moderate FeO*, high Al_2O_3) are due to accumulation of plagioclase phenocrysts, as previously suggested (Crawford et al. 1987; Woodhead 1988; Jackson 1993; Lee et al. 1995).

Based on the observation that plagioclase is denser than the average arc magma for reasonable oxidation states and water contents, Woodhead (1988) suggested that plagioclase sinks along with pyroxene and olivine, yielding cumulate gabbro as a result of crystal settling. However, Lee et al. (1995) argued that Mariana arc melts are sufficiently Fe-rich that plagioclase would either float or remain suspended due to even weak convection. Iron contents of glass inclusions are comparable to those of tephra glasses of Lee et al. (1995) (figure 2) and Straub (1995), supporting an hypothesis whereby the plagioclase-rich nature of Mariana arc lavas reflects accumulation of plagioclase in the upper parts of fractionated, Fe-rich magma chambers. Eruptions preferentially tap the upper parts of these

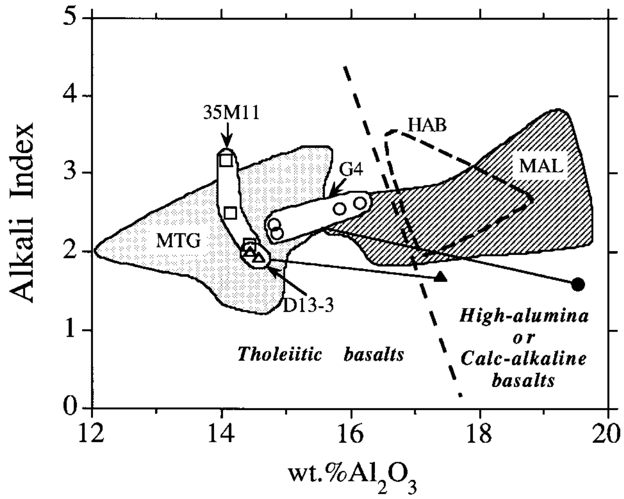


Figure 4. Tholeiite–high-Al basalt discriminant diagram (Middlemost 1975) for adjusted olivine-hosted glass inclusions (open symbols) and their host lavas (solid symbols), with connecting tie-lines. Note also fields for Mariana tephra glasses (MTG), Mariana arc lavas (MAL), and seven high-alumina basalts (HAB) of Kuno (1960, 1968). MTG data are from Lee et al. (1995). MAL represent a compilation of 91 major element analyses from Larson et al. (1974), Dixon and Batiza (1979), Stern (1979), Meijer and Reagan (1981), Banks et al. (1984), and Hole et al. (1984). Sample 35M11 (gabbroic cumulate) is shown for glass inclusion compositions only. The compositions of high-alumina basalts as originally defined by Kuno (1960) lie in the high-alumina or calc-alkaline basalt fields on this diagram, along with most Mariana arc lavas. Most olivine-hosted glass inclusions from this study plot in the tholeiite field of Kuno's Al_2O_3 vs. $Na_2O + K_2O$ diagram (not shown). Alkali index $\{= (Na_2O + K_2O)/[(SiO_2 - 43)*0.17]\}$ and the boundary between tholeiitic and high-alumina or calc-alkaline basalts are from Middlemost (1975).

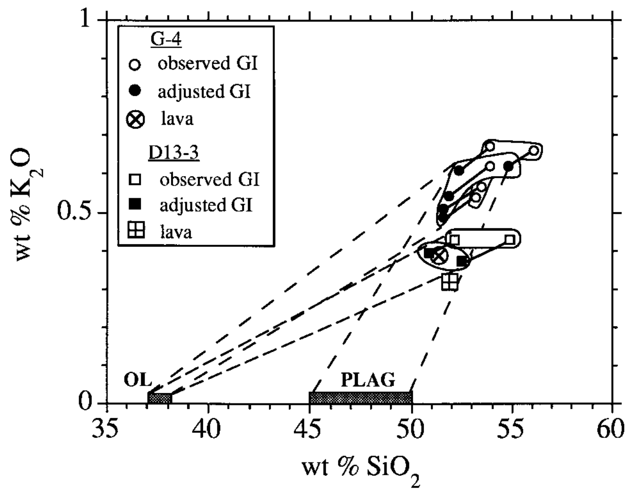


Figure 5. Plot of weight % K_2O vs. SiO_2 for glass inclusions in olivines and their host lavas. Bars labeled OL and PLAG represent analyses of selected olivine and plagioclase. Dotted lines connect glass inclusions and mineral compositions. Corrected and observed (raw) data are connected by short tie lines. Lava compositions do not correspond to corrected glass compositions but are displaced toward plagioclase, showing the effects of plagioclase accumulation.

magma chambers, so that lavas deviate from liquid lines of descent in the direction of plagioclase accumulation. This effect is responsible for the striking differences in Fe, Ti, and Al concentrations between Mariana arc lavas and glass inclusions. Thus, glass inclusions or tephra glasses are more reliable indicators of mafic melt compositions. The effect of plagioclase accumulation on bulk rock compositions is shown on a K_2O vs. SiO_2 diagram (figure 5), in which the bulk rock compositions of the lavas do not correspond with olivine-hosted melt compositions but plot between compositions of glass inclusions and host plagioclase. A simple lever rule calculation indicates an excess plagioclase accumulation of 16–40% for these samples.

High-alumina basalt could be restricted to magmatic arc environments not because of specific source characteristics, but because of unique thermal regimes that provide appropriate conditions of magmatic convective velocities, leading to mineralogic sorting and favoring plagioclase retention in lavas (Brophy 1989*a*, 1989*b*). Nonetheless, ocean-floor environments contain some examples of high-alumina basalts resulting from plagioclase accumulation (e.g., Bryan 1983). These are exceptions to the more general result that modal proportions observed in mid-ocean tholeiites approximate variations obtained in low-pressure equilibrium crystallization experiments. This idea is supported by a strong positive correlation between the total amount of phenocrysts and the proportion of plagioclase in the phenocryst assemblages as a result of selective gravitational sorting (Bryan 1983).

Accumulation of plagioclase may be responsible for the high-alumina basalts of the Mariana arc and some basalts in mid-ocean tectonic settings. However, we admit that plagioclase accumulation is not the cause of all high-alumina lavas. High-alumina hydrous melts are documented as glass inclusions at Fuego, Guatemala, by Sisson and Layne (1993) and as intercumulus liquids in gabbroic cognate inclusions in the Lesser Antilles by Arculus and Wills (1980). More recently, Wagner et al. (1995) showed that evolved high-alumina basalts at Medicine Lake volcano contain a high-alumina melt phase, as well as containing accumulated plagioclase.

Felsic Melts in the Mariana Arc. Glass inclusion

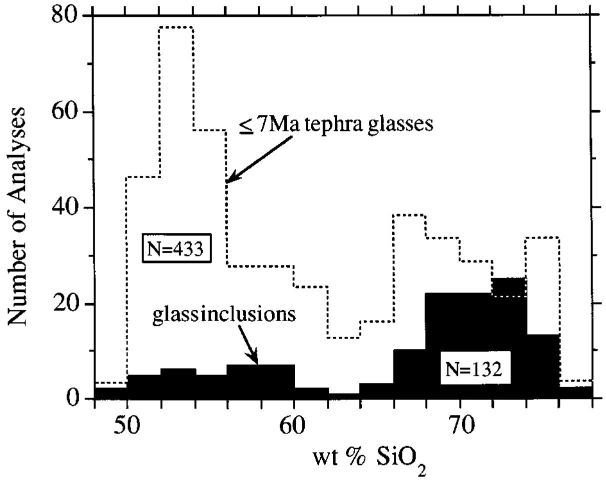


Figure 6. Frequency distribution of SiO_2 contents for all glass inclusion analyses (black). Also shown (dotted field) is the field for 0–7 Ma Mariana tephra glass (Lee et al. 1995).

compositions define a bimodal distribution of silica contents, with a pronounced minimum at 62–64 wt % SiO_2 (figures 2 and 6). This is similar to the bimodal distribution of silica contents observed for 0–7 Ma tephra glasses (Lee et al. 1995). The felsic mode of the glass inclusions defines a broad peak at about 68–76% SiO_2. The felsic mode is defined by many more inclusions than the mafic mode, reflecting the abundance of felsic glass inclusions in plagioclase and the relative abundance of plagioclase phenocrysts relative to olivine. Although the approximate position of felsic and mafic modes are similar, the relative importance of felsic vs. mafic modes in the glass inclusion data is just the opposite of the dominant mode defined by 0–7 Ma tephra glasses of Lee et al. (1995), where the mafic mode dominates. Apparently, different parts of the Mariana arc magmatic system are sampled by tephra (preferentially mafic) and glass inclusions (preferentially felsic). Nevertheless, the conclusion from both glass occurrences that Mariana arc magmas are characteristically bimodal seems inescapable and further confirms the idea that felsic melts are a ubiquitous if enigmatic component of the magmatic system.

It is noteworthy that plagioclase ranging from An_{45} to almost An_{80} contain glass inclusions with $>70\%$ SiO_2. This indicates that felsic melts are in equilibrium with a wide range of plagioclase compositions normally expected to be associated with mafic and intermediate melts, similar to the situation for Tongan low-K dacites (Ewart 1979). These results indicate that felsic magmas are common as cryptic components of Mariana arc magmatic systems, and that plagioclase growth commonly occurs where felsic melts reside.

Implications for Magmatic Evolution. Because Mariana arc lavas are commonly porphyritic, previous efforts to model melt evolution from chemical variations within lava suites are suspect. Glass inclusions provide a superior record of melt evolution. Adjusted compositions of olivine-hosted glass inclusions correspond to basalt and basaltic andesite, with SiO_2 contents between 49 and 55%, with an average of 51.5%. The most primitive inclusion was found in a pyroxene-rich gabbroic cumulate (35M11): 6.9 wt % MgO, Mg # = 52, and 49 wt % SiO_2. These results are similar to other efforts to identify the most primitive Mariana arc melts. For example, the most primitive tephra glasses of Straub (1995) have 6% MgO, whereas the most primitive tephra of Lee et al. (1995) have Mg# = 55. These melts are not in equilibrium with mantle peridotite and have experienced significant fractionation of Mg-rich minerals such as olivine and/or pyroxene. Glass inclusion and tephra glass arrays indicate that maximum FeO* and TiO_2 contents are found in the most mafic glasses (figure 2), indicating that Fe-rich phases such as magnetite or ilmenite did not begin to crystallize until fractionation proceeded to compositions corresponding to the most primitive glasses (Mg# ~ 50).

Because plagioclase fractionation is likely to produce a negative correlation between negative Eu anomaly and silica content, Woodhead (1988) suggested that basaltic andesites (~53% SiO_2) with no Eu anomalies most closely approximate the composition of Mariana arc parental magmas. More mafic lavas are produced by cumulus enrichment of gabbroic assemblage minerals, while fractionation produces more evolved lavas. This example, as well as our study, point out a lack of mantle-derived primary melts among Mariana arc lavas, although comparison of these two studies shows systematic differences in compositions, especially in FeO*, MgO, TiO_2, and Al_2O_3 contents (see Lee et al., 1995 for details). The evolved nature of the most primitive Mariana arc glasses indicates that mafic magmas do not reach the upper parts of magma chambers before extensive crystallization of olivine and/or pyroxene (Nicholls and Ringwood 1973), or that the magmatic evolutionary sequence tapped by both tephra and inclusions does not sample magma reservoirs when these are filled with primitive material. Because we cannot evaluate the second possibility, we turn our attention to the first alternative, that is, primary magmas do not reach the upper portions of the Mariana arc magmatic plumbing system.

It is not obvious why primary magma cannot be identified in the tephra or inclusion data sets. Primitive melts (glasses with Mg# >65) are abundant in some localities in the Mariana arc, such as at "cross-chain" volcanoes such as Kasuga 2 and 3 (Stern et al. 1993) and from the back-arc basin spreading ridge (Gribble et al. 1996), but are uncommon from along the arc magmatic axis. One possibility is that thickened arc crust behaves as a density filter (Cox 1980; Stolper and Walker 1980; Woodhead 1988), trapping high-density mafic melts to fractionate at the base of the crust. This argument is not attractive for Mariana arc magmas, because the bulk composition of intra-oceanic arcs is thought to be mafic (e.g., Pearcy et al. 1990); in this case, primitive melts should not be denser than the crust. However, recent geophysical experiments in the northern IBM arc lead to the interpretation of a mid-crustal felsic layer (Suyehiro et al. 1996), and this would provide an effective density filter. Regardless of whether or not Mariana arc crust acts as a density filter, Mg-rich primitive magmas have lower densities than the Fe-rich melts commonly found in tephra and inclusions, and it is a mystery why the former should not be sampled by tephra or glass inclusions if such material is present in Mariana arc magma chambers. It may be that primitive mafic melts undergo fractionation within separate and deeper magma chambers, or that the primitive magma resides deep within a compositionally zoned magma chamber. Neither of these alternatives is particularly attractive, the first because it is not obvious why multiple magma chambers should form and be maintained, the second because density stratification would favor the Fe-rich fractionated magma lying beneath Fe-poor primitive magma. Nevertheless, some sort of density stratification is indicated, because of the bimodal nature of tephra and inclusions, evidence that high-density Fe-rich mafic melts coexist with low-density felsic melts, and the observation that plagioclase is concentrated in the upper portions of the magma chamber.

Implications for Magma Mixing. Suggestions that magma mixing is important for controlling melt evolution in the Mariana arc have been made in recent years (e.g., Jackson 1993; Straub 1995). More than half of the samples studied here show evidence for magma mixing. Such evidence includes: mafic inclusions in more evolved host lavas, disequilibrium phenocryst assemblages, and disequilibrium textures in plagioclase such as resorption and complex zoning. Mafic inclusions are common in many of the more evolved lavas. These typically

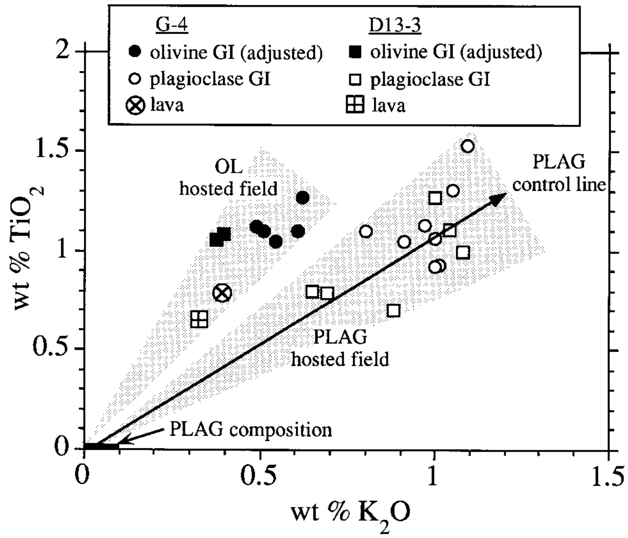


Figure 7. Plot of incompatible components TiO_2 versus K_2O for samples with glass inclusions in coexisting olivine and plagioclase, compared with whole-rock compositions. Stippled fields encompass the two groups of glass inclusions. Compositions of representative plagioclase hosts are indicated by a thick solid bar. Note that post-entrapment crystallization of plagioclase-hosted melts (PLAG control line) cannot account for differences in Ti-K relationships in olivine and plagioclase-hosted glass inclusions from the same sample.

include elongate or acicular mafic minerals, indicating rapid crystal growth, and are composed mainly of pyroxene and plagioclase with a vesicular glassy matrix. Mafic inclusions commonly have a chilled margin of clean glass. Such mafic inclusions are produced by the rapid cooling of hot mafic melt in contact with cooler felsic magma (Heiken and Eichelberger 1980; Eichelberger 1980; Sakuyama 1984; Bacon and Metz 1984; Koyaguchi 1986).

In addition to the microscopic characteristics of magma mixing described above, glass inclusion data support the general hypothesis that magma mixing is important for Mariana arc melt evolution. For example, at a given TiO_2 content, glass inclusions in plagioclase contain about twice as much K_2O as olivine-hosted inclusions from the same sample (figure 7). Because both K and Ti are effectively excluded from both olivine and calcic plagioclase, any post-entrapment crystallization of the host minerals will cause both elements to increase in the residual melt along a vector that is directly away from host mineral compositions. Examination of figure 7 indicates that, regardless of post-entrapment crystallization, plagioclase-hosted inclusions are compositionally distinct from olivine-hosted inclusions. This requires that olivine and plagioclase were in equilibrium with distinct and different melts, and that these crystals were mixed together after entrapment of melt inclusions.

Conclusions

Major element compositions of glass inclusions in olivine and plagioclase from Mariana arc lavas confirm inferences based on studies of tephra glass that porphyritic mafic lavas do not represent magmatic liquids. Our data further indicate that selective accumulation of plagioclase crystals and magma mixing are the causes of this difference. Mafic Mariana arc liquids correspond to normal tholeiites, not high-alumina basalts, and are invariably fractionated. Glass inclusion data confirm the tephra-based observation that the most primitive arc glasses are evolved Fe-rich mafic melts with Mg# of 52 and 49% SiO_2. Not all Mariana arc magmatic liquids are mafic: glass inclusions define a bimodal population in terms of silica. Abundant felsic glass inclusions in plagioclase indicate that high-silica melts are common in Mariana arc magmatic systems even though felsic lavas are rarely reported.

Our data provide compelling evidence for plagioclase accumulation in lavas and for mixing between coexisting felsic and Fe-rich mafic melts. Because of the high density of Fe-rich melts, this increases the likelihood of plagioclase floatation or suspension in Mariana arc magmatic systems. Furthermore, the abundance of felsic and subordinate mafic glass inclusions in plagioclase indicates that entrapment occurred near a magmatic interface between Fe-rich mafic and felsic melts. These constraints can be satisfied by calling on the development of shallow, zoned magma chambers, where Fe-rich melt is overlain by felsic melt. This would allow for preferential accumulation of plagioclase near the interface between these two liquids, where eruptions would readily yield hybrid and porphyritic lavas. We envision these relationships as shown in figure 8.

Our results indicate that Mariana arc magmatic evolution needs to be critically re-evaluated. Specifically the paradigm based on lava compositions, that fractional crystallization is responsible for the bulk of the compositional variation, is untenable. It is clear that inferences about magmatic evolution based on the composition of porphyritic arc lavas should be viewed with suspicion and be must be complemented by studies of melt proxies such as tephra glasses or glass inclusions if they are to be credible.

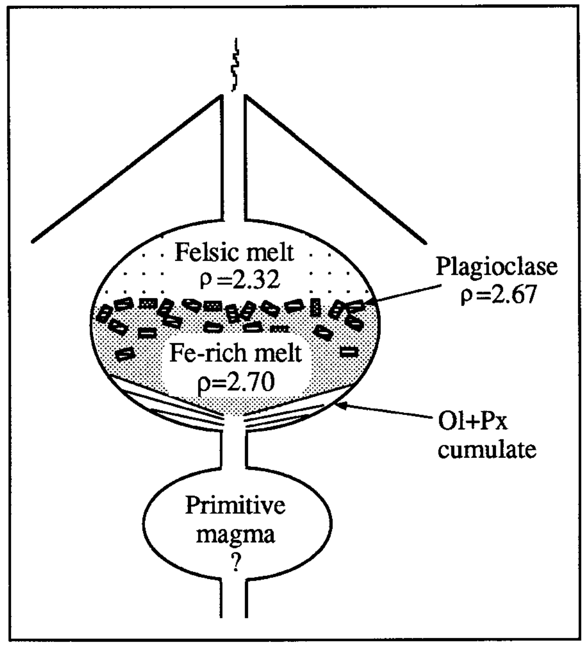


Figure 8. Schematic diagram showing shallow-level magmatic evolution in the Mariana arc leading to the formation of plagioclase-porphyritic lavas. Primitive mantle-derived melts from a deeper magma chamber periodically replenish the upper-level magma chamber and are not trapped by minerals entrained in lavas. The upper-level magma chamber is strongly zoned, with a lower Fe-rich melt fractionating to produce wherlitic cumulates at the base, overlain by a felsic layer. Mafic minerals typically sink in the Fe-rich magma, whereas plagioclase crystals accumulate along a zone of neutral buoyancy between the Fe-rich mafic and felsic melt zones. Floating plagioclase encounters cooler felsic reservoir at the interface, trapping felsic melts as a result of rapid growth. This explains occurence of predominantly felsic and minor mafic glass inclusions in plagioclase crystals. Tapping of zoned magma chambers should give rise to early explosive felsic eruption, followed by effusive mafic eruptions laden heavily with admixed plagioclase phenocrysts. This zoned reservoir model might explain the bimodal silica distribution observed for tephra glasses (Lee et al. 1995) and glass inclusions (this study) in the Marianas. Density for most mafic and most felsic glasses was calculated using the molar volume data of Bottinga and Weill (1970).

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