Earth, Planets and Space
a SpringerOpen Journal

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Polybaric crystallization differentiation of H_2O-saturated island arc low-K tholeiite magmas: a case study of the Izu-Oshima volcano in the Izu arc

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Abstract

Island arc low-K tholeiites are basaltic magmas erupting from frontal arc volcanoes of juvenile arcs associated with the subduction of old and cold plates. We investigated the origins of geochemical variation in volcanic rocks having multiple phase saturated liquid compositions from the Izu-Oshima volcano in the northern Izu arc. The geochemical variations in the liquids fall between two endmember trends, namely higher- and lower-Al/Si trends. Polybaric differentiation of H_2O-saturated melts between a 4-km-deep magma chamber and degassed melts near the surface should be responsible for the observed variation in the liquids.

Keywords: Island arc low-K tholeiite; Volcanic front; Ca-rich plagioclase; Experimental petrology; Izu-Oshima volcano

Background

With a worldwide average of 3 to 5 wt.% H_2O, island arc magmas are characterized by higher volatile concentrations than magmas erupting from other tectonic settings with <1 wt.% H_2O (e.g., Stern 2002; Plank et al. 2013). At generally ≥90 mol%, H_2O is the most abundant volatile component dissolved in island arc magmas (Shinohara 2008), with the occasional exception of CO_2-rich magmas (e.g., Sisson and Bronto 1998). The dissolved H_2O in melts contributes to the diverse geochemistry of island arc magmas, ranging from subalkaline (low-K, medium-K, and high-K series) to alkaline magma series (Kuno 1960; Kuno 1966; Miyashiro 1974; Tatsumi and Eggins 1995). In most cases, the alkalinity, or the K_2O content, of volcanic rocks increases across the arc away from the trench. Subalkaline magma series are represented in oceanic island arc settings, whereas high-K and alkaline magma series are more common in active continental margin tectonic settings. The spatial correlations between the geochemistry of these magma series and geophysical perspectives on magma generation have been discussed since being first reported by Kuno (1966) and Sugimura (1967), respectively.

Among the island arc magmas, low-K series rocks, known as island arc low-K tholeiite magmas, are infrequently found. This rock series occurs only in frontal arc volcanoes associated with the subduction of old and cold plates and/or early stages of arc volcanism (e.g., Ishizuka et al. 2006). Examples of such arcs include the Izu-Bonin-Mariana, northeastern Japan, Kurile, and Tonga-Kermadec, South Sandwich, Lesser Antilles, and Bismarck arcs. The geochemical features of island arc low-K tholeiites include lower concentrations of TiO_2, NiO, and Cr_2O_3 and higher concentrations of K_2O, Rb, Ba, Cs, Pb, and Sr than those in mid-ocean ridge basalts (MORBs) (e.g., Jakeš and White 1972; Masuda and Aoki 1978; Perfit et al. 1980). In addition, island arc low-K tholeiites are more radiogenic than MORBs (Jakeš and Gill 1970).

Although most arc magmas exhibit calc-alkaline differentiation trends (e.g., Gill 1981), island arc low-K tholeiites are characterized by a tholeiitic differentiation trend marked by Fe enrichment in the early stages of differentiation. This tholeiitic differentiation trend has been reproduced in melting experiments with anhydrous basalts at 0.1 MPa and on low-H_2O (≤2 wt.%) basalts at low pressure (≤200 MPa; e.g., Grove and Baker 1984; Hamada and Fujii 2008; Tatsumi and Suzuki 2009; Zimmer et al. 2010), which is consistent with the low

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H_2O (≤2 wt.%) recorded in melt inclusions (e.g., Kazahaya et al. 1994; Saito et al. 2005).

The H_2O concentration of island arc low-K tholeiites has been debated during the last decade. For example, island arc low-K tholeiite is characterized by Ca-rich plagioclase (~An_{90}) as phenocrysts (e.g., Ishikawa 1951; Amma-Miyasaka and Nakagawa 2002). Crystallization of Ca-rich plagioclase requires hydrous basaltic melts with ≥3 wt.% dissolved H_2O (Sisson and Grove 1993; Takagi et al. 2005; Feig et al. 2006; Kuritani et al. 2014). Other compositional attributes such as Ca/Na and Al/Si ratios are also critical in crystallizing Ca-rich plagioclase from basaltic melts (Hamada and Fujii 2007). While some researchers have debated whether island arc low-K tholeiite magma is dry or wet, other researchers have stated that both dry and wet primary magmas can be generated beneath frontal arc volcanoes (Tamura et al. 2005; England and Katz 2010).

Methods

The concentration of dissolved H_2O in pre-eruptive basaltic melts, particularly that of primitive or primary melts, provides information on the pressure and temperature (P-T) conditions of their generation, differentiation pathways, and potential explosivity during eruption. However, a consensus with regard to the H_2O concentration of island arc low-K tholeiitic melts remains elusive. In this paper, we investigated the conditions of crystallization differentiation, particularly the dissolved H_2O concentration in melts by considering previously reported chemical compositions for volcanic rocks from the Izu-Oshima volcano, a frontal arc volcano in the northern Izu arc, along with the results of hydrous melting experiments on relevant magmas to evaluate the dissolved H_2O concentration in island arc low-K tholeiitic melts.

Geological overview of the Izu-Oshima volcano

The Izu-Oshima volcano is an active, frontal arc volcano located approximately 110 km SSW of Tokyo (34°44′ N, 139°24′ E) at the vent of the central scoria cone and has erupted low-K island arc tholeiite magmas throughout its history. The Izu-Oshima volcano includes three distinct stratigraphic units: the Senzu Group (>40,000 YBP), the pre-caldera Older Oshima Group (40,000 to 1,500 YBP), and the co- and post-caldera Younger Oshima Group (<1,500 YBP; Nakamura 1964; Isshiki 1984; Kawanabe 1991). During the past 1,500 years, the Younger Oshima Group has experienced 12 major eruptions with a total volume of erupted magma of >0.6 km^3 dense rock equivalent (DRE; Nakamura 1964). Each eruption begins with scoria and ash falls, which are followed by lava flows. The most voluminous eruption occurred in 1777 with the emergence of the central cone of 1 km wide and 200 m high. The latest eruptions occurred in 1986 to 1987 and consisted of summit eruptions and fissure eruptions from two vents. The volume of eruptive products from the summit was 1.8×10^{-2} km^3 DRE and that from the fissure vents was 3.4×10^{-2} km^3 DRE (Endo et al. 1988). Continued inflation of the volcanic edifice since the 1986 to 1987 eruptions (Onizawa et al. 2013) and detection of volcanic CO_2 gas in soil (Watanabe 2013) suggest that the magma accumulation rate beneath the Izu-Oshima volcano has recently accelerated as has the potential for eruptions in the near future.

Geochemistry of erupted rocks from the Izu-Oshima volcano

Aphyric lava flows with <5 vol.% phenocrysts and porphyritic lava flows with up to 20 vol.% plagioclase phenocrysts are scattered in drilling core samples from the Izu-Oshima volcano (Fujii et al. 1996; Okayama 2005). The apparent volume ratio of aphyric versus porphyritic lavas is approximately 1:1 in the drilling core samples of the Older Oshima Group (Fujii et al. 1996). During the post-caldera stage (the Younger Oshima Group), porphyritic lavas with accumulated plagioclase phenocrysts erupted at the early stage of each summit eruption and were followed by eruptions of aphyric lavas (Nakano and Yamamoto 1991). These observations suggest that plagioclase accumulated by floating in the basaltic melt during the dormant stage, which resulted in the formation of a porphyritic magma layer in the upper part of the magma chamber and its emission at the onset of each eruption (Aramaki and Fujii 1988).

It is evident that the whole-rock composition of such porphyritic rocks does not represent the liquid composition and therefore cannot be used to investigate the evolution of liquids beneath the Izu-Oshima volcano throughout its history. In the present study, we selected 68 volcanic rocks, including aphyric rocks and groundmasses of porphyritic rocks that exhibit multiple phase saturated liquid compositions representative of low-K series rocks from Fujii et al. (1996) and Okayama (2005) (Figure 1a and Additional file 1: Table S1). These rocks, referred to hereafter as 'liquids,' also define a tholeiitic series on FeO^*/MgO-SiO_2 (Figure 1b).

The MgO content of these liquids is ≤6 wt.% (Figure 2) and is not considered to be primitive because of the significant degree of crystallization differentiation (approximately 50 wt.%; Aramaki and Fujii 1988) that occurred in the magma chambers before eruption. Variations in K_2O (Figure 2a) and ratios of incompatible elements such as the K/Zr ratio (40-87; Figure 2b), are distinguished at a given MgO content, which suggests variations in processes in the source mantle. Two groups of magmas are identified by the K/Zr ratio. For the purposes of this study, we defined a lower-K subgroup, K/Zr < 60, and a higher-K subgroup, K/Zr ≥ 60 (Figure 2b). The observed variations

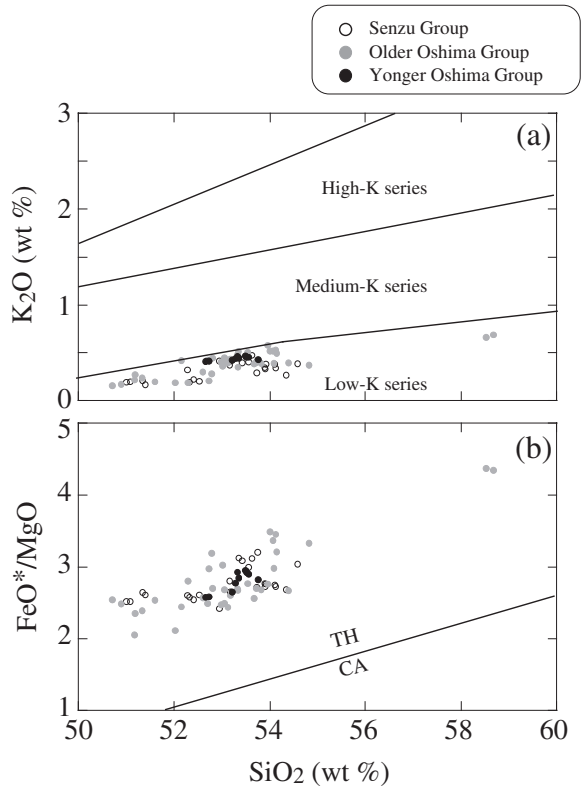

Figure 1 Classification of volcanic rocks from the Izu-Oshima volcano using discrimination diagrams. (a) K_2O versus SiO_2 (wt.%) variation diagram. Boundary lines dividing the high-, medium-, and low-K series are after Middlemost (1975), Peccerillo and Taylor (1976), and Gill (1981). **(b)** FeO*/MgO versus SiO_2 (wt.%) variation diagram to discriminate tholeiite (TH) versus calc-alkaline (CA) trends (Miyashiro 1974).

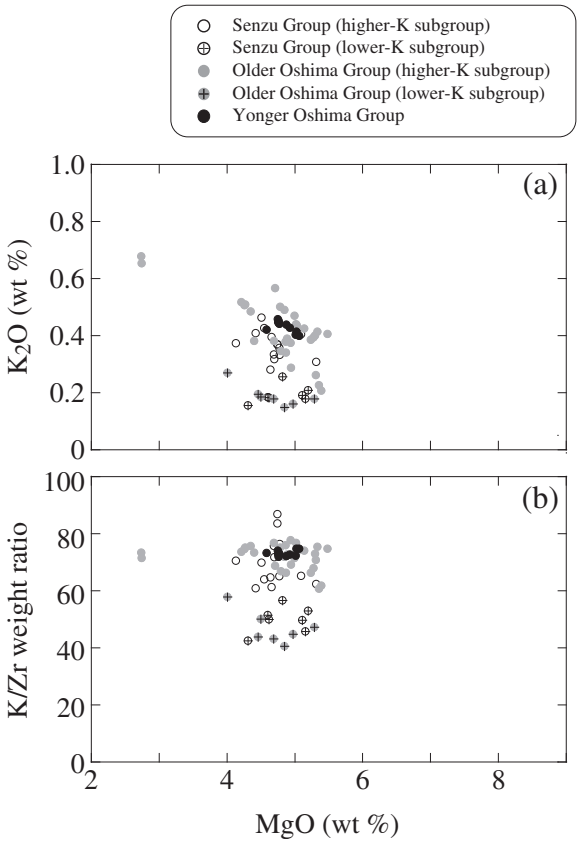

Figure 2 Geochemical variation of liquids of the Izu-Oshima volcano. (a) K_2O versus MgO (wt.%) variation diagram. **(b)** K/Zr versus MgO (wt.%) variation diagram for liquids of the Izu-Oshima volcano. Analytical errors are estimated to be within the symbols, approximately 0.5% relative standard deviation (RSD) for K_2O (wt.%) and approximately 1% RSD for K/Zr (e.g., Tani et al. 2002).

of liquids can be explained as mixtures of magmas derived from two different primary magmas (Okayama 2005). Although the liquids of the Senzu Group and the Older Oshima Group fall into both subgroups, all of the liquids of the Younger Oshima Group are categorized as belonging to the higher-K subgroup. The K_2O content of the lower-K subgroup liquids is nearly constant with decreasing MgO content (Figure 2a), which is an enigmatic geochemical feature that may not be related to crystallization differentiation. Below, we focus on the higher-K subgroup liquids to investigate the conditions of crystallization differentiation of magmas beneath the Izu-Oshima volcano.

The observed variations in selected major elements of the higher-K subgroup liquids, including SiO_2, Al_2O_3, FeO*, and CaO versus MgO as well as Al_2O_3/SiO_2 versus MgO (Figure 3), can be regarded as the results of crystallization differentiation from the higher-K primary magma. Similar to most island arcs elsewhere, liquids of the Izu-Oshima volcano, particularly those of the Senzu Group and Older Oshima Group, show broad geochemical variation ($3 \leq MgO \leq 7$ wt.%), which suggests repeated injection of undifferentiated magmas and extensive crystallization differentiation. Liquids of the Younger Oshima Group exhibit narrower geochemical variation ($4.5 \leq MgO \leq 5.5$ wt.%), which suggests a near steady-state mass balance between the cumulative volume of erupted rocksand the volume of magma injected into the magma chambers. Two endmember trends, referred to here as the higher-Al/Si trend and lower-Al/Si trend, are distinguished in Figure 3. The higher-Al/Si trend is depleted in SiO_2 and FeO* and enriched in Al_2O_3, Al_2O_3/SiO_2 ratio, and CaO at a given MgO compared with the lower-Al/Si trend. The Izu-Oshima liquids fall between the higher- and lower-Al/Si trends and thus may be mixtures of the two endmembers or may have been derived under intermediate conditions between those responsible for creating the two endmembers.

The most abundant phenocryst found in porphyritic volcanic rocks is plagioclase, usually 5 to 10 vol.% and sometimes up to 20 vol.%, followed by <1 vol.% of olivine, orthopyroxene, and clinopyroxene (augite and pigeonite).

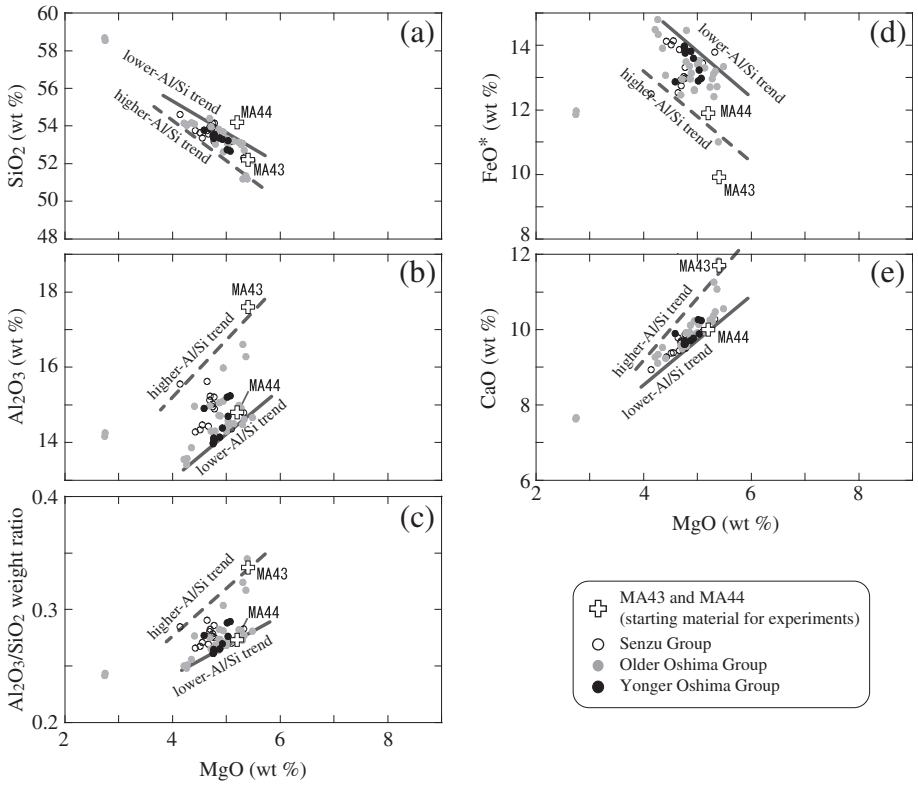

Figure 3 Major element versus MgO variations in higher-K subgroup liquids of Izu-Oshima volcano. (a) SiO_2. **(b)** Al_2O_3. **(c)** Al_2O_3/SiO_2 weight ratio. **(d)** FeO* (wt.%). **(e)** CaO (wt.%). Fe content is given as FeO* (total iron), and the composition is normalized to 100 wt.%. All of the geochemical data are listed in Additional file 1: Table S1.

Island arc low-K tholeiites are characterized by Ca-rich plagioclase phenocrysts (~An_{90}). Some of these crystals are nearly uniform in composition with slight oscillatory zoning in their cores (An_{90}-An_{91}; Figure 4a), whereas other plagioclase shows normal and reverse zonings (An_{87}-An_{85}-An_{92}; Figure 4b). The anorthite content in the plagioclase rims is An_{74} (Figure 4b), which is significantly lower than that its core regions ($An_{\geq 85}$), which suggests a final crystallization from degassed melts prior to eruption. The presence of Ca-rich plagioclase included by olivine (~Fo_{77}; Figure 4c) demonstrates that the plagioclase crystallized earlier than the Fo_{77} olivine. The Fo_{77} olivine is interpreted to have crystallized from differentiated melts with FeO*/MgO approximately 2.4 ± 0.2 by weight, assuming that the Fe^{2+}/Mg partition coefficient between the olivine and melt = 0.3 (Roeder and Emslie 1970) and Fe^{3+}/Fe_{total} of arc basaltic melts is equal to 0.18 to 0.32 (Kelley and Cottrell 2009).

Hydrous melting experiments on island arc low-K tholeiite magmas

Two series of hydrous melting experiments on island arc low-K tholeiites were conducted by Hamada and Fujii (2007, 2008). In their first series of experiments (Hamada and Fujii 2008), liquid lines of descent from high-Mg island arc tholeiite (IAT60, Additional file 2: Table S2) as a starting material were obtained with 0.7, 1.6, and 2.7 wt.% bulk H_2O at crustal pressure conditions of 200 to 700 MPa by using an internally heated pressure vessel and a piston-cylinder apparatus. The oxygen fugacity (f_{O_2}) during the experiment was approximately 1 log unit above the Ni-NiO buffer (NNO + 1). The purpose of this series of experiments was to clarify the combined effects of crustal pressure and dissolved H_2O in melts on the fractional crystallization of island arc low-K tholeiite magmas. The obtained liquid compositions are plotted in Figure 5 for comparison with the natural liquid compositions shown in Figure 3. It should be noted that because IAT60 (approximately 8 wt.% MgO) is richer in MgO than the liquids reported from the Izu-Oshima volcano (≤6 wt.% MgO), Figures 3 and 5 cannot be directly compared; nevertheless, the experimental results are helpful in understanding major element variations in natural liquids derived from a single primary magma.

The SiO_2 content of experimental liquids remained nearly constant (approximately 52 wt.%) with a decreasing MgO content under H_2O-poor conditions and at higher

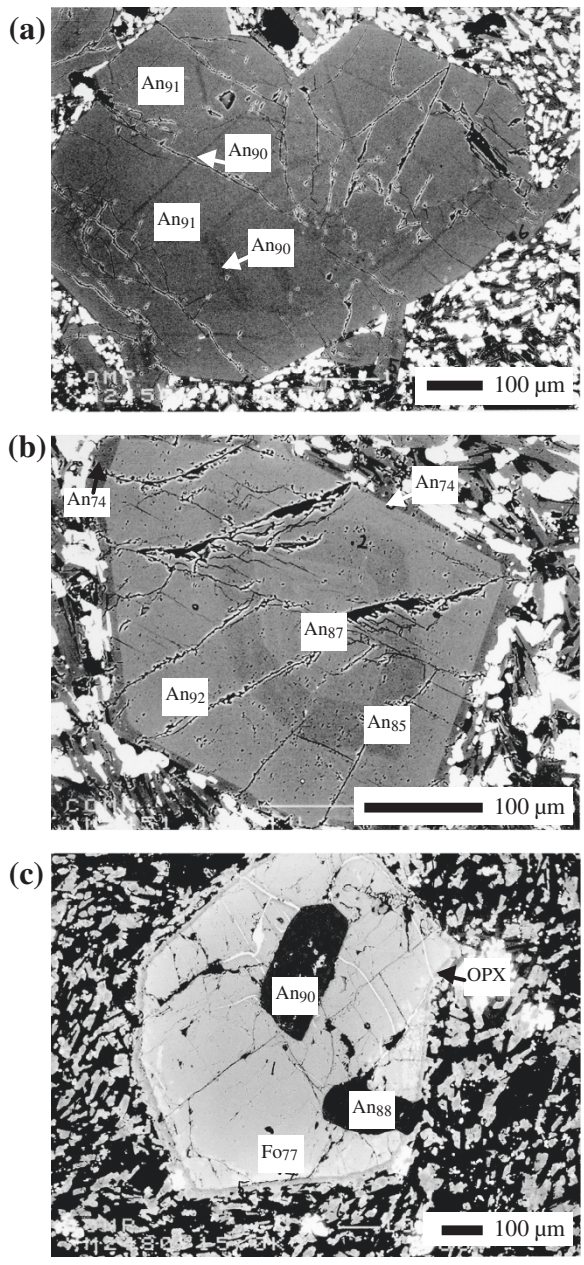

Figure 4 Backscattered electron images of representative phenocrysts. (a) Nearly homogeneous plagioclase with slight oscillatory zoning in its core (An_{90}-An_{91}). **(b)** Plagioclase with normal and reverse zoning. **(c)** Plagioclase included by olivine.

pressures, whereas it increased up to 56 wt.% under H_2O-rich conditions and at lower pressures (Figure 5a). The suppression of increased SiO_2 content was attributed to earlier crystallization of orthopyroxene (SiO_2 ~ 54 wt.%) at a higher pressure. The Al_2O_3 content and Al_2O_3/SiO_2 ratio steadily decreased under lower H_2O conditions due to earlier crystallization of plagioclase and initially increased before decreasing under higher H_2O conditions. These results occurred because the crystallization of plagioclase was delayed relative to that of mafic minerals (Figure 5b,c). In contrast, the FeO* content increased with 0.7 and 1.6 wt.% H_2O but decreased with 2.7 wt.% H_2O due to earlier crystallization of magnetite (Figure 5d). The CaO content of the experimental liquids was consistently lower than that of the natural liquids (Figure 5e). The CaO content of multiple phase saturated liquids was controlled by the ratio of normative high-Ca pyroxene to normative low-Ca pyroxene. The projection of the normative composition of the natural liquids from the plagioclase apex to the olivine-clinopyroxene-quartz pseudo-ternary diagram demonstrates that crystallization differentiation occurred at a pressure lower than 200 MPa (Figure 6).

Comparison of the geochemical variations in the liquids from the Izu-Oshima volcano (Figure 3) with those in the experimental results (Figure 5) suggests that the higher- and lower-Al/Si trends can be reproduced under more and less hydrous conditions, respectively. Figure 6 also demonstrates that the higher-Al/Si trend was derived at a higher pressure less than 200 MPa than the lower-Al/Si trend at a lower pressure.

An additional point to be considered is the origin of Ca-rich plagioclase phenocrysts in island arc low-K tholeiites. In their second series of experiments, Hamada and Fujii (2007) conducted hydrous melting experiments on two drilling core samples of volcanic rocks from the Izu-Oshima volcano, labeled as MA43 and MA44 (MgO approximately 5 wt.%; Additional file 2: Table S2), to constrain the origin of Ca-rich plagioclase. Synthesis of the hydrated glasses of MA43 and MA44 revealed that these two samples represent less differentiated liquid compositions on the higher- and lower-Al/Si trends, respectively (Figure 3). The experiments were conducted at 250 MPa using an internally heated pressure vessel. The bulk H_2O content ranged from 1 to 6 wt.%. Details of the procedures and techniques have been described by Hamada and Fujii (2007). In the melting experiments on MA43, plagioclase crystallized as the liquidus phase at all H_2O contents (≤6 wt.%) and the crystallization temperature of plagioclase was linearly suppressed with increasing bulk H_2O content (Figure 7a). The anorthite content of the plagioclase increased from ~ An_{80} under nearly anhydrous conditions to $An_{\geq 90}$ with $H_2O \geq 3$ wt.% (Figure 7b). In the melting experiments on MA44, plagioclase crystallized as the liquidus phase under low-H_2O (≤2 wt.%) conditions; however, augite replaced the plagioclase as the liquidus phase at $H_2O \geq 2$ wt.% in melts. Ca-poor plagioclase (~An_{75}), augite, and pigeonite co-crystallized as liquidus phases at approximately 1,150°C and with approximately 2 wt.% H_2O (Figure 7c). The anorthite content of the plagioclase increased from approximately An_{70} under nearly anhydrous conditions to An_{80} with approximately 4 wt.% H_2O (Figure 7d). Increases in anorthite content of plagioclase crystallized from the MA44 melt were

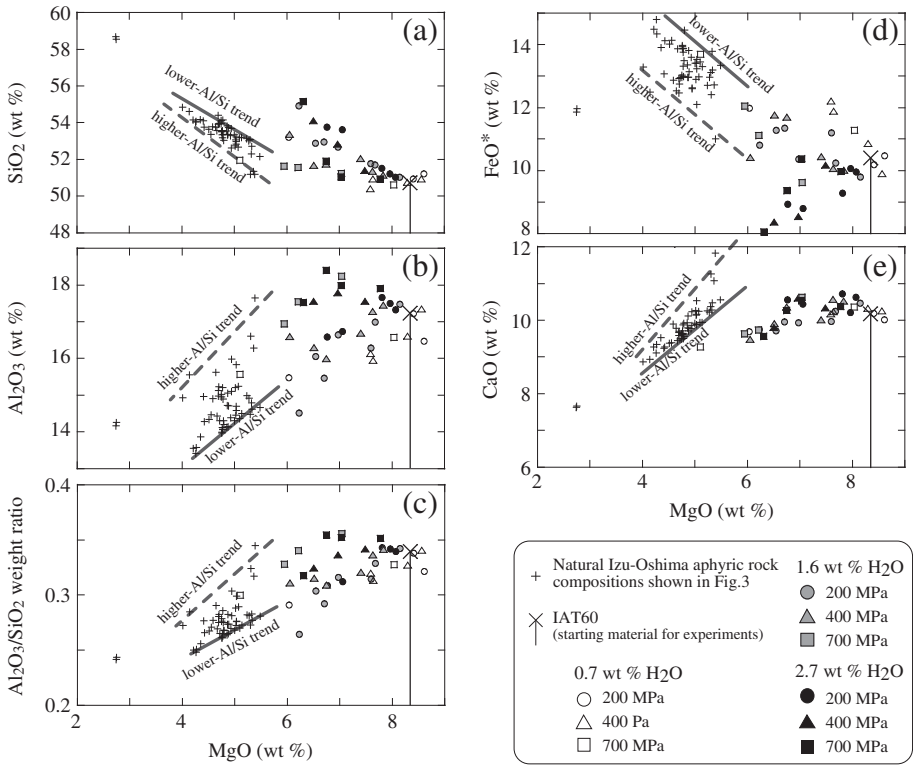

Figure 5 Major element versus MgO variation diagram of melt compositions. Major element versus MgO variation diagram of melt compositions obtained through hydrous melting experiments by Hamada and Fujii (2008). **(a)** SiO_2 (wt.%). **(b)** Al_2O_3 (wt.%). **(c)** Al_2O_3/SiO_2 weight ratio. **(d)** FeO* (wt.%). **(e)** CaO (wt.%). Liquid compositions obtained from the volcanic rocks from the Izu-Oshima volcano are also shown for comparison with experimental results. Fe content is given as FeO* (total iron), and the compositions of both natural volcanic rocks and experimental liquids are normalized to 100 wt.%.

suppressed compared with that crystallized from the MA43 melt (Figure 7b,d) because augite replaced the plagioclase as the liquidus phase with increasing bulk $H_2O \geq 2$ wt.% in the melting experiments on MA44 (Figure 7c). In short, Ca-rich plagioclase ($An_{\geq 90}$) can be crystallized from melts of the higher-Al/Si trend with ≥3 wt.% H_2O but cannot be crystallized from melts of the lower-Al/Si trend at any H_2O concentration. Ca-poor plagioclase rims (~An_{75}) cannot be crystallized from melts of the higher-Al/Si trend and are likely crystallized from the melts of the lower-Al/Si trend under H_2O-poor conditions.

Olivine, a minor but common mineral occurring in volcanic rocks from the Izu-Oshima volcano, was not crystallized from either MA43 or MA44 melts at 250 MPa or at 0.1 MPa (Hamada 2002). This result proves that the olivine was not actually in equilibrium with the MA43 and MA44 melts, which should be situated on the augite-pigeonite-plagioclase cotectic in the basalt tetrahedron rather than in the primary field of olivine. The olivine may have been crystallized from a less differentiated melts (MgO ≥ 6 wt.%; Ikehata et al. 2010) and incorporated into slightly differentiated magmas such as MA43 and MA44 (MgO approximately 5 wt.%).

Results and discussion

Implications for the origin of the lower-K subgroup liquids

Three types of magma have been identified in island arc low-K tholeiites from the Izu-Oshima volcano: (i) a lower-K subgroup, (ii) higher-Al/Si trend of a higher-K subgroup, and (iii) lower-Al/Si of a higher-K subgroup. The lower-K and higher-K subgroups exhibit distinct differences in their trends at a given MgO content (Figure 2), which indicates that the primary magmas of these two subgroups are different.

The trend observed for the lower-K subgroup with a nearly constant K_2O content and a decreasing MgO content or increasing SiO_2 content is enigmatic. The constant K_2O content may be explained by fractionation of amphibole (Davidson et al. 2013) because K is a compatible element of this mineral (Tiepolo et al. 2007). Amphibole can be crystallized from basaltic melts and basaltic andesite melts as a near-liquidus phase under

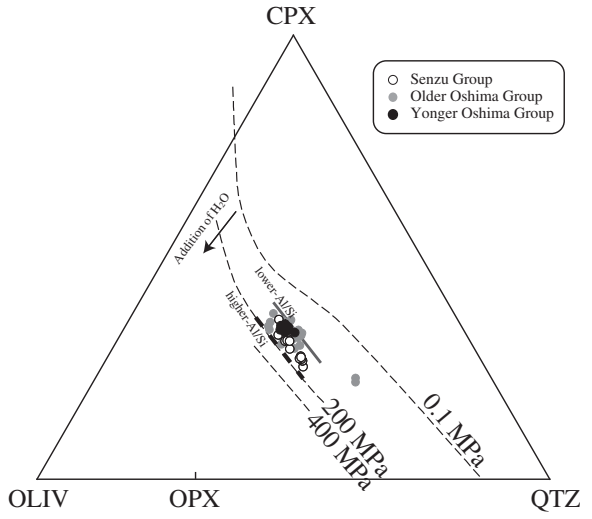

Figure 6 Projection of normative composition of liquids. Projection of normative composition of liquids (aphyric lavas and groundmasses of porphyritic lavas) on the pseudo-ternary diagram after the schemes of Tormey et al. (1987) and Grove (1993). The olivine-plagioclase-clinopyroxene cotectic at 0.1 MPa is from Walker et al. (1979); the olivine-plagioclase-clinopyroxene cotectic at 200 MPa is from Berndt et al. (2005); and the orthopyroxene-plagioclase-clinopyroxene cotectic at 400 MPa is from Hamada and Fujii (2008). The addition of H_2O expands the stability field of clinopyroxene at a given pressure, resulting in a shift in the cotectic curve toward the olivine apex.

high H_2O conditions (≥5 wt.%; Adam et al. 2007; Almeev et al. 2013) and from andesites under lower H_2O conditions (approximately 4 wt.%; Eggler and Burnham 1973), although no direct evidence exists to prove that crystallization of amphibole occurred beneath the Izu-Oshima volcano. Geochemical trends similar to those of the lower-K subgroup have been termed 'low SiO_2 group' at the Iwate volcano in the northeastern Japan arc (Nakagawa 1993), which suggests that this cryptic trend is actually a ubiquitous feature of island arc low-K tholeiite magmas.

Two endmember trends resulting from polybaric crystallization

Two endmember trends, the higher- and lower-Al/Si trends, were identified in the geochemical variation of liquids (Figure 3); all of the plotted liquid compositions can be explained either by the mixing of these two endmember trends or by differentiation at intermediate conditions between those responsible for the endmembers. The higher-Al/Si trend is characterized by suppressed enrichment of SiO_2 and FeO* and delayed decreases in Al_2O_3 and the Al_2O_3/SiO_2 ratio with decreasing MgO compared with those of the lower-Al/Si trend. Results of the hydrous melting experiments on IAT60, described in Section 'Hydrous melting experiments on island arc low-K tholeiite magmas', show that the two endmember trends were derived from crystallization differentiation under different H_2O conditions and at different depths. The higher-Al/Si trend can be explained by crystallization differentiation under more hydrous conditions and at higher pressures less than 200 MPa. The lower-Al/Si trend can be explained by less anhydrous conditions and at lower pressure.

Ca-rich plagioclase ($An_{\geq 90}$) can be crystallized from moderately hydrous melts of the higher-Al/Si trend with ≥3 wt.% H_2O but cannot be crystallized from melts of the lower-Al/Si trend at any H_2O concentration. In contrast, Ca-poor plagioclase rims (~An_{75}) cannot be crystallized from melts of the higher-Al/Si trend and were likely crystallized from the melts of the lower-Al/Si trend under H_2O-poor conditions (Figures 3 and 7). These experimental constraints, reported by Hamada and Fujii (2007), demonstrate that higher Al/Si ratio and H_2O content in melts are critical for crystallizing Ca-rich plagioclase.

The H_2O concentration can vary between liquids of higher- and lower-Al/Si trends, characterized by higher H_2O and higher pressure and by lower H_2O and lower pressure, respectively. Beneath the Izu-Oshima volcano, 4-km-deep magma chamber and 8-10-km-deep magma chamber were detected as seismic scatters (Mikada et al. 1997). This geophysical constraint is consistent with the estimated pressure at which multiple phase saturated liquids differentiate, which is less than 200 MPa or shallower than the 8-10-km-deep magma chamber, as determined by using the pseudo-ternary diagram as a geobarometer (Figure 6). Hamada et al. (Hamada et al. 2011; Hamada et al. 2013) demonstrated that the melts beneath the Izu-Oshima volcano dissolved >5 wt.% H_2O at the 8-10-km-deep magma chamber, which resulted in the interpretation that the H_2O concentration in the melts at depths shallower than the 8-10-km-deep magma chamber were controlled by the solubility of H_2O as a function of pressure. Using MA43 as an example and assuming 1,100°C, if pre-eruptive liquids dissolve approximately 3 wt.% H_2O, they become saturated with H_2O at pressures of 60 MPa (Papale et al. 2006). With upper crustal densities in the range of 2,200 kg m^{-3} for volcanic edifices to 2,600 kg m^{-3} for basement rocks and constraints of the seismic velocity structure in crust beneath the Izu-Oshima volcano (Onizawa et al. 2002), these pressures would equate to the onset of H_2O saturation at depths of approximately 3 km. Geochemical arguments developed herein suggest that the erupted liquids are final products of H_2O-saturated crystallization differentiation between the geophysically imaged 4-km-deep magma chamber and the surface.

Although differentiation processes in the 8-10-km-deep magma chamber are not clearly constrained by using

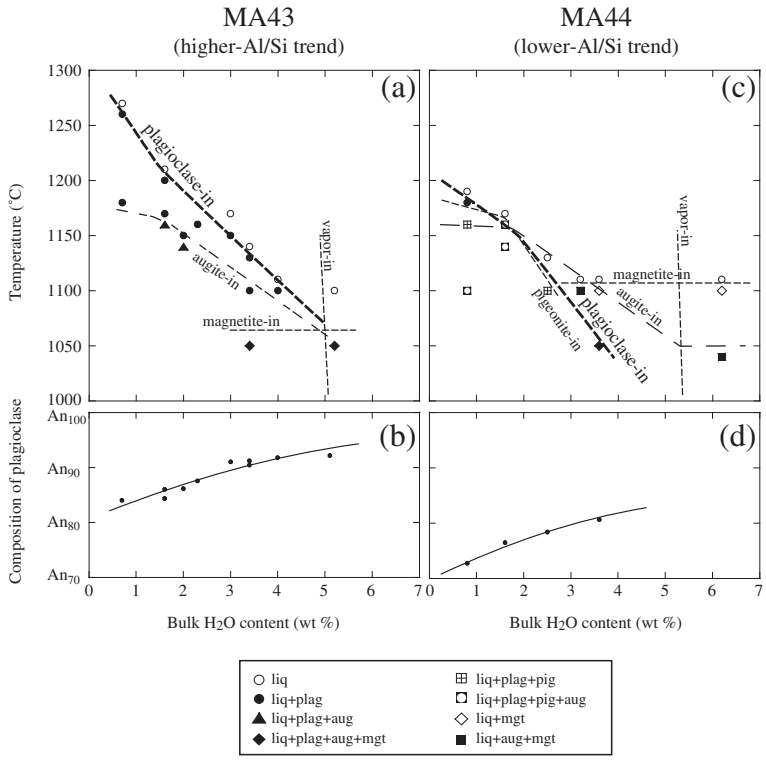

Figure 7 Phase diagrams for MA43 and MA44 and changes in composition of crystallized plagioclase. (a) Phase diagram for MA43 and **(b)** composition of plagioclase crystallized from MA43 melt at 250 MPa, plotted against bulk H_2O content (wt.%). **(c)** Phase diagram for MA44 and **(d)** composition of plagioclase crystallized from MA44 melt at 250 MPa, plotted against bulk H_2O content (wt.%). Data modified from Hamada and Fujii (2007).

the composition of liquids including aphyric lavas and groundmasses of porphyritic lavas, they may have yielded the non-primitive liquids ($6 \leq MgO \leq 8$ wt.%) detected in the olivine-hosted melt inclusions (Ikehata et al. 2010) and crystallized Ca-rich plagioclase (Hamada et al. 2011, 2013).

By definition, island arc low-K tholeiites are characterized by a tholeiitic differentiation trend. The origin of the tholeiitic versus calc-alkaline differentiation trend is essentially controlled by the H_2O concentration in melts. The tholeiitic differentiation trend can be reproduced under low H_2O (≤2 wt.%) conditions (e.g., Grove and Baker 1984; Hamada and Fujii 2008; Tatsumi and Suzuki 2009; Zimmer et al. 2010). Consistent with such conditions, the multiple phase saturation point for the MA44 was approximately 1,150°C and approximately 2 wt.% H_2O (Figure 7c), where Ca-poor plagioclase (An_{75}), augite, and pigeonite co-crystallize as liquidus phases; this temperature is also consistent with the estimated temperature of the basaltic magmas that erupted in 1986 based on pyroxene geothermometry (Fujii et al. 1988). The tholeiitic differentiation trend observed for the Izu-Oshima volcano may have been controlled by the lower-Al/Si trend, which was reproduced under low H_2O conditions (≤2 wt.% H_2O) in the melting experiments. Such low H_2O conditions can be explained by degassing of magma at a low pressure (≤40 MPa assuming 1,100°C; Papale et al. 2006). We inferred that smaller amounts of melts with ≥3 wt.% H_2O of the higher-Al/Si trend, including Ca-rich plagioclase, ascended primarily from the 4-km-deep magma chamber and also from the 8-10-km-deep magma chamber (Hamada et al. 2011) before injecting into shallower, low-H_2O magmas of the lower-Al/Si trend. The geochemical variations in the liquids, shown in Figure 3, can be interpreted either as the mixing of liquids of these two endmember trends or by differentiation at intermediate depths between those responsible for the endmember trends throughout the eruptive history of the Izu-Oshima volcano.

Conclusions

The origins of geochemical variations in the island arc low-K tholeiites from the Izu-Oshima volcano were investigated using the liquid compositions obtained from aphyric rocks and groundmasses of porphyritic rocks in addition to the results of hydrous melting experiments. Three types of liquids were distinguished using geochemical data from volcanic rocks: (i) a lower-K

subgroup, (ii) higher-Al/Si trend of a higher-K subgroup, and (iii) lower-Al/Si trend of a higher-K subgroup. Fractionation of amphibole may have been responsible for the lower-K subgroup, although its origin remains unknown. For liquids of the higher-K subgroup, higher- and lower-Al/Si trends were identified as endmember trends. Geochemical variations in the higher-K subgroup liquids can be explained either by mixing of these two endmember trends or by differentiation at intermediate depths between those of the endmember trends. By applying the results of melting experiments on hydrous basalts, the higher- and lower-Al/Si trends were reproduced by upper crustal crystallization differentiation of H_2O-saturated magmas in approximately 4-km-deep magma chamber (moderately hydrous melts with approximately 3 wt.% H_2O) and near the surface (nearly degassed melts), respectively. Such polybaric crystallization of H_2O-saturated magmas should be a ubiquitous feature of island arc low-K tholeiites. Ca-rich plagioclase ($An_{\geq 90}$), commonly found in island arc low-K tholeiites, can be crystallized from moderately hydrous melts of the higher-Al/Si trend but not from melts of the lower-Al/Si trend at any H_2O concentration.

Additional files

Additional file 1: Table S1. Whole-rock composition of major elements (wt.%) and selected trace elements (ppm) of aphyric rocks and groundmasses of porphyritic rocks of the Izu-Oshima volcano analyzed by X-ray fluorescence spectroscopy. The data were compiled from Fujii et al. (1996) and Okayama (2005) and were normalized to 100 wt.%. Sample MA43, a porphyritic rock of the Older Oshima Group, listed with an asterisk, was used as starting material for the hydrous melting experiments (see Additional file 2: Table S2). ap, aphyric rock; gm, groundmass; pp, porphyritic rock.

Additional file 2: Table S2. Chemical compositions of starting materials used for hydrous melting experiments by Hamada and Fujii (2007, 2008). Fe content is given as FeO* (total iron), and the composition is normalized to 100 wt.%.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
The manuscript was written mainly by MH. YO, TK, AY, and TF were responsible for obtaining the geochemical data for volcanic rocks from the Izu-Oshima volcano shown in the figures and listed in Additional file 1: Table S1. All of the authors discussed the final version of this manuscript and reached an agreement on the revised version for re-submission. All authors read and approved the final manuscript.

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MH is a scientist at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). He earned his Ph.D. in igneous petrology at the University of Tokyo in 2006. He studies the role of water in differentiation and eruption of arc basaltic magmas by conducting hydrous melting experiments and analyses of melt inclusions. His current research focuses on trace amounts of hydrogen accommodated in plagioclase as a tracer of H_2O in arc basaltic magmas. YO studied the evolution of magma of the Izu-Oshima volcano throughout its eruptive history as a master's course graduate student at the University of Tokyo during 2003 to 2005. She provided the geochemical data for volcanic rocks from the Izu-Oshima volcano used in this paper. She is currently a science communicator at the National Museum of Emerging Science and Innovation in Tokyo. TK and AY are staff scientists in igneous petrology and volcanology at the Earthquake Research Institute, University of Tokyo and analyzed the drilled volcanic rocks from Izu-Oshima volcano. TF is an igneous petrologist and volcanologist who is currently a professor emeritus of the University of Tokyo. He also provided the geochemical data for volcanic rocks from the Izu-Oshima volcano used in this paper. He has provided valuable discussion and advice to MH for more than 15 years on the geochemical evolution of magmas beneath the Izu-Oshima volcano.

Acknowledgements
We thank professors Eiichi Takahashi, Jun-Ichi Kimura, and Jon Blundy for their discussion and Professor Yasuo Ogawa and Dr. Tatsuhiko Kawamoto for their editorial handling. This manuscript has been significantly improved by critical reviews and encouragement from two anonymous reviewers. This study was partially supported by KAKENHI (Grant-in-Aid for Young Scientists (B) No. 24740355 to MH) from the Japan Society for the Promotion of Science.

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Received: 24 September 2013 Accepted: 24 March 2014
Published: 22 April 2014

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doi:10.1186/1880-5981-66-15
Cite this article as: Hamada *et al.*: Polybaric crystallization differentiation of H_2O-saturated island arc low-K tholeiite magmas: a case study of the Izu-Oshima volcano in the Izu arc. *Earth, Planets and Space* 2014 **66**:15.