

# Operation of subduction factory and production of andesite

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The subduction factory processes raw materials such as oceanic sediments and basaltic crust, selectively extracts particular subduction components and manufactures magmas, their solidified materials and continental crust as products. The waste materials from the factory, such as chemically modified oceanic materials and delaminated mafic arc lower crust are transported down to the deep mantle modified their compositions and ultimately recycled as mantle plumes. Andesite composes the bulk continental crust and therefore is the major product in the subduction factory. Two types of andesites, calc-alkalic and tholeiitic series, are commonly recognized in a single arc volcano. We propose a new mechanism for production of these two magma series on the basis of data obtained by Sr isotopic micro-analyses of plagioclase in volcanic rocks from Zao Volcano, NE Japan. Tholeiitic magmas having constant and enriched isotopic signatures are produced by anatexis of the pre-existing mafic lower crust, whereas calc-alkalic magmas, having compositions similar to the bulk continental crust, are products of mixing a mantle-derived, hence isotopically depleted, basaltic magma and crust-derived felsic tholeiites.

**Keywords:** Subduction factory, Hotspot, Recycling, Andesite, Basalt

## INTRODUCTION

The term, ‘andesite’ was first coined in the 1930’s for intermediate volcanic rocks from the Andes Mountains of Bolivia and Chile, which are distinct from trachytes in Europe since they contain hornblende and plagioclase phenocrysts. Andesites are currently defined broadly (e.g., Gill, 1981) as hypersthene–normative, i.e., sub-alkalic, volcanic rocks with SiO<sub>2</sub> from 53 to 63 wt% and further subdivided into low-silica and high-silica andesites, 53 to 57 wt% and 57 to 63 wt% SiO<sub>2</sub>, respectively. Andesite can be megascopically defined as grey-colored, porphyritic volcanic rocks containing plagioclase, but not quartz, alkali feldspar, or feldspathoid as phenocrysts.

Andesite erupts in > 80% of arc volcanoes, typifies magmatism in subduction zones that create > 20% of current terrestrial magmatic products and is the most dominant volcanic rock in mature continental arcs, but it is less voluminous in immature oceanic arcs. In addition to this volumetric importance, andesites have characteristic chemical compositions. The continental crust, the geochemical reservoir for light elements and the most differentiated end-member among components within the solid

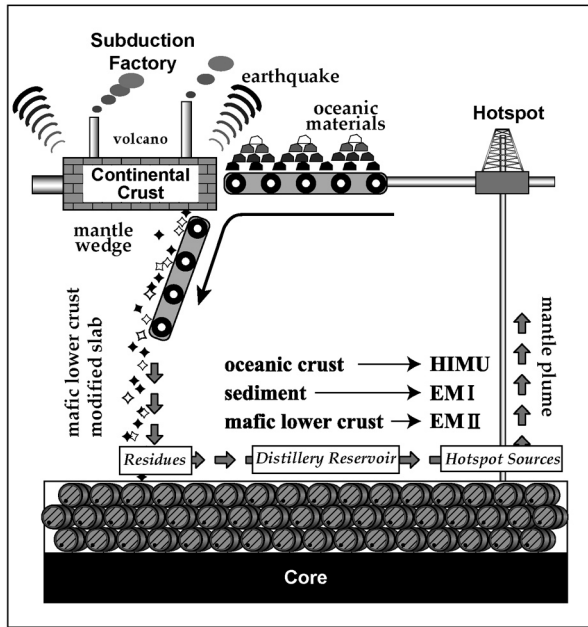
Earth, is of overall andesitic composition (e.g., Taylor, 1995; Rudnick, 1995). Knowledge of andesite genesis should therefore provide key constraints on the origin of continental crust and differentiation processes during early Earth evolution.

Herein we outline material circulation in subduction zones, where andesite forms, and discuss the origin of andesites, in particular genetic links between calc-alkalic and tholeiitic andesites.

## SUBDUCTION FACTORY

Subduction zones, where the oceanic lithospheres sink into the mantle, have been ‘factories’ (Tatsumi, 2005) since plate tectonics began on Earth (Fig. 1). Oceanic materials such as pelagic/terrigenous sediments, altered/fresh basaltic oceanic crust and mantle lithosphere enter the factory as raw materials. These materials, together with mantle wedge peridotites, are processed into products such as magmas, their solidified materials and ultimately continental crust, during which the entire factory adjusts and deforms, causing magmatism and earthquakes.

The subduction factory, as do other factories, emits waste materials, such as slab materials (sediments and

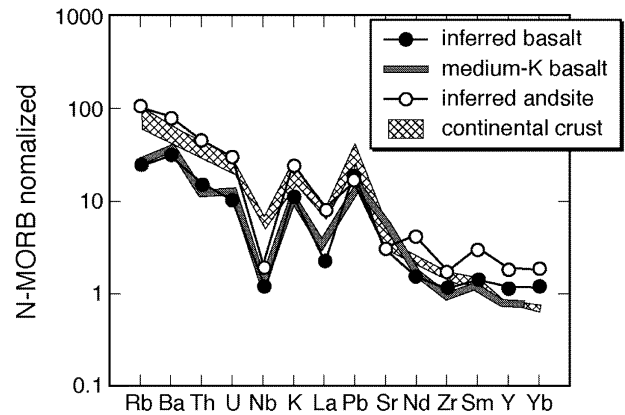


**Figure 1.** Conceptual framework of the subduction factory. Raw materials, such as oceanic sediments, oceanic crust, mantle lithosphere, and mantle wedge materials, are fed into the factory and are manufactured into arc magmas and continental crust. The waste materials or residues processed in this factory, such as chemically modified slab components (oceanic crust and sediments) and delaminated mafic lower arc crust, sink into the deep mantle, are stored and are recycled as raw materials for mantle plume-related hotspot magmatism.

basaltic crust), which are chemically modified via dehydration and/or partial melting, and possibly delaminated lower continental crust. These waste materials founder into the Earth's deeper interior and reside somewhere in the deep mantle and, because of their significant mass and characteristic compositions, may contribute greatly to the evolution of mantle; assuming steady state subduction of 7 km-thick oceanic crust for 3 billion years, accumulated crust materials with basaltic compositions occupy ~10% of the lower mantle.

### Basalt genesis

Although basalts are not always the major surface products of the subduction factory, primary magmas generated in the mantle wedge are likely to be basaltic in composition. Basalts erupted in subduction zones are noted for their distinct chemistry compared with those at divergent plate boundaries and intraplate settings. In particular, they are elevated in large-ion-lithophile elements (e.g., Cs, Rb, K, Ba, Pb, Sr) and depleted in high-field-strength elements (e.g., Ta, Nb, Zr, Ti) (Fig. 2). Such characteristic trace element compositions likely arise from subducting oceanic lithosphere through metasomatic reactions bet-



**Figure 2.** N-MORB normalized incompatible element characteristics of an average medium-K oceanic arc basalt (Tatsumi and Eggins, 1995), an inferred basalt magma (Tatsumi and Kogiso, 2003), the bulk continental crust (Taylor, 1995; Rudnick, 1995), and an inferred andsite magma (Tatsumi and Kogiso, 2003).

ween the subducting lithosphere and the overlying mantle wedge. What is the nature of the metasomatic agent that enriches the source region of subduction zone magmas? Since the pioneer work of Nicholls and Ringwood (1973), many petrologists have favored mechanisms including slab melting and subsequent melt-mantle interaction. Slab melting may take place exclusively in arc-trench systems where a young and hot plate is being subducted (Peacock et al., 1994; Furukawa and Tatsumi, 1999), and could yield the unusually  $\text{SiO}_2$ -rich arc magmas known as high-Mg andesite, e.g., adakite from the Aleutian Islands (Yogodzinski et al., 1994), boninite from the Boniin Islands, W Pacific (Pearce et al., 1992), and sanukitoid in SW Japan (Tatsumi and Hanyu, 2003). Elliot et al. (1997), on the other hand, further suggested that generation of some basaltic magmas in the Mariana arc might also be triggered by slab melting.

Alternatively, fluid phases released by dehydration reactions within the subducting lithosphere may be a likely metasomatic agent responsible for the characteristic geochemical signatures. To examine the chemical characteristics of such slab-derived fluid phases, several experimental studies have been conducted on the distribution of elements between aqueous fluids and solid minerals (e.g., Tatsumi et al., 1986; Brenan et al., 1995; Keppler, 1996). On the basis of these experimental data, together with reasonable assumptions on  $\text{H}_2\text{O}$  contents in both subducting oceanic materials and arc magmas (1.5 wt%  $\text{H}_2\text{O}$ ), the pre-flux and original subarc mantle compositions (a depleted MORB source), Tatsumi and Kogiso (2003) demonstrated that the geochemical characteristics of arc basalts could be reasonably explained by addition of elements from subducting sediments (20%) and oceanic

crust (80%) through dehydration processes (Fig. 2).

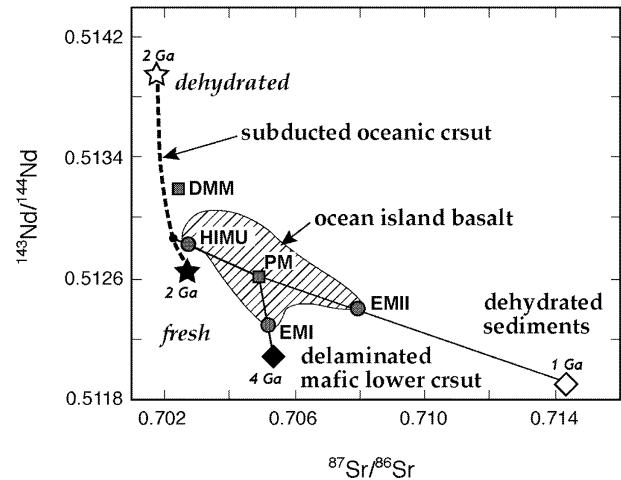
### Continental crust formation

The bulk continental crust has a composition equivalent to andesites that typify arc magmatism and hence is believed to be created at convergent plate margins (e.g. Kelemen, 1995; Taylor, 1995; Rudnick, 1995). On the other hand, modern-day, mantle-derived magmatism in such settings is dominated by basalt. This dilemma faces anyone interested in the theory of continental crust formation. Since the geotherm was steeper during the Archean, when the majority of continental crust was created, it is possible that slab melting, instead of slab dehydration as at present, was responsible for production of dominantly andesitic as opposed to basaltic magmas (Shirey and Hanson, 1984; Martin, 1987; Drummond and Defant, 1990; Kelemen, 1995; Rapp et al., 1999). Results of both high-P experiments (Rapp et al., 1999) and geochemical modeling (Tatsumi, 2000a) have demonstrated that slab melting can account for both the major and trace element characteristics of bulk andesitic continental crust. If this is the case, then the residue of slab melting, with a composition significantly modified from that of the mantle, may have formed a geochemical reservoir in the deep mantle and could have been recycled as a hotspot source. However, the isotopic characteristics of such slab residues do not match those of any proposed geochemical end-member mantle component (Tatsumi, 2000a).

Alternatively, delamination of the lower part of initial arc crust may also produce andesitic continental crust compositions, since the lower arc crust may be composed of mafic lithologies including dense minerals such as garnet and Fe-Ti oxides that ultimately sink into the mantle (Turcotte, 1989; Kay and Kay, 1993; Nakajima and Arima, 1998). Tatsumi (2000b) and Tatsumi and Kogiso (2003) modeled this mechanism geochemically, including slab-dehydration induced mantle melting, basaltic magma generation, and remelting of the initial basaltic crust, and demonstrated that this process can reasonably explain the incompatible trace element characteristics of the bulk andesitic continental crust (Fig. 2). The fate of delaminated lower crustal materials, which may be termed 'anti-continental' materials, and their role in mantle evolution will be addressed on in the following section.

### Recycled waste materials and hotspot sources

Oceanic crust and sediments, from which particular components are extracted during subduction, are injected into the mantle, resulting in significant chemical heterogeneity in the deep mantle. Although the physical properties of



**Figure 3.** Isotopic compositions of inferred waste materials from the subduction factory (dehydrated/fresh oceanic crust, Tatsumi and Kogiso, 2003; dehydrated sediment, Aizawa et al., 1999; delaminated anti-continental crust, Tatsumi and Kogiso, 2003) and mantle geochemical reservoirs (DMM, HIMU, EMI, EMII, and PM) that have been proposed to explain the isotopic diversity observed for ocean island (oceanic hotspot) basalts. The evolution of deep mantle reservoirs may be comprehensively explained by contribution of recycled waste materials from the subduction factory and primitive mantle (PM).

descending surficial and mantle materials have been investigated at high pressures (e.g., Ringwood, 1991; Ono et al., 2001; Guinot and Andraut, 2004), the location in the mantle where subduction components are stored is still beyond consensus.

Geochemical studies on mid-ocean ridge basalts (MORBs) and ocean island basalts (OIBs) have suggested that at least four end-member components or geochemical reservoirs in addition to primitive mantle are needed in the mantle to explain the isotopic diversity of oceanic basalts (e.g., Zindler and Hart, 1986); depleted MORB mantle (DMM), enriched mantle I and II (EMI and EMII), and high- $\mu$  mantle (HIMU). It is generally accepted that DMM occupies the shallowest upper mantle, whereas other enriched mantle components typify magmas rising from deep-seated hotspots. There are possibly three geochemical end-members in the deep mantle, while three waste materials –sediments, basaltic oceanic crust and delaminated anti-continental crust– are generated in the subduction factory. It may therefore be illuminating to discuss linkages among these components.

The HIMU, or high  $\mu$  ( $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$ ), source is characterized by higher  ${}^{206}\text{Pb}/{}^{204}\text{Pb}$  and  ${}^{187}\text{Os}/{}^{186}\text{Os}$ , but depleted MORB-like  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  and  ${}^{143}\text{Nd}/{}^{144}\text{Nd}$  compared to other end-member components (Zindler and Hart, 1986; Hauri and Hart, 1993). These isotopic signatures, particularly high  ${}^{206}\text{Pb}/{}^{204}\text{Pb}$  have been generally consid-

ered to be related to depletion of Pb relative to U by dehydration processes in subduction zones (e.g., Chauvel et al., 1992; Brenan et al., 1995; Kogiso et al., 1997). Because Nd is extracted from subducting altered oceanic crust more readily than Sm (Keppler 1996; Kogiso et al. 1997), ancient residual dehydrated oceanic crust has higher  $^{143}\text{Nd}/^{144}\text{Nd}$  than the HIMU component (Fig. 3), suggesting that HIMU cannot be created solely by the contribution of dehydrated subducting crust. Instead, Tatsumi and Kogiso (2003) demonstrated that isotopic signatures of HIMU could be reasonably explained by accumulation of both fresh and dehydrated MORB crust in the deep mantle since  $\sim 2$  Ga (Fig. 3).

The role of subducting sediments in the evolution of EMII is commonly advocated, because oceanic sediments generally have high  $^{87}\text{Sr}/^{86}\text{Sr}$  and relatively low  $^{143}\text{Nd}/^{144}\text{Nd}$  (e.g., Devey et al., 1990). Experimental results on sediment dehydration and associated element transport (Aizawa et al., 1999; Johnson and Plank, 1999) have demonstrated that chemically modified, dehydrated ancient subducted oceanic sediments, a waste material from the subduction factory, may evolve to an enriched component having high  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$ . Aizawa et al. (1999) further suggest that the isotopic signature of the EMII component can be achieved by the addition of small amounts ( $\sim 1$  wt%) of dehydrated sediments to primitive mantle (Fig. 3).

Linkages between delaminated arc crust and EMI are then examined. To make andesitic continental crust, melting residue after extraction of felsic melts needs to be removed and delaminated from initial arc crust. This 'anti-continental' material could contribute to evolution of a deep-seated geochemical reservoir. Important for evaluating the isotopic evolution of melt residues in the initial basaltic crust is the degree of separation of felsic melts from partially molten crust, as the viscosity of felsic melts may be about two orders of magnitude higher than that of basaltic melts under similar hydrous conditions. Geochemical modeling incorporating the effects of remaining felsic melts (Tatsumi and Kogiso, 2003) indicates that the Sr-Nd-Pb isotopic characteristics of EMI can be best explained by contribution of 3-4 Ga delaminated crustal material with a 10-15% felsic melt component (Fig. 3).

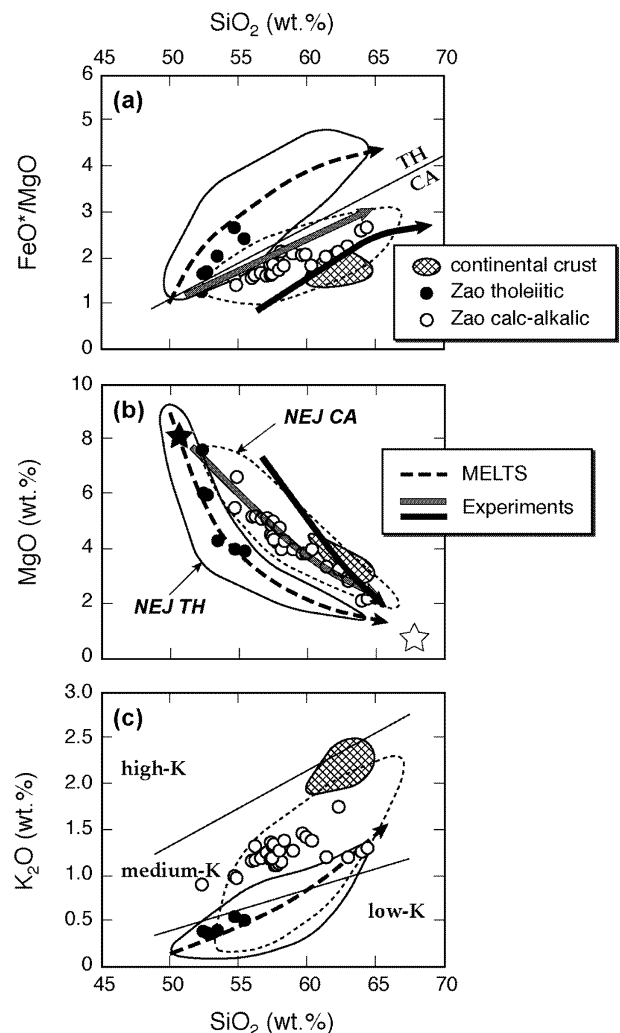
Raw materials entering the subduction factory are processed into magmas, which erupt as characteristic arc volcanism and construct continental crust. The waste materials from the factory, such as chemically modified subducting sediment and crust, and melt residue delaminated from initial arc crust, have accumulated in the deep mantle and probably evolved into enriched geochemical reservoirs such as EMII, HIMU and EMI, respectively (Fig. 3). Magmas, which tap these deep-seated geochemi-

cal end-member components, erupt where mantle plumes rise from the deep mantle. It is thus possible to conclude figuratively that the subduction zone has been working as a zero-emission factory, in which the waste materials are completely recycled and reused as raw materials within the hotspot factory. Recycling of surface crustal materials through subduction factories and mantle plumes may have played the central role in the evolution of the solid Earth.

## ANDESITE GENESIS

### Calc-alkalic vs. tholeiitic series

Two distinctive differentiation trends, tholeiitic (TH) and



**Figure 4.** Major element characteristics for calc-alkalic (CA) and tholeiitic (TH) rocks from NE Japan (NEJ) arc and Zao volcano and bulk continental crust. Lines with arrow indicate the liquid lines of descent obtained by MELTS calculations and experiments by Grove and co-workers (see Text). Mixing of basaltic and felsic magmas can explain a rather linear trend for CA series rocks (b).

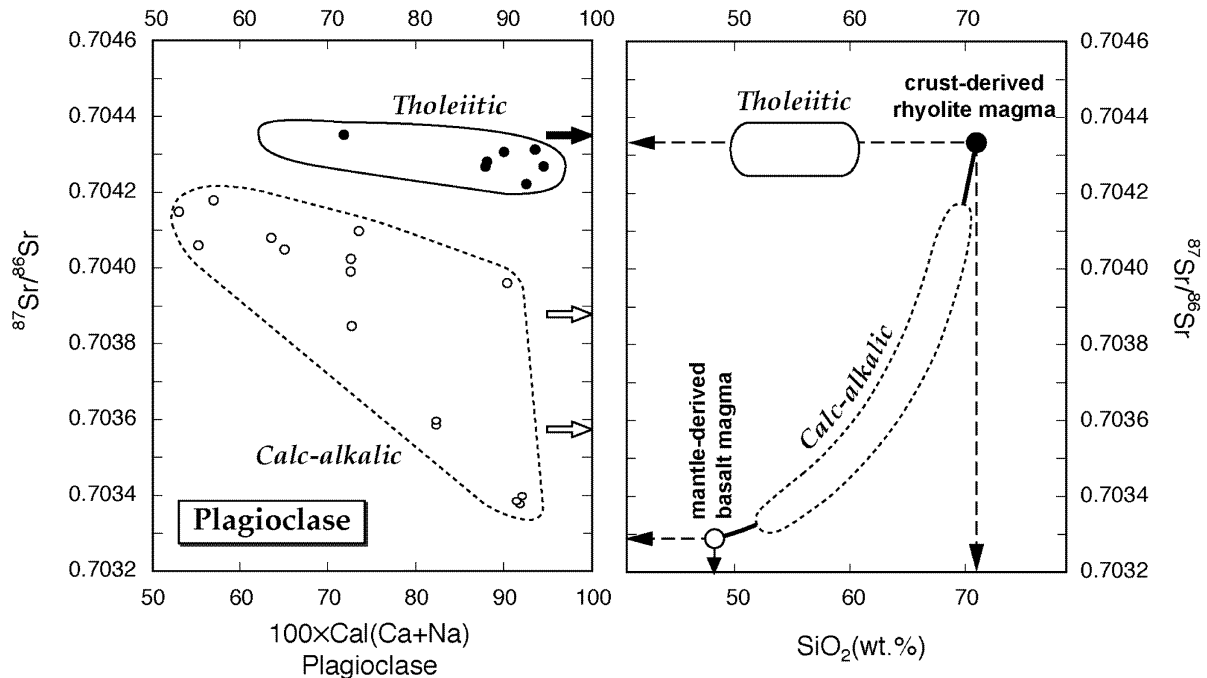
calc-alkalic (CA), are recognized in the sub-alkalic volcanic rocks, denoting the presence or absence of relative iron-enrichment during magmatic differentiation (Wager and Deer, 1939).  $\text{FeO}^*/\text{MgO}$  vs.  $\text{SiO}_2$  variation plots ( $\text{FeO}^*$ , total iron as  $\text{FeO}$ ) (Miyashiro, 1974) are commonly used to distinguish these two magma series (Fig. 4); CA and TH trends generally have steeper and gentler slopes, respectively, than the straight line in Figure 4. Although the definition of CA vs. TH should be based exclusively on differences in degree of relative iron-enrichment, inconsistent usage of these magma series has in the past caused confusion. One such example is the interchangeable use of the terms medium-K and CA series (e.g., Hess, 1989). While it has been well documented that CA andesites tend to be more enriched in  $\text{K}_2\text{O}$  than TH andesites (Fig. 4), there are some CA andesites that can be classified as low-K andesites (Fig. 4) while medium-K magmas can display TH trends (e.g., Tatsumi and Eggins, 1995). Another problem is the application of Miyashiro's discrimination line as a simple compositional discriminant rather than "trend slope" comparison (e.g., Hunter and Brake, 1995).

One of the most distinct chemical differences between CA and TH series rocks, other than the difference in degree of iron-enrichment, is the characteristic differentiation trend of  $\text{MgO}$  vs.  $\text{SiO}_2$  (Fig. 4); while TH rocks show a concave trend, CA rocks exhibit a rather straight trend. It is generally accepted that the TH differentiation trend can be reproduced by separation of phenocryst phases such as olivine, plagioclase and pyroxene from a parental basaltic magma (e.g. Sakuyama, 1981; Grove and Baker, 1984; Fujinawa, 1988), which is also suggested by MELTS modeling (Ghiorso and Sack, 1995) for a basaltic magma in the presence of 0.5 wt%  $\text{H}_2\text{O}$  at 0.5 GPa under a QFM buffer (Fig. 4). This rather simple mechanism is further supported by the following two petrographic observations. Firstly, composition and assemblage of the phenocryst phases change systematically with increasing degrees of crystallization and decreasing temperatures. Secondly, TH andesites exhibit little or no evidence for disequilibrium, such as the presence of banded structures, reversely zoned phenocrysts, dusty zones within single phenocryst phase, and thermodynamic disequilibrium mineral assemblages. It should be stressed here that the above characteristics in TH rocks could be conversely explained by remelting of pre-existing basaltic crust, which will be discussed later.

On the other hand, the genesis of CA andesites poses a considerable question for debate. One possible cause for the characteristic CA trend is the effective separation of Fe-Ti oxide that can prevent iron-enrichment (e.g., Osborn, 1959; Gill, 1981). Grove and co-workers (e.g.,

Sisson and Grove, 1993; Grove et al., 2003) provided a comprehensive experimental data set of liquid lines of descent for basaltic and andesitic magmas under hydrous conditions, demonstrating that a high magmatic  $\text{H}_2\text{O}$  content reduces the stability of silicate minerals. This has less effect on Fe-Ti oxide stability, resulting in early magnetite crystallization in hydrous magmas. It is thus likely that hydrous basalt, and even mantle-derived andesitic magmas, can fractionate to form a CA trend (Fig. 4). If this is the case, then the primary factor controlling the production of the two arc magma series is the  $\text{H}_2\text{O}$  content in the magma source region; i.e., more hydrous for CA magma generation. This scenario is consistent with the observations that CA andesites are generally  $\text{H}_2\text{O}$ -rich, and that arc TH magmas are relatively poor in  $\text{H}_2\text{O}$  (Sisson and Layne, 1993). However, this elegant explanation does not address the following two problems. Firstly, because of the smaller temperature difference between the liquidus and solidus for hydrous compared to anhydrous magmas, a  $\text{H}_2\text{O}$ -rich magma would solidify within the crust rather than fractionate to produce a more differentiated magma. Secondly, CA andesites commonly exhibit the disequilibrium petrographic characteristics, which suggest a role for magma mixing in their formation (Eichelberger, 1975; Sakuyama, 1981; Bloomfield and Arculus, 1989; Clyne, 1999). Mixing of mafic and felsic end-member magmas can form linear trends on variation diagrams (Fig. 4).

If we accept magma mixing as the mechanism responsible for the petrographic and chemical characteristics of CA andesites, then an ensuing question involves the origin of end-member components in magmas, one basaltic and higher- $T$ , the other a more differentiated and lower- $T$ . A key observation in this problem is the systematic difference in isotopic composition between CA and TH series rocks, e.g., as documented in Quaternary volcanoes in the NE Japan arc (Fujinawa 1988; Tatsumi and Kogiso, 2003). If this observation may be generalized to other arcs, then the two end-member magmas would be derived from different sources. Therefore, 'self mixing' (Couch et al., 2001) or 'internal mixing,' in which felsic and mafic magmas are essentially co-magmatic, does not likely play a major role in CA andesite formation. Alternatively, a felsic, end-member magma could form by anatexis of preexisting arc crust and mix with a mantle-derived basaltic magma, which may be considered 'external mixing'. Furthermore, the origin of the basaltic end-member magma is still a matter of debate. Is it a TH basalt? Or, does a mantle-derived CA basalt exist?



**Figure 5.** Sr-isotopic compositions of plagioclase in Zao volcanic rocks (a) and a possible mechanism for generation of the two types of magmas and their inferred isotopic signatures (b).  $^{87}\text{Sr}/^{86}\text{Sr}$  of bulk rock samples are shown by arrows in (a).  $^{87}\text{Sr}/^{86}\text{Sr}$  of plagioclase and the bulk rock for tholeiitic series is constant, whereas that for calc-alkalic series is highly variable and correlates inversely with An-content of plagioclase (a). This may suggest the contribution of two end-member magmas to formation of mixed calc-alkalic magmas, basaltic and rhyolitic having low and high  $^{87}\text{Sr}/^{86}\text{Sr}$ , respectively (b). The felsic end-member magma would be co-magmatic with tholeiitic series magmas because of an identical  $^{87}\text{Sr}/^{86}\text{Sr}$  (b).

### A new concept for andesite genesis: a case study of Zao Volcano

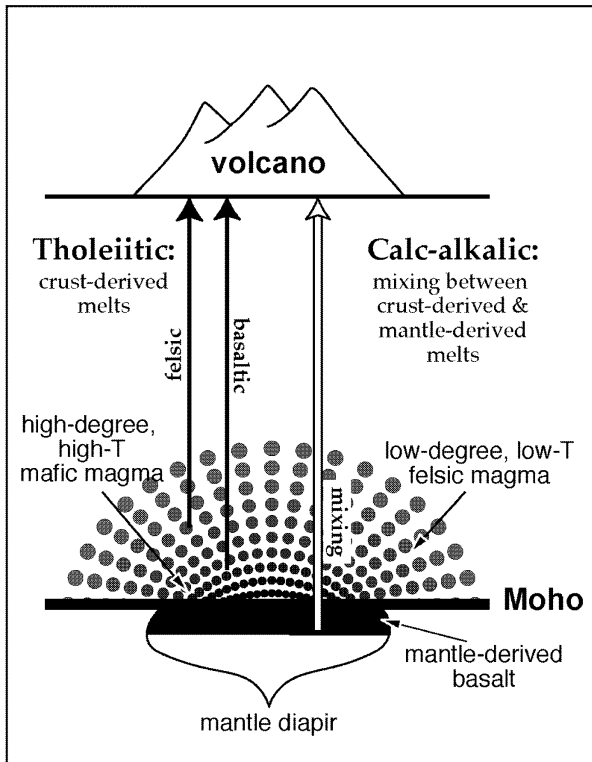
To improve our understanding of andesite genesis, detailed descriptions of the two magma series rocks from a single volcano are needed. For a target, we selected Zao Volcano on the volcanic front of the NE Japan arc, where TH and CA rocks, both showing chemical signatures identical to the general characteristics described above, erupted during early and late stages, respectively (Fig. 4). Furthermore, Zao CA rocks exclusively show disequilibrium petrographic signatures (Sakayori, 1992). The processes responsible for forming the two magma series at this particular volcano, therefore, may be applied to arc magmatism in general.

New insights into andesite genesis are based on precise Sr-isotope micro-analyses (100–300  $\mu\text{m}$  diameter) of plagioclase (Takahashi et al., 2006), the most common phenocryst phase in andesites. Applying this technique to Zao volcano, they revealed isotopic signatures of plagioclase crystals in CA and TH rocks (Fig. 5a). Plagioclase occurring both as phenocrysts and in a groundmass in TH rocks shows that  $^{87}\text{Sr}/^{86}\text{Sr}$  is constant at  $0.7043 \pm 0.0001$  ( $2\sigma$ ), whereas that in CA rocks varies between 0.7042 and 0.7034 (Fig. 5a). These results suggest that TH and CA

magmas differentiate in closed/equilibrium and open/disequilibrium systems, respectively, which is consistent with petrographic and chemical characteristics of the Zao volcanic rocks.

$^{87}\text{Sr}/^{86}\text{Sr}$  of plagioclase in CA rocks correlates inversely with An-content (Fig. 5a). This, together with evidence for magma mixing for the CA series involving at least two end-member magmas, suggests that basaltic and felsic magmas crystallizing An-rich and An-poor plagioclase could have  $^{87}\text{Sr}/^{86}\text{Sr}$  of  $< 0.7034$  and  $> 0.7042$ , respectively (Fig. 5b). Isotopic compositions of an inferred felsic end-member magma are close to those of TH rocks. It is thus reasonable to speculate that such a felsic magma is co-magmatic with the TH series. On the other hand, the basaltic end-member magma for mixed CA rocks should tap a magma source different from that for TH and felsic magmas. One possible source would be the mafic lower crust, if we accept the upper mantle as the TH magma source. However, the extremely depleted  $^{87}\text{Sr}/^{86}\text{Sr}$  signature inferred for the basaltic magma source of the CA series magmas is not consistent with crustal origin for such a basaltic magma.

Two different basaltic magmas, the TH and CA series, therefore, may be produced in the subarc upper mantle. Assuming a homogeneous, pre-fluxed, original



**Figure 6.** A model for generation of two types of magmas beneath arc volcanoes. Tholeiitic magmas are produced by anatexis of mafic lower crust, which may be triggered by heat from a mantle diapir rising to the crust–mantle boundary. Difference in temperature during melting causes variable degrees of melting, ultimately resulting in compositional variations in tholeiitic magmas. A mantle diapir-derived basalt magma will entrain intra-crustal tholeiitic melts to form mixed calc-alkalic magmas.

mantle source for the two magma series,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios estimated for the two types of Zao basaltic magmas (i.e.,  $^{87}\text{Sr}/^{86}\text{Sr} < 0.7034$  and  $> 0.7042$ ) suggest that the mantle source for CA magmas is more metasomatized by radiogenic, slab-derived components than that for TH magmas. However, such a significant difference in isotopic ratios cannot be quantitatively explained solely by differing contributions of the slab component.

Although we are convinced that arc TH magmas originate from a mantle-derived basaltic magma via fractional crystallization, belief in such a mechanism could hinder a better understanding of genetic relations between CA and TH magmas. Therefore, we would like to propose that TH magmas are produced by anatexis of pre-existing basaltic lower crust (Figs. 5b and 6), which is consistent with isotopic observations of Zao volcanic rocks. Chemical variations in TH series rocks could therefore result from different degrees of anatexis, which is consistent with inferred liquid lines of descent for the TH magmas as previously discussed (Fig. 4). This mechanism can also explain the petrographic characteristics of TH rocks such

as systematic changes in phenocryst assemblages. If we accept a crustal origin for the TH series magmas, then the basaltic magma, characterized by a depleted isotopic signature and being an end-member component for CA series, is likely to have originated in the mantle.

Because the major element composition of the NE Japan arc's primary magma is unknown, the  $P$ - $T$  conditions of its segregation from the mantle cannot be estimated currently. However, it is reasonable to assume that such magmas, at least those beneath the volcanic front, are separated from the upper-most mantle near the mantle–crust boundary, because seismic observations suggest a low-velocity region immediately beneath the Moho (e.g., Zhao, 2001). High- $T$  mantle, probably in the form of a mantle diapir (e.g., Tatsumi et al., 1983), may lie immediately beneath the crust, causing variable extents of crustal anatexis to form TH series magmas (Fig. 6). During ascent of a mantle-derived magma, it likely mixes with TH magmas distributed within the crust to produce magmas exhibiting CA trends and disequilibrium petrographic characteristics.

## CONCLUSIONS

A possible scenario explaining the origin of tholeiitic and calc-alkalic magmas beneath a single Quaternary volcano on the NE Japan arc is a mirror image of the existing model; the former originates by variable degrees of anatexis of the mafic lower crust, whereas the latter is primarily of mantle origin mixed with intra-crustal tholeiitic magmas. This new concept may elucidate the isotopic signatures of the two arc magma series deduced from plagioclase micro-analyses, as well as petrographic and chemical characteristics. To further investigate this mechanism, detailed isotopic work on phenocryst phases and bulk rocks for two magma series from a single volcano is needed.

The continental crust, one geochemical reservoir within the solid Earth and the major product in the subduction factory, is characterized by compositions similar to those of calc-alkalic andesites. Andesitic continental crust could form by mixing of mantle-derived basaltic magma with crust-derived felsic melt (Tatsumi and Kogiso, 2003). This process is almost identical to that operating in present-day arcs as proposed herein. However, a poorly understood process required to create andesitic continental crust is the delamination of mafic lower crust formed as a melting residue. If such a process occurs, then we may understand the origin of a deep-seated mantle geochemical reservoir, EMII. Geophysical investigations of crustal delamination are needed.

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