

The subduction factory: How it operates in the evolving Earth

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ABSTRACT

The subduction factory processes raw materials such as oceanic sediments and oceanic crust and manufactures magmas and continental crust as products. Aqueous fluids, which are extracted from oceanic raw materials via dehydration reactions during subduction, dissolve particular elements and overprint such elements onto the mantle wedge to generate chemically distinct arc basalt magmas. The production of calc-alkalic andesites typifies magmatism in subduction zones. One of the principal mechanisms of modern-day, calc-alkalic andesite production is thought to be mixing of two end-member magmas, a mantle-derived basaltic magma and an arc crust-derived felsic magma. This process may also have contributed greatly to continental crust formation, as the bulk continental crust possesses compositions similar to calc-alkalic andesites. If so, then the mafic melting residue after extraction of felsic melts should be removed and delaminated from the initial basaltic arc crust in order to form “andesitic” crust compositions. The waste materials from the factory, such as chemically modified oceanic materials and delaminated mafic lower crust materials, are transported down to the deep mantle and recycled as mantle plumes. The subduction factory has played a central role in the evolution of the solid Earth through creating continental crust and deep mantle geochemical reservoirs.

INTRODUCTION

Subduction zones, where the oceanic plates sink into the mantle, have been “factories” since plate tectonics began on Earth (Fig. 1). Oceanic materials such as pelagic and terrigenous sediments, altered and fresh basaltic oceanic crust, and mantle lithosphere enter the factory as raw materials. These materials, together with mantle-wedge peridotites, are processed into products, during which the entire factory adjusts and deforms, causing magmatism and earthquakes. The products of the factory are arc magmas, their solidified materials, and ultimately continental crust. Such products may be volumetrically small, as the continental crust occupies <1% of the total mass of solid Earth. However, they possess “differentiated” compositions, quite distinct from a chondritic bulk Earth, which suggests that the origin of products from the subduction factory should provide a clue to understanding the evolution of the solid Earth.

The subduction factory, as do other factories, emits waste materials, such as slab materials, which are chemically modified through complex dehydration and/or melting processes

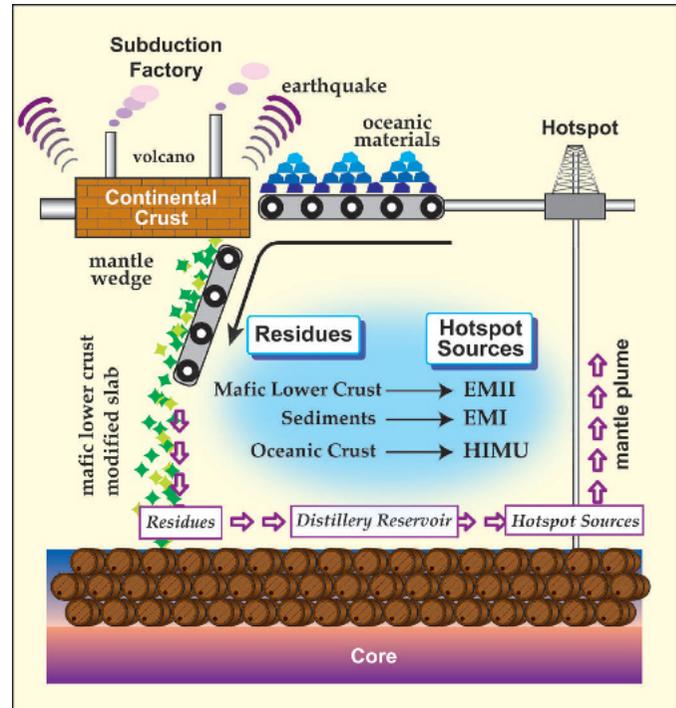


Figure 1. Role of the subduction factory in the evolution of the solid Earth. Raw materials, such as oceanic sediments, oceanic crust, mantle lithosphere, and wedge materials, are fed into the factory and are manufactured into arc magmas and continental crust. The waste materials or residues processed in this factory, such as chemically modified slab components (oceanic crust and sediments) and delaminated mafic lower arc crust, are transported and stored in the deep mantle and recycled as raw materials for mantle plume-related hotspot magmatism. EMI—enriched mantle type I; EMII—enriched mantle type II; HIMU—high- μ mantle.

during subduction, and possibly delaminated mafic lower-arc crust. These waste materials founder into Earth’s deeper interior, reside somewhere in the deep mantle, and may contribute greatly to the evolution of mantle because of their significant mass and characteristic compositions; assuming steady-state subduction of the entire 7-km-thick oceanic crust for 3 billion years, accumulated crust materials with basaltic compositions occupy ~10% of the lower mantle.

This paper outlines how the subduction factory creates products and discusses its role in the evolution of Earth’s mantle.

PRODUCTION PROCESSES

Subduction zones are sites of intensive volcanism and are creating >20% of the current terrestrial magmatic products.

Although the interaction of physical and chemical processes occurring in subduction zones is complex, arc magmatism exhibits characteristics common to not all but most arc-trench systems. One of these general characteristics is the presence of paired lines of volcanoes. Another is the negative correlation between the volcanic arc width and the subduction angle (Fig. 2A). In other words, the depth to the surface of the subducting lithosphere is constant at ~110 km and ~170 km, respectively, beneath the trenchward limit of the volcanic arc (the volcanic front) and the backarc-side volcanoes (Fig. 2B). This characteristic volcano distribution relative to subduction depth suggests an important role of pressure-dependent processes such as dehydration reactions in magma generation in the subarc mantle. As emphasized by Tatsumi and

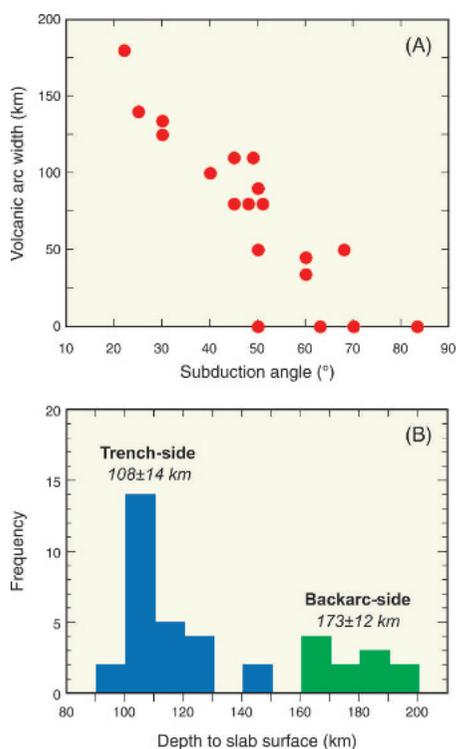


Figure 2. Tectonic characteristics of subduction zone magmatism (Tatsumi and Eggins, 1995). (A) Negative correlation between the subduction angle and the volcanic arc width. (B) Constant depths to the surface of the subducting lithosphere beneath the trench-side (volcanic front) and backarc-side volcanic chains in volcanic arcs. Noted values are the average depths and one standard deviation. These observations suggest the primary role of pressure-dependent reactions in production of arc magmas.

Eggins (1995), the characteristic depths correspond to pressures expected for the dehydration of amphibole and chlorite (110 km) and phlogopite (170 km) in the hydrous peridotite layer at the base of the mantle wedge, which is formed by addition of slab-derived aqueous fluids beneath the forearc and dragged downward on the subducting plate.

Within any volcanic arc, lava chemistry tends to change systematically with distance from the volcanic front. The degree of silica saturation decreases toward the backarc (Kuno, 1966) with increasing concentrations of incompatible elements such as K, Rb, and Zr, a relationship known as the *K-h* (K, potassium; *h*, height above the slab) relationship (Dickinson, 1975). A possible origin of this observation is separation of a primary magma from an adiabatically rising mantle diapir at a greater depth by a lower degree of partial melting toward the backarc, which may be caused by the presence of a thicker lithosphere beneath the backarc side of a volcanic arc (e.g., Tatsumi et al., 1983; Zhao et al., 1992; Furukawa, 1993).

Selective enrichment of particular incompatible elements in arc basalts has been well established since the pioneer work by Pearce and Cann (1973). This can be intuitively attributed to addition of the slab-derived component to the original mantle wedge. Herein the geochemical characteristics of arc magmas and their possible causes including element transport from the downgoing oceanic lithosphere will be further outlined.

Basaltic Magma

Although basalts are not always the major surface products of the subduction factory, 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 in other tectonic 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. 3). Such characteristic compositions likely arise from subducting oceanic lithosphere through metasomatic reactions between the subducting lithosphere and the overlying mantle wedge. What is the nature of the metasomatic process that

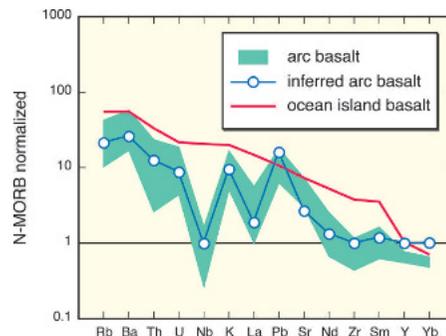


Figure 3. Normal mid-oceanic-ridge basalt (N-MORB)-normalized (Sun and McDonough, 1989) incompatible element characteristics of arc basalts (Tatsumi and Eggins, 1995), an arc basalt magma inferred from geochemical modeling on element transport by dehydration of subducting sediments and altered oceanic crust (Tatsumi and Kogiso, 2003), and a hotspot-related oceanic-island basalt (Sun and McDonough, 1989).

enriches the source region of subduction zone magmas? Since the work of Nicholls and Ringwood (1973), many petrologists have favored mechanisms including slab melting and subsequent melt-mantle interaction. A majority of researchers, however, currently believe that the subducting lithosphere dehydrates but does not melt except in arc-trench systems where a young and hot plate is being subducted (Peacock et al., 1994). During the Archean, however, temperatures of both the upper mantle and the subducting crust might have been higher, which could cause slab melting, rather than slab dehydration (Martin, 1987). This possibility will be discussed later.

Under upper mantle *P-T* conditions, H_2O exists as a supercritical fluid, which can dissolve additional components and elements to a certain extent. Therefore, aqueous fluid phases released by dehydration reactions within the subducting lithosphere may be a likely metasomatic agent responsible for the characteristic trace element signatures. To elucidate the geochemical 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 of H_2O contents (1.5 wt%) in both subducting oceanic

materials and arc magmas, the preflux and original subarc mantle compositions (normal mid-oceanic-ridge basalt source), Tatsumi and Kogiso (2003) demonstrated that the geochemical characteristics of arc basalts could be reasonably explained by addition of elements from subducting sediments and oceanic crust through dehydration processes (Fig. 3). On the other hand, Elliott et al. (1997) suggested that slab-derived melts are one possible medium for modifying the mantle wedge so as to make potential sources for some basaltic magmas even in the Mariana arc where subduction of the oldest oceanic lithosphere on Earth causes arc magmatism. Miscibility between silicate melts and hydrous fluids under upper mantle conditions (e.g., Bureau and Keppeler, 1999) could explain the complex metasomatic agents in subduction zones as products of both melting and dehydration.

If element transport by slab-derived fluid phases could be accepted as one major process responsible for the distinctive chemistry of arc basalt magmas, then the fate of dehydrated and chemically modified residues (both sediments and basalts), especially their role in the mantle evolution, should be equally interesting.

Andesitic Magma

Andesite erupts in >80% of arc volcanoes, typifies magmatism in subduction zones, and is the most dominant volcanic rock in mature continental arcs. In addition to this volumetric importance, 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.

Although andesite is defined simply as sub-alkalic, intermediate volcanic rock, its origin is not unique. Two distinctive differentiation trends, tholeiitic (TH) and calc-alkalic (CA), are recognized in the andesitic volcanic rocks of arcs, denoting the presence or absence of relative iron-enrichment

during magmatic differentiation (Wager and Deer, 1939). FeO^*/MgO versus SiO_2 variation plots (FeO^* , total iron as FeO) (Miyashiro, 1974) are commonly used to distinguish the two magma series (Fig. 4A); CA and TH trends generally have steeper and gentler slopes, respectively, than the straight line in Figure 4A. Although the definition of CA versus 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). Another problem is the applica-

tion of Miyashiro's discrimination line as a simple compositional discriminant rather than applying a more desirable "trend slope" comparison (e.g., Hunter and Blake, 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 MgO versus SiO_2 (Fig. 4B); while TH rocks tend to show a concave trend, CA rocks exhibit a straighter trend. It is generally accepted that the TH differentiation trend can be largely reproduced by fractionation 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 supported by MELTS modeling (Ghiorso and Sack, 1995) for a basaltic magma in the presence of 0.5 wt% H_2O at 0.2 GPa under a quartz-fayalite-magnetite (QFM) buffer (Fig. 4).

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 coworkers (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 H_2O 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 H_2O content in the magma source region (i.e., more hydrous for CA magma generation). However, this elegant explanation may not account for the observation that CA andesites commonly exhibit the following disequilibrium petrographic characteristics, which suggest a role for magma mixing in their formation (Eichelberger, 1975; Sakuyama, 1981; Bloomfield and Arculus, 1989; Clyne,

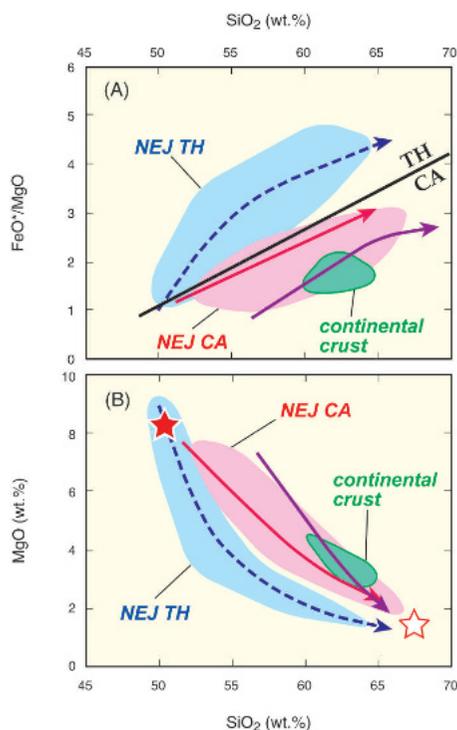


Figure 4. Major element characteristics for calc-alkalic (CA) and tholeiitic (TH) rocks from NE Japan (NEJ) arc and the bulk continental crust (data from Tatsumi and Kogiso, 2003). (A) CA and TH trends generally have steeper and gentler slopes, respectively, than the straight line in a SiO_2 versus FeO^*/MgO diagram (Miyashiro, 1974). (B) While TH rocks tend to show a concave trend in a SiO_2 versus MgO diagram, CA rocks exhibit a rather straight trend. Solid and broken lines with arrows indicate the liquid lines of descent obtained by experiments at 0.2 GPa by Grove and coworkers (e.g., Sisson and Grove, 1993; Grove et al., 2003) and MELTS calculation (see text). Mixing of basaltic and felsic magmas (filled and open stars in Fig. 4B) can explain a rather linear trend for CA series rocks.

1999): (1) the presence of plagioclase phenocrysts with a dusty zone containing fine melt inclusions and with a wide range of compositions; (2) the presence of reversely zoned pyroxene phenocrysts with rounded cores mantled by rims with higher Mg/Fe ratios; (3) the presence of subhedral to rounded olivine phenocrysts rimmed by pyroxene; and (4) the occurrence of disequilibrium mineral assemblages such as Mg-rich olivine and quartz. Mixing of mafic and felsic end-member magmas can form linear trends on variation diagrams (Fig. 4).

If we accept magma mixing as one possible 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 formed at higher *T*, the other more differentiated and formed at lower *T*. A key observation in this problem is a systematic difference in isotopic composition between CA and TH series rocks, as documented at least in some 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 could 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? To improve our understanding of andesite genesis, detailed descriptions of the two magma series rocks from a single volcano are needed.

Continental Crust Formation

The continental crust has an average composition equivalent to CA andesites (Fig. 4) that typify arc magmatism and hence is believed to be created at convergent plate margins (e.g., Kelemen, 1995; Taylor, 1995; Rudnick, 1995). However, modern-day, mantle-derived

magmatism in such settings is dominated by basalt. This dilemma faces anyone interested in the theory of continental crust formation. Herein, possible alternative solutions are considered: (a) direct production of andesitic magmas, and (b) mechanical fractionation of basaltic arc crust to remove the mafic part.

The majority of continental crust was created in the Archean, when the geotherm was steeper and hotter, and it is possible that Archean slab melting, instead of slab dehydration as at present, could have been 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). High-*P* experiments (Rapp et al., 1999) demonstrated that slab melting and subsequent interaction of Si-rich slab-melt with Mg-rich mantle can reproduce andesitic compositions similar to the continental crust. Modeling based on geochemical formulation of partial melting and melt-solid reactions (Tatsumi, 2000a)

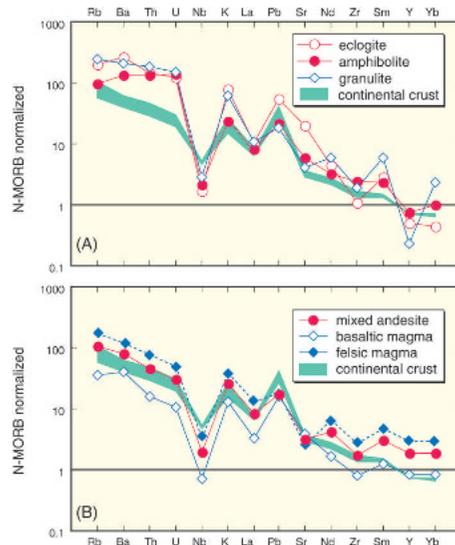


Figure 5. Normal mid-oceanic-ridge basalt (N-MORB)-normalized (Sun and McDonough, 1989) incompatible element characteristics of the bulk continental crust (Taylor, 1995; Rudnick, 1995) and modeled inferred andesite magmas. (A) Andesitic magmas are assumed to be produced by slab melting under three representative *P-T* conditions (eclogite, amphibolite, and granulite facies) and subsequent melt-mantle interactions (Tatsumi, 2000a). (B) An andesitic magma is produced by mixing between a basaltic magma produced by slab dehydration induced by mantle melting and a felsic magma formed by remelting of the initial basaltic arc crust (Tatsumi and Kogiso, 2003).

has confirmed that this mechanism can also account for trace element characteristics of bulk andesitic continental crust (Fig. 5A).

Alternatively, an andesitic magma having compositions similar to the bulk continental crust can be also produced by mixing of a basaltic magma generated by mantle melting induced by slab dehydration with a felsic magma produced by partial melting of the initial basaltic arc crust, as geochemically modeled by Tatsumi and Kogiso (2003) (Fig. 5B). This process of andesitic crust formation is identical to that envisioned for CA andesite production operating in current subduction zones. Although this mixing process can create the andesitic crust, the composition of the total crust is still basaltic, not andesitic. In order to make an andesitic continental crust, therefore, the mafic lower crust, which is a melting residue after segregation of felsic magma, should be extracted from the arc crust. One possible extraction mechanism would be delamination of the lower part of initial basaltic arc crust, because the melting residue may be composed of mafic rocks, containing 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; Jull and Kelemen, 2001).

In summary, the major and incompatible trace element characteristics of andesitic bulk continental crust can be explained by either slab melting or by magma mixing in association with delamination of mafic lower crust. However, waste materials after processing are different for the two mechanisms: melting residue of basaltic oceanic crust at mantle pressures and that of basaltic arc crust at crust pressures for the slab melting and delamination, respectively. This difference will be further examined isotopically in the following section.

RECYCLING PROCESSES

Surface materials such as crust and sediments, from which certain components are extracted during subduction, are injected into the mantle, resulting in significant chemical heterogeneity in the deep mantle. Although the physical properties of descending surficial and mantle materials have been investigated

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

It has been suggested from geochemical studies on mid-oceanic-ridge basalts (MORBs) and oceanic-island basalts (OIBs) that at least four end-member components or geochemical reservoirs in addition to primitive mantle are needed to explain the isotopic diversity of oceanic basalts (e.g., Zindler and Hart, 1986; Hofmann, 1997): depleted MORB mantle (DMM), enriched mantle types I and II (EMI and EMII), and high- μ mantle (HIMU). It is generally believed that DMM, with its distinct isotopically depleted signature, occupies the shallowest upper mantle, whereas other enriched mantle components typify magmas rising from deep-seated hotspots. It may therefore be illuminating to discuss linkages among three enriched geochemical end-members in the deep mantle and waste materials generated in the subduction factory such as sediment, oceanic crust, and possibly delaminated mafic lower crust.

Dehydrated Oceanic Crust and HIMU

The HIMU, or high- μ ($\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$), 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 considered 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. 6A), 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

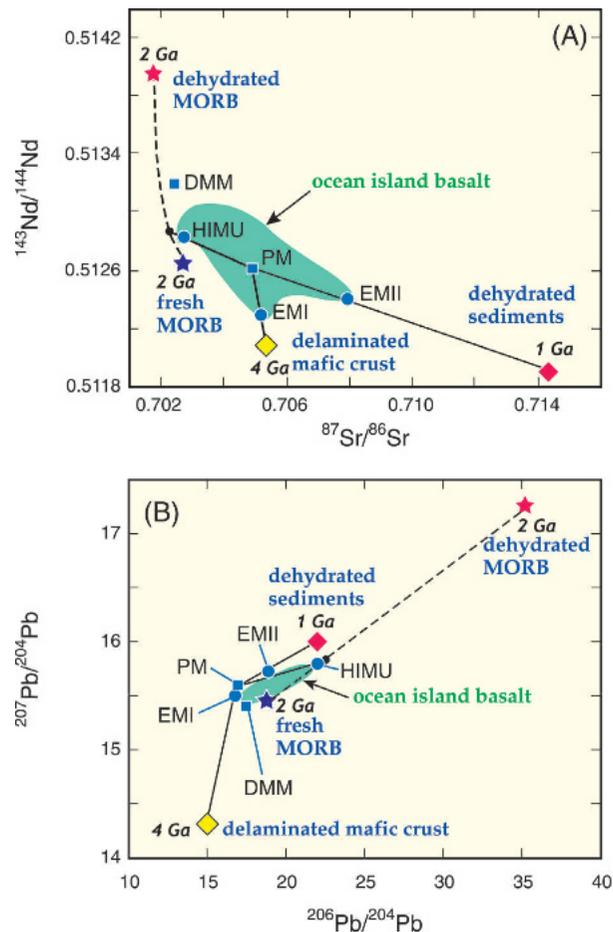


Figure 6. Isotopic compositions of inferred waste materials from the subduction factory (dehydrated/fresh oceanic crust, Tatsumi and Kogiso, 2003; dehydrated sediment, Aizawa et al., 1999; delaminated mafic lower crust, Tatsumi and Kogiso, 2003) and mantle geochemical reservoirs (DMM—depleted mid-oceanic-ridge basalt mantle; HIMU—high- μ mantle; EMI—enriched mantle type I; EMII—enriched mantle type II; MORB—mid-oceanic-ridge basalt; PM—primitive mantle) that have been proposed to explain the isotopic diversity observed for ocean island basalts. Evolution of deep mantle reservoirs may be comprehensively explained by contribution of recycled waste materials from the subduction factory and primitive mantle.

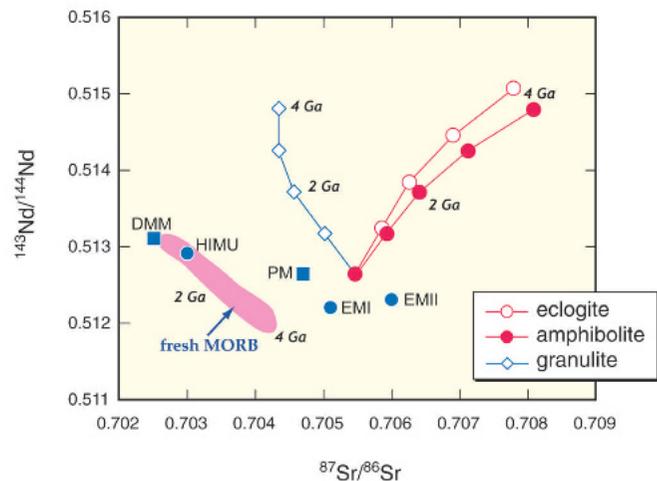


Figure 7. The isotopic evolution of the slab restites produced after extraction of slab melts at three representative P - T conditions (eclogite, amphibolite, and granulite facies; Tatsumi 2000b) and fresh mid-oceanic-ridge basalt (MORB) (Tatsumi and Kogiso, 2003), with ages of formation. Isotopic compositions of mantle geochemical reservoirs (DMM—depleted MORB mantle; HIMU—high- μ mantle; EMI—enriched mantle type I; EMII—enriched mantle type II; and PM—primitive mantle) are also shown. Mixing of slab restites with fresh MORB and/or PM cannot explain the geochemical characteristics of enriched geochemical reservoirs such as EMI, EMII, and HIMU.

both 2 Ga fresh and dehydrated MORB crust in the deep mantle (Fig. 6).

Dehydrated Sediment and EMII

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 (~1 wt%) of 1 Ga dehydrated sediments to primitive mantle (Fig. 6).

Melting Residue of Sinking Oceanic Crust

Partial melting of the sinking basaltic oceanic crust may have taken place more widely during Earth's early history and could have contributed to continental crust formation. If this is the case, then the restites of slab melting, with compositions distinct from the bulk mantle, may have formed a geochemical reservoir in the deep mantle and could have been recycled as a hotspot source. Figure 7 shows the Sr-Nd isotopic evolution of the predicted slab restites formed under three representative P - T conditions (Tatsumi, 2000a). The isotopic characteristics of these slab residues and their mixtures with fresh MORB crusts do not match those of any proposed geochemical end-member mantle component. This may lead to the conclusion that the slab melting did not play the major role in the continental crust formation during the Archean, although it could account for the geochemical characteristics of the bulk continental crust.

Delaminated Mafic Lower Crust and EMI

We now examine linkages between delaminated arc crust and EMI. To make andesitic continental crust, melting residue following extraction of felsic melts needs to be removed and delaminated

from initial basaltic arc crust. This mafic lower crust 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 mixed with a 10%–15% felsic melt component (Fig. 6).

CONCLUSIONS

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. Magmas that tap these deep-seated geochemical 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 nearly as a zero-emission factory in which the solid waste materials (i.e., excluding magmatic gases) are largely 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.

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CORRECTION

In the March 2005 *GSA Today* article by Fastovsky and Sheehan, “The extinction of the dinosaurs in North America,” the second paragraph under the heading “Causes: So What Killed the Dinosaurs?” (p. 7) should read:

Our interest, however, is in published models that are grounded in data and that are potentially testable. In this category, Archibald and Bryant (1990), basing their interpretations upon patterns of vertebrate survivorship,

proposed marine regression with associated habitat fragmentation as the ultimate cause of the K-T extinctions. In this model, multiplication and lengthening of river systems due to a marine regression led to a diminution and fragmentation of coastal plain habitats, in turn causing range reductions and eventual extinction. A variation on this model was proposed by Archibald (1996, 1997) and Dingus and Rowe (1997), who suggested that the regression in combination with latest Cretaceous igneous activity and the asteroid impact caused the extinction of the dinosaurs.