Magma genesis beneath Northeast Japan arc: A new perspective on subduction zone magmatism

Tetsu Kogiso a *, Soichi Omori b, Shigenori Maruyama b

a Graduate School of Human and Environmental Studies, Kyoto University, Yoshida-nihommatsu, Sakyo, Kyoto 606-8501, Japan
b Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan

ABSTRACT

It is being accepted that earthquakes in subducting slab are caused by dehydration reactions of hydrous minerals. In the context of this “dehydration embrittlement” hypothesis, we propose a new model to explain key features of subduction zone magmatism on the basis of hydrous phase relations in peridotite and basaltic systems determined by thermodynamic calculations and seismic structures of Northeast Japan arc revealed by latest seismic studies. The model predicts that partial melting of basaltic crust in the subducting slab is an inevitable consequence of subduction of hydrated oceanic lithosphere. Aqueous fluids released from the subducting slab also cause partial melting widely in mantle wedge from just above the subducting slab to just below overlying crust at volcanic front. Hydrous minerals in the mantle wedge are stable only in shallow (<120 km) areas, and are absent in the layer that is dragged into deep mantle by the subducting slab. The position of volcanic front is not restricted by dehydration reactions in the subducting slab but is controlled by dynamics of mantle wedge flow, which governs the thermal structure and partial melting regime in the mantle wedge.

© 2009 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

1. Introduction

Subduction zone is a location where significant chemical differentiation processes occur, such as the generation of continental crust and transfer of chemical heterogeneity into the deep mantle, both of which play fundamental roles in the chemical evolution of the Earth. Chemical differentiation in subduction zones is promoted mainly by liberation of aqueous fluids from subducting oceanic lithosphere (slab) and resultant magma generation. Therefore, quantitative modeling of fluid liberation in the subducting slab and its relevance to magma genesis in subduction zones is critical for better understanding of the Earth’s chemical evolution. Generation of aqueous fluids and silicate magmas in subduction zones has also been one of the most important issues in the area of igneous petrology, and many researchers have proposed a variety of petrologic models for the fluid and magma genesis in subduction zones (e.g., Nicholls and Ringwood, 1972; Wyllie and Sekine, 1982; Kushiro, 1983, 1989, Schmidt and Poli, 1998; Kimura and Yoshida, 2006). However, there is little consensus on what are keys to explain the important features of subduction zone magmatism, such as the existence of volcanic front and across-arc variations of magma chemistry and volume.

Recent progress in seismological studies of Northeast Japan arc (e.g., Nakajima and Hasegawa 2007; Kita et al., 2006) provided us with highly precise distribution of intraslab earthquakes and detailed seismic velocity structures in the mantle wedge beneath NE Japan (Hasegawa et al., 2009-this issue). In addition, new experimental and theoretical data on hydrous phase relations in peridotite and basalt systems (e.g., Omori et al., 2002, 2004; Komabayashi et al., 2004; Grove et al., 2006) allowed us to know precise pressure-temperature conditions of fluid and magma generation in subduction zones. Moreover, it is widely accepted that embrittlement caused by liberation of fluids from hydrous minerals in subducting slab is a potential cause of intraslab earthquakes (Raleigh, 1967; Kirby et al., 1996; Seno and Yamanaka, 1996, Jung et al., 2004). In the context of this “dehydration embrittlement” hypothesis, the distribution of intraslab seismicity can be linked with stability limits of hydrous minerals in subducting slab, which in turn allows estimating detailed thermal structure of subducting slab (e.g., Omori et al., 2002; Hacker et al., 2003; Omori et al., 2004, 2009-this issue). The thermal structure of subducting slab is an essential parameter for quantitative modeling of magma genesis in subduction zones. In this paper, we combine the latest results of seismic studies of NE Japan with hydrous phase relations in peridotite–basalt systems, and propose a new petrologic model for subduction zone magmatism on the basis of the dehydration embrittlement hypothesis.

2. Subduction zone magmatism: key features and previous models

There are several important features that characterize subduction zone magmatism (Fig. 1). Here we review key features of subduction zone magmatism, and illuminate some problems that have not been
zones, because H2O considerably lowers solidus temperatures of subducting slab play critical roles in generating magmas at subduction – proposed as the main cause for basaltic basaltic crust in the subducting slab (e.g., Nicholls and Ringwood, disputed.

mechanisms of magma genesis in subduction zones have been generated at settings in which the mantle is being cooled by occurrence of magmatism itself, that is, the fact that hot magmas are well explained by previous petrologic models for subduction zone

1960), in particular its correspondence to the depth of subducting slab

surface around 100–130 km (Gill, 1981; Tatsumi, 1986) (Fig. 1). This feature has led some researchers to propose that the locus of magma genesis is controlled by depth-dependent dehydration reactions within and/or above subducting slab (e.g., Tatsumi, 1986, 1989). Tatsumi (1989) attributed the constancy of the slab surface depth beneath volcanic front to dehydration reaction of amphibole in peridotite, which he thought occurs at ~110 km depth just above the subducting slab and forms a hydrous column to cause flux melting in the mantle wedge. However, recent compilations of high-pressure hydrous phase relations (e.g., Schmidt and Poli, 1998; Iwamori, 1998; Omori et al., 2002) revealed that amphibole in the peridotitic system breaks down at pressures less than 3.0 GPa, which corresponds to ~90 km depth. Moreover, it has been shown that serpentine and chlorite have the largest contribution to the H2O budget in peridotite and that amphibole breakdown plays only minor role (Schmidt and Poli, 1998; Omori et al., 2002). Because dehydration reactions of serpentine and chlorite are highly temperature-dependent, there are no major depth-dependent dehydration reactions that can produce considerable amounts of aqueous fluids in mantle wedge at ~110 km depth. Another explanation for the constancy of the slab surface depth is that flow and thermal regime in mantle wedge controls the location of volcanic front (e.g., Kushiro, 1983; Spiegelman and McKenzie, 1987; Iwamori, 1998). Kushiro (1983) suggested that the location of volcanic front should be controlled by the position of wet solids in peridotite in mantle wedge because magmas are generated by continuous addition of aqueous fluids from subducting slab. Spiegelman and McKenzie (1987) numerically demonstrated that streamlines of melt in mantle wedge can converge to one point beneath overlying crust owing to corner flow of solid mantle dragged by subducting slab. Iwamori (1998) numerically simulated migration and chemical reactions of aqueous fluids in solid peridotite flow in mantle wedge, and suggested that extensive melting in mantle wedge occur at fixed depths because similar flux of fluids and flow pattern of solid can be attained regardless of age of subducting slab.

2.1. Occurrence of magmatism

The most important feature of subduction zone magmatism is the occurrence of magmatism itself, that is, the fact that hot magmas are generated at settings in which the mantle is being cooled by subduction of cold oceanic lithosphere. There is a consensus that aqueous fluids released from hydrous minerals brought by the subducting slab play critical roles in generating magmas at subduction zones, because H2O considerably lowers solidus temperatures of magma source materials (e.g., Kushiro, 1969). However, detailed mechanisms of magma genesis in subduction zones have been disputed.

One possible mechanism is hydrous partial melting of oceanic basaltic crust in the subducting slab (e.g., Nicholls and Ringwood, 1972; Kay, 1980; Wyllie and Sekine, 1982). This mechanism had been proposed as the main cause for basaltic–andesitic magmas that dominate subduction zones. However, later melting experiments on hydrous basaltic systems (e.g., Beard and Lofgren, 1991; Rushmer, 1991; Wolf and Wyllie, 1994; Rapp and Watson, 1995) demonstrated that hydrous melting of basaltic crust dominantly produces silicic magmas with particular chemical characteristics like tonalite or adakite, which are limited in volcanic arcs beneath which hot magmas are observed not only in major elements but also in incompatible trace element concentrations (e.g., Gill, 1981; Sakuyama and Nesbitt, 1986) and radiogenic and stable isotopic ratios (e.g., Nohda and Wasserburg, 1981; Hawkesworth et al., 1993; Ishikawa and Nakamura, 1994). The volume variation was first pointed out by Sugimura et al. (1963) who showed that the volume of erupted magmas in NE Japan is largest in the volcanic front and sharply decreases toward the Japan sea. The magma volume decrease toward backarc side has been reported in many volcanic arcs since then (Marsh, 1979; Tatsumi and Eggins, 1995). Some researchers suggested that two volcanic chains occur in many single arcs because the magma volume does not seem to decrease monotonously to the backarc side (Miyashiro, 1974; Marsh, 1979; Tatsumi and Eggins, 1995), although it is not accepted as a general feature of subduction zone magmatism (Ishikawa and Nakamura, 1994; Kondo et al., 1998; K. Kaneko, pers. comm. 2009).

Across-arc variations of chemistry and volume of erupted magmas are also important. Kuno (1959, 1960) reported alkali contents of magmas increase toward the backarc side in the NE Japan arc. After Kuno’s pioneer works, many researchers reported such increasing alkali contents toward backarc side in many volcanic arcs in the world (e.g., Miyashiro, 1974; Dickinson, 1975; Tatsumi and Eggins, 1995; Kimura and Yoshida, 2006). The across-arc chemical variations in magmas are observed not only in major elements but also in incompatible trace element concentrations (e.g., Gill, 1981; Sakuyama and Nesbitt, 1986) and radiogenic and stable isotopic ratios (e.g., Nohda and Wasserburg, 1981; Hawkesworth et al., 1993; Ishikawa and Nakamura, 1994). Cross-arc chemical variations in magmas are observed not only in major elements but also in incompatible trace element concentrations (e.g., Gill, 1981; Sakuyama and Nesbitt, 1986) and radiogenic and stable isotopic ratios (e.g., Nohda and Wasserburg, 1981; Hawkesworth et al., 1993; Ishikawa and Nakamura, 1994). The volume variation was first pointed out by Sugimura et al. (1963) who showed that the volume of erupted magmas in NE Japan is largest in the volcanic front and sharply decreases toward the Japan sea. The magma volume decrease toward backarc side has been reported in many volcanic arcs since then (Marsh, 1979; Tatsumi and Eggins, 1995). Some researchers suggested that two volcanic chains occur in many single arcs because the magma volume does not seem to decrease monotonously to the backarc side (Miyashiro, 1974; Marsh, 1979; Tatsumi and Eggins, 1995), although it is not accepted as a general feature of subduction zone magmatism (Ishikawa and Nakamura, 1994; Kondo et al., 1998; K. Kaneko, pers. comm. 2009).

Across-arc variations of magma chemistry and volume have been attributed to physical conditions of magma genesis that tend to be affected by subduction of oceanic lithosphere. Before the concept of plate tectonics was established, Kuno (1959) already proposed that arc magmas are generated along the deep seismic zone (Wadati–Benioff zone) and attributed the chemical variations of arc magmas to

2.2. Formation of volcanic front

Another key feature is the formation of volcanic front (Sugimura, 1960), in particular its correspondence to the depth of subducting slab

---

**Fig. 1.** Schematic illustration of the key features of subduction zone magmatism.
the different depth of magma generation. Later high-pressure melting experiments on basalt systems (e.g., Green and Ringwood, 1967; Kushiro, 1968) revealed that the depth of the Wadati–Benioff zone (i.e., subducting slab) is too deep to explain chemical characteristics of magmas. Nevertheless, it is widely accepted that the depth of magma generation and/or segregation plays a key role in producing across-arc chemical variations, because further high-pressure experiments (Kushiro, 1983; Tatsumi et al., 1983) has demonstrated that alkali basalts that dominate in backarc side volcanism can segregate from peridotite at deeper part in mantle wedge than tholeiitic basalts in the volcanic front. Chemistry of aqueous fluids released from subducting slab is also an important parameter that affects the across-arc chemical variations, especially in trace element concentrations (Gill, 1981; Tatsumi and Kogiso, 1997; Hochstaedter et al., 2001; Kimura and Yoshida, 2006; Nakamura et al., 2008).

The cause of the volume decrease toward backarc side is controversial. One explanation is that flux of slab-derived fluids, which promote partial melting in mantle wedge, is largest beneath volcanic front and decreases toward backarc side (Gill, 1981; Tatsumi, 1989; Cagnioncle et al., 2007). However, as described above, there are no dehydration reactions that can supply large amounts of fluids just below volcanic front. Another explanation is the existence of partial melting zone inclined toward backarc side, in which the largest extent of melting sufficient for melt segregation can be achieved at the upper end below volcanic front (Marsh, 1979; Kushiro 1983; Schmidt and Poll, 1998). Such inclined partial melting zone in mantle wedge can be formed because strong focusing of flow in the wedge corner caused by Newtonian temperature-dependent or non-Newtonian rheology produces high temperature zone slanted toward backarc side (Furukawa, 1993; van Keken et al., 2002; Kelemen et al., 2003). This thermal structure in the wedge corner can also explain the across-arc difference in magma segregation depth.

### 3. New view of subduction zone magmatism

The most remarkable progress in recent studies of subduction zone is the increasing acceptance of the dehydration embrittlement hypothesis as the cause of intraslab earthquakes (e.g., Kirby et al., 1996; Jung et al., 2004; Hasegawa et al., 2009-this issue). As Hasegawa et al. (2009-this issue) summarized, an assumption that intraslab earthquakes occur where hydrous minerals dehydrate in subducting slab can well explain many important phenomena in subduction zone: the existence of double seismic zone in the slab, uneven distribution of earthquakes within it, seismic velocity structure of the slab and so on (Omori et al., 2002, 2004; Kita et al., 2006; Tsuji et al., 2008; Omori et al., 2009-this issue; Nakajima et al., 2009). The dehydration embrittlement hypothesis has great significance for modeling of subduction zone magmatism because it allows us to link intraslab earthquakes to the thermal structure of subducting slab and mantle wedge by comparing loci of earthquakes with pressure–temperature limits of hydrous mineral stabilities (Hacker et al., 2003; Omori et al., 2002; Yamazaki and Seno, 2003; Omori et al., 2004; Nakajima et al., 2009). The thermal structure of subducting zone, which is critical to understand subduction zone magma genesis, has been estimated only by numerical simulations (e.g., Davies and Stevenson, 1992; Furukawa, 1993; Iwamori, 1998; Kelemen et al., 2003), but now it can be determined by seismic observations and hydrous phase relations. Here we summarize recent progress in studies on seismology of NE Japan with regard to the relevance to modeling magma genesis (Fig. 2) as well as recent studies on phase relations of hydrous minerals and melts in basalt and peridotite systems.

#### 3.1. Seismic observations

A notable feature of the seismic activities in NE Japan is the presence of a double-planed seismic zone in the subducting pacific slab (Umino and Hasegawa, 1975; Hasegawa et al., 1978). The two planes of the double seismic zone converge to one plane at around 180 km depth (Hasegawa et al., 1978), beneath which the earthquake activity decreases in the slab. If dehydration embrittlement induces intraslab earthquakes, the location of the double seismic zone should be loci of dehydration reactions in the subducting slab (Omori et al., 2002; Hacker et al., 2003), which imposes strong constraints on the thermal structure of the subducting slab. Recently, Kita et al. (2006) precisely relocated intermediate-depth (50–150 km) earthquakes beneath NE Japan by applying the double-difference hypocenter location method (Waldhauser and Ellsworth, 2000), and revealed dense concentration of seismicity at depths of 70–90 km in the upper plane of the double seismic zone (Fig. 2). This “upper-plane seismic belt” is located near the upper boundary of the subducting Pacific slab, probably in the basaltic crust in the slab (Kita et al., 2006). The existence of the upper-plane seismic belt implies that major dehydration reactions occur in the basaltic slab at these depths (Hacker et al., 2003; Omori et al., 2004; Omori et al., 2009-this issue; see discussion below). Kita et al. (2006) also show that thicknesses of both the upper and lower planes of the double seismic zone are ~15 km or thinner, suggesting that dehydration reactions in the slab occur just within restricted zones.

Tsuji et al. (2008) determined detailed seismic velocity structure of the subducting Pacific slab by double-difference tomography method (Zhang and Thurber, 2003). The obtained tomography image shows the existence of a thin (~10 km) low-velocity layer at the top of the slab (Fig. 2). The low-velocity layer gradually disappears at depths of 70–90 km, which corresponds to the depth of the upper-plane seismic belt found by Kita et al. (2006). Tsuji et al. (2008) also show that a low-velocity layer exists in the mantle wedge just above the Pacific slab at depths greater than 70–90 km (Fig. 2). This low-velocity layer corresponds to that already found by previous studies (Matsuzawa et al., 1986; Kawakatsu and Watada, 2007), which continues to deeper than 200 km (Tonegawa et al., 2008). These observations suggest that dehydration reactions take place in subducting hydrated basaltic slab at depths around 70–90 km where expelled aqueous fluids move to the mantle wedge and form a hydrous layer just above the slab (Tsuji et al., 2008; Nakajima et al., 2009) and that the hydrous layer in the mantle wedge is dragged into depths greater than 200 km by the subducting slab (Kawakatsu and Watada, 2007; Tonegawa et al., 2008). It is also shown that another thin low-velocity layer exists around the lower plane of the double seismic zone within the subducting slab (Tsuji et al., 2008; Nakajima et al., 2009), suggesting significant amounts of aqueous fluids released also along the lower seismic plane.

Intensive seismic tomography studies beneath NE Japan (e.g., Hasegawa et al., 1991; Zhao et al., 1992; Tsumura et al., 2000; Nakajima et al., 2009).
et al., 2001; Hasegawa and Nakajima, 2004) have revealed the existence of a prominent low-velocity zone in the mantle wedge that is inclined toward backarc side subparallel to the subducting slab (Fig. 2). This low-velocity zone is observed in the whole region of NE Japan, that is, the low-velocity zone has sheet-like shape. The low-velocity zone also has high Vp/Vs ratios and high seismic attenuation (Zhao et al., 1992; Nakajima et al., 2001; Tsumura et al., 2000), and extends from depths around 150 km to the Moho just beneath the volcanic front (Zhao and Hasegawa, 1993; Zhao et al., 1994; Nakajima et al., 2001; Hasegawa and Nakajima, 2004). The existence of the sheet-like inclined low-velocity-high-attenuation zone is thought to correspond to the locus of upwelling flow in the mantle wedge, in which peridotite is partially molten (e.g., Iwamori and Zhao, 2000; Hasegawa and Nakajima, 2004). The presence of small amounts of partial melts in the inclined low-velocity-zone is supported by detailed investigations of its seismic attenuation structure (Nakajima and Hasegawa, 2003; Nakajima et al., 2005). Detailed tomographic images of the inclined low-velocity zone obtained by Hasegawa and Nakajima (2004) show that there are several very low-velocity areas in the low-velocity zone, and that their positions well correspond to the locations of volcanic clusters and loci of low-frequency microearthquakes observed (Okada and Hasegawa, 2000). On the basis of these observations, Hasegawa and Nakajima (2004) proposed that partial melts segregated from the very low-velocity areas in the low-velocity zone rise vertically to the overlying crust and cause volcanisms and low-frequency microearthquakes.

3.2. Subsolidus phase equilibria in hydrous systems

Subsolidus phase relations of hydrous minerals in peridotite and basalt systems have been determined in detail by high-pressure experiments and thermodynamic calculations in the last decades (e.g., Schmidt and Poli, 1998; Iwamori, 1998; Omori et al., 2002; Iwamori, 2004; Omori et al., 2004; Okamoto and Maruyama, 2004; and references therein). Omori et al. (2009-this issue) newly constructed P–T phase diagrams in the model system MgO–Al2O3–SiO2–H2O (MASH) for peridotite compositions and Na2O–CaO–FeO–MgO–Al2O3–SiO2–H2O (NCFMASH) for basalt composition by thermodynamic calculations.
and semi-quantitative analysis of high-pressure experiments. Details of calculation, chemical compositions and thermodynamic data of phases encountered in the model are described in Omori et al. (2009-this issue). The phase diagrams determined for model lherzolite, harzburgite, and oceanic crust (mid-oceanic ridge basalt: MORB) compositions are shown in Fig. 3. Principal hydrous phases that can release large amounts of fluids in peridotite systems are serpentine, brucite, talc and chlorite (Fig. 3a–b). Although amphibole is also a major hydrous mineral in natural peridotite systems including Na2O (e.g., Schmidt and Poli, 1998; Grove et al., 2006), its contribution to H2O budget in subducting slab peridotite is much smaller than above three minerals (Iwamori, 1998, 2007). So the phase diagram in the MASH system is a good approximation of hydrous phase equilibria in peridotite of subducting slab and mantle wedge. Thus the major dehydration reactions in subducting slab occur under P–T conditions where serpentine, brucite, talc and chlorite decompose (between thick lines in Fig. 3a–b). The high-pressure end of this “main dehydration field” is around 6–7 GPa (∼200 km depth) (Omori et al., 2002, 2009-this issue), which is close to the depth at which the two planes of the double seismic zone converge (Fig. 2). It should be noted that decomposition reactions of these minerals are highly temperature-dependent, that is, they occur within narrow temperature interval (∼200 °C; Fig. 3a–b), suggesting these reactions are useful to estimate temperature distribution in subducting slab in the context of the dehydration embrittlement hypothesis (e.g., Omori et al., 2002).

In the hydrous basalt system (Fig. 3c), major dehydration reactions are decomposition of Ca-amphibole (∼2 GPa), epidote (1–2.5 GPa), lawsonite and Na-amphibole (∼2 GPa). The Ca-amphibole decomposition reaction is pressure-dependent, that is, its decomposition occurs at nearly constant pressure over a range of temperature (Fig. 3c). In contrast, decomposition reactions of lawsonite and Na-amphibole are rather temperature-dependent than pressure-dependent. Thus, loci of dehydration in basaltic slab is sensitive to temperature at depths greater than ∼70 km. This means that the uneven distribution of earthquakes within the basaltic slab (Kita et al., 2006) is also useful to estimate temperature distribution in subducting slab (Omori et al., 2009-this issue).

3.3. Melting phase relations of hydrous systems

Grove et al. (2006) precisely determined melting phase equilibria of hydrous lherzolite at near-solidus conditions by careful observations of high-pressure experiment products, and found that the solidus temperature of peridotite is as low as 800 °C at 3.2 GPa (Fig. 3d). A surprising result of their experiments is that chlorite appears as a stable phase above the solidus at pressures higher than 2.8 GPa. This means that hydrous peridotite will melt even below the stability limit of chlorite. Melting phase equilibria of hydrous basaltic system determined for a typical MORB composition (Liu et al., 1996; Schmidt and Poli, 1998) showed that the solidus of hydrous MORB basalt locates around 700 °C at 1–2 GPa, which is also well below the stability limit of chlorite in hydrous peridotite (Fig. 3d). These data imply that basalt and peridotite necessarily melt at depths greater than ~80–100 km if their temperatures are higher than the chlorite stability limit.

The other important feature of hydrous melting of peridotite is complete miscibility between aqueous fluid and silicate melt at high pressures (Mibe et al., 2007). In situ observation of high-pressure and high-temperature experimental runs by synchrotron radiation X-ray radiography (Mibe et al., 2007) revealed that aqueous fluid and hydrous silicate melt in a peridotite system become indistinguishable above 3.8 GPa and ~1000 °C (Fig. 3d). Therefore, at depths greater than ∼110 km, there can exist one supercritical liquid at higher temperatures, which changes its composition with increasing temperature gradually from H2O-rich to silicate-rich at around 1000 °C.

4. Modeling for magma genesis

On the basis of the recent seismic and petrologic studies summarized above, we propose a new petrologic model for magma

---

**Fig. 4.** Seismic data in the cross section beneath Kurikoma–Chokai line of NE Japan arc. The position of the cross section is shown as a line in the inset. Red triangles in the inset are Quaternary volcanoes, among which Sengan area (see text) is circled. (a) S-wave velocity perturbation determined by Nakajima et al. (2001). Gray and red circles are microearthquakes and low-frequency microearthquakes, respectively (Okada and Hasegawa, 2000). (b) Detailed S-wave velocity perturbation determined with double-difference tomography method by Nakajima et al. (2009). The image (a) was obtained so that the long wave-length (∼20 km) structure around the central part of the mantle wedge is clearly determined (Nakajima et al., 2001). On the other hand, the image (b) was obtained so that the shorter wave-length (∼5 km) structure near the slab surface is clearly determined (Nakajima et al., 2009). Thus, the difference between (a) and (b) is due to the differences not only in tomographic inversion method but also in region that is well resolved by each method. (c) Locations of intraslab earthquakes determined with double-difference hypocenter location method by Kita et al. (2006, 2008). The inclined line is the position of the slab surface (Kita et al., 2008). Colors indicate distance from the slab surface: red = <10 km, green = 10–23 km, blue = >23 km, gray = above slab surface.
genesis in NE Japan arc. The seismic data we employed for modeling are the vertical cross sections of seismic tomography in the mantle wedge (Nakajima et al., 2001), high-resolution tomography near the top of the subducting slab (Nakajima et al., 2009), and distribution of earthquakes in the subducting slab (Kita et al., 2006, 2008) along the line connecting Kurikomayama and Chokaisan volcanoes (Fig. 4).

4.1. Thermal structure

For estimating temperature distribution in subduction zone, we employ several major assumptions in the context of the dehydration embrittlement hypothesis as follows.

(1) The location of the double seismic zone in the subducting Pacific slab corresponds to the main dehydration field in the P-T diagram of the hydrous peridotite (Omori et al., 2002) (Fig. 3a). The inner edge of the double seismic zone is where brucite in harzburgite or talc in lherzolite decomposition starts, and the outer edge is where chlorite decomposition ends.

(2) Thickness of basaltic crust in the subducting slab is 7 km. The earthquakes within 7 km from the upper boundary of the subducting slab are caused by dehydration reactions in the basaltic system.

(3) The bulk composition of peridotite in the mantle wedge and in the subducting slab is depleted lherzolite, except that the uppermost portion of the peridotite slab consists of harzburgite (i.e., the upper plane of the double seismic zone is within the harzburgite portion). The bulk of subducting oceanic crust is average MORB (Omori et al., 2002, 2009-this issue).

When employing the assumption (1), we didn’t take into account the earthquakes between the upper and lower plane of the double seismic zone at ~60–90 km depths. The wide distribution of these “interplane” earthquakes at these depths can be explained by continuous decomposition of brucite if we include Fe in the bulk system (Omori et al., 2002; Omori and Komabayashi, 2007). Other assumptions we employed to determine the thermal structure are described and discussed below. We used here constraints obtained from petrologic studies only in order to clarify the difference from the thermal structure determined by seismic studies and numerical modeling (e.g., Iwamori, 1998; Kelemen et al., 2003; Nakajima and Hasegawa, 2003; Nakajima et al., 2005).

The temperature distribution in the mantle wedge is difficult to estimate because few petrologic constraints are available. Ueki and Iwamori (2007) investigated thermal and chemical conditions of magma genesis beneath the volcanic front of NE Japan by dense sampling and petrologic analyses of volcanic rocks in Sengan area (Fig. 4), and revealed by thermodynamic calculations with pMELTS (Ghiorso et al., 2002) that parental magmas were produced at 1250–1300 °C and 1.0–1.5 GPa with 0.3–0.5 wt.% H2O. Thus we assume that the temperature at the Moho just below the volcanic front is around 1300 °C.

To estimate temperatures around the inclined low-velocity zone in the mantle wedge, we focused our attention to the change of velocity anomaly values near the center of the low-velocity zone. The S-wave velocity perturbation value abruptly changes around +1% to −3% on both side of the low-velocity zone (Fig. 4a). We interpret that this abrupt change corresponds to a sudden increase of melt fraction, because velocity reduction rates are correlated with melt fraction in addition to aspect ratio of melt pore and temperature (Nakajima et al., 2005). Melting experiments on hydrous depleted peridotite (Kubo, 2003) demonstrated that melt fraction of depleted peridotite under hydrous condition remains very low (<10%) between the hydrous solidus and the dry solidus and steeply increases around dry solidus temperature. Therefore, we assume that the position of the −1 to −3% contours of the S-wave velocity perturbation roughly matches the solidus of dry depleted peridotite (Robinson et al., 1998; Wasylenki et al., 2003; Laporte et al., 2004). The temperature distribution in the subducting slab and mantle wedge determined with these assumptions is shown in Fig. 5.

4.2. Distribution of hydrous minerals and aqueous fluids

From the temperature distribution determined above and hydrous phase relations (Figs. 3 and 5), we estimated the stability fields of hydrous minerals, aqueous fluids and silicate melts in the subducting slab and mantle wedge (Fig. 6). We assumed that aqueous fluids liberated from the double seismic zone migrate vertically much faster than slab subduction and mantle wedge flow just for simplicity. As the
slab continues subducting, aqueous fluids are continuously supplied, and the liberated fluids hydrate the overlying portion of the slab and the mantle wedge along migration paths. Thus the slab above the double seismic zone and the mantle wedge would be locally saturated with H₂O along fluid migration paths. Therefore, we drew the stability fields of hydrous minerals and silicate melts, and possible distribution of free aqueous fluids for H₂O-saturated conditions (Fig. 6), but we do not mean that these phases are uniformly distributed within the respective stability fields.

Our estimation shows that hydrous minerals (mainly serpentine) can be present in the wedge corner and in the subducting slab between the double seismic zone if aqueous fluids are supplied there (Fig. 6a). This is consistent with high Poisson’s ratios observed within the wedge corner and subducting slab beneath Kanto area of Japan (Kamiya and Kobayashi, 2000; Omori et al., 2002). It should be noted that the stability fields of hydrous minerals in the mantle wedge are limited to the wedge corner shallower than 120 km (Fig. 6a). This results from the temperature distribution determined by extrapolation of the outer boundary of the double seismic zone (= stability limits of hydrous phases in peridotite) into the mantle wedge, which crosses the slab surface at around 120 km depth. This means that no hydrous minerals exist at the bottom layer of the mantle wedge deeper than 120 km, that is, the bottom layer dragged by the subducting slab into deep mantle is free from hydrous minerals even though aqueous fluids are being supplied from the subducting slab. In the basaltic slab, hydrous minerals are stable up to ∼120 km depth, but major dehydration reactions occur around 60–80 km depths (Fig. 3c). This corresponds to the depth of the lower end of the low-velocity layer at the top of the slab (Fig. 4b; Nakajima et al., 2009), suggesting that the low-velocity layer in the slab is consistent with the presence of hydrated basaltic slab.

Major dehydration reactions occur between talc/brucite and chlorite stability limits in the peridotite slab (the main dehydration field of Fig. 3a–b) as well as at shallower (<120 km) part of the basaltic slab (Fig. 3c). Therefore, free aqueous fluids can be present within the double seismic zone and basaltic slab because aqueous
fluids are continuously liberated there as the slab sinks (Fig. 6b). In the wedge corner, aqueous fluids are continuously supplied from the subducting slab, but the mantle flow is thought to be quite slow (e.g., Kelemen et al., 2003). Therefore, the supplied fluids can hydrate peridotite in the corner until it becomes oversaturated with H2O along fluid migration paths. Thus free fluids can also be present in the wedge corner (Fig. 6b). On the other hand, in the slab between the upper and lower planes of the double seismic zone, it is unclear whether free fluids can be present. Because the supply of liberated fluids from the lower seismic plane will stop when all hydrous minerals completely decompose, the liberated fluids will be completely consumed by hydration of surrounding peridotite if their flux is small. The fluid flux from the lower seismic plane depends on the amounts of hydrous minerals there, which is to be quantitatively investigated in future studies.

4.3. Locus of partial melting

Since aqueous fluids are supplied to the basaltic slab from the double seismic zone below, the basaltic slab can be saturated with H2O along fluid migration paths even above the stability limits of hydrous minerals in the basalt system (Fig. 3c). This causes partial melting within the basaltic slab at depths around 120 km and deeper (Fig. 6) where the temperature of the basaltic slab exceeds the hydrous solidus of basalt (Fig. 3d). In other words, slab melting necessarily occurs beneath NE Japan if we accept the dehydration embrittlement hypothesis.

Partial melting also occur in a wide area of the mantle wedge (Fig. 6), because the temperatures in most parts of the mantle wedge exceed the hydrous solidus of peridotite (Figs. 3 and 5). It should be noted that the partial melting area extends from just above the subducting slab. Melt fraction increases toward the center of the inclined low-velocity zone and become highest just below the volcanic front, if we assume that the S-wave velocity perturbation correlates with melt fraction (Nakajima et al., 2005). Thus the position of the volcanic front corresponds to the area of maximum melt fraction in the mantle wedge, and is not related to hydrous phase stabilities (see discussion below).

5. Discussion

5.1. Slab melting

An important feature of the petrologic model we proposed here is that partial melting occurs in the subducting slab. In previous studies on subduction zone magmatism, it has widely been thought that slab melting occurs only where relatively young oceanic lithosphere is subducting (e.g., Drummond and Defant, 1990; Peacock, 2003). Therefore, in the NE Japan, where a very old (∼130 Ma) oceanic plate is subducting, slab melting has never been considered to occur (e.g., Tatsumi, 1989; Iwamori, 2007). However, in the context of the dehydration embrittlement hypothesis, the subducting Pacific oceanic crust inevitably undergoes partial melting because of the melting phase relations of hydrous basalt (Fig. 3). This means that slab melting commonly occur in subduction zones worldwide. This is consistent with the numerical model incorporating temperature-dependent viscosity (Kelemen et al., 2003), which demonstrated that slab surface temperature can exceed wet solidus of basalt even if subducting slab is older than 80 Myr.

Slab melting can be one of the main factors to produce across-arc variations in arc basalt chemistry. The across-arc geochemical variations of arc basalts were well documented by thorough petrological and geochemical studies (e.g., Sakuyama and Nesbitt, 1986; Shibata and Nakamura, 1997; Hochstaedter et al., 2001; Ishizuka et al., 2003; Kimura and Yoshida 2006). These studies attributed the across-arc variations to many different processes, such as different degrees of partial melting in the mantle wedge, difference in chemistry of slab-derived fluids, differences in amounts of slab-derived components and so on (see Kimura and Yoshiida (2006) for details). Some of the previous studies suggested that partial melting of subducting sediments contribute to produce the across-arc variations even in old subduction zones like Izu-Mariana (e.g., Johnson and Plank, 1999; Ishizuka et al., 2003). Because the solidus temperatures of sediment and basalt are similar under hydrous conditions (Schmidt and Poli, 1998; Johnson and Plank, 1999), partial melting of basaltic slab can occur if sediment melting occurs. In our model, subducting slab releases aqueous fluids into overlying mantle wedge at shallower depths (∼120 km), whereas it supplies partial melts (or supercritical liquid) from the basaltic slab at deeper depths (∼120 km). Thus liquid phases released from the subducting slab change their chemical compositions with increasing depth, and such changes in chemistry of slab-derived fluid/melt can be another important factor to make across-arc chemical variations of basalt chemistry. Detailed experimental studies for chemistry of fluids, melts and supercritical liquids released from hydrous basalt and peridotite compositions will advance our understanding of the role of slab melting to arc basalt chemistry.

5.2. Low-velocity layer at the bottom of the mantle wedge

Another remarkable aspect of our model is the absence of hydrous minerals in the mantle wedge just above the subducting slab at depths deeper than 110 km. Many previous models have proposed that hydrous minerals are stable in the bottom layer of the mantle wedge if subducting slab is as cold as the Pacific slab beneath NE Japan and that the layer is dragged into deep mantle by subducting slab (Tatsumi, 1989; Schmidt and Poli, 1998; Iwamori, 2004). These previous models suggested that hydrous minerals in the dragged layer are stable beneath volcanic front and deeper. In our model, however, hydrous minerals are stable only at shallow (∼120 km) depths in the mantle wedge corner. Therefore, the thin low-velocity layer just above the slab around 70–90 km depths found by the double-difference tomography (Tsuij et al., 2008; Nakajima et al., 2009) corresponds to the hydrous mineral stability area of our model (Figs. 2 and 6). However, the low-velocity layer found at the deeper portion (Kawakatsu and Watada, 2007; Tonegawa et al., 2008) does not indicate the presence of hydrous minerals there.

The deep low-velocity layer, which was found by the receiver function technique (Kawakatsu and Watada, 2007; Tonegawa et al., 2008), is not necessarily a thin “layer”, because the thickness of the low-velocity “layer” cannot be constrained solely by the receiver functions. Instead, the receiver function technique is sensitive to an sharp velocity change within a short length scale. Such a sharp velocity change can be attained in our model. Our model predicts that partial melting in the mantle wedge occurs just above the subducting slab and in the slab at deeper than ∼120 km (Fig. 6). Below this partial melting zone, hydrous minerals and/or free aqueous fluids are present, and the boundary of these zones are nearly parallel to the slab surface (Fig. 6b). Although amounts of aqueous fluids and hydrous minerals in the slab are difficult to constrain, it is clear that the fraction of “liquid” (silicate melt or aqueous fluid) in a certain volume of peridotite/basalt abruptly increases around the solidus with increasing temperature in a hydrous peridotite and basalt systems (Fig. 7). Therefore, the fraction of partial melts in the partial melting zone is much higher than the fraction of aqueous fluids in the slab, at least along fluid migration paths. Thus, the bottom of the partial melting zone can be a sharp velocity-jump boundary (Fig. 7), which can be detected by the receiver function technique.

5.3. Position of volcanic front

Since the major dehydration reactions in the slab are essentially temperature-dependent (Fig. 3), there is no rationale for the idea that the position of volcanic front is controlled chiefly by pressure-
dependent dehydration reactions in the mantle wedge (Tatsumi, 1986, 1989). Therefore, such “single phase dehydration model” is no longer valid for subduction zone magmatism, as already pointed out by Schmidt and Poli (1998). Our model predicts that chlorite and serpentine decompose beneath the volcanic front in the mantle wedge (Fig. 6), which seems to indicate that these decomposition reactions in the mantle wedge control the position of volcanic front. However, the position of these decomposition reactions is chiefly governed by the temperature distribution in the mantle wedge. In addition, partial melting widely occurs in the mantle wedge, so the position of chlorite and serpentine decomposition does not have direct relevance to the position of volcanic front. Thus, the thermal structure in the mantle wedge is the key to the formation of volcanic front and the constancy of the depth to the slab surface beneath volcanic front.

Many researchers proposed that the inclined low-velocity zone corresponds to the locus of partial melting (Kushiro, 1987; Iwamori and Zhao, 2000; Hasegawa and Nakajima, 2004; Nakajima et al., 2005). Hasegawa and Nakajima (2004) suggested that the inclined low-velocity zone indicates the position of a sheet-like upwelling flow in the mantle wedge where significant partial melting occurs. Iwamori (1998, 2007) numerically demonstrated that flow pattern in the mantle wedge and fluid flux from the slab are not changed significantly even if angle and age of subducting slab vary, suggesting that a similar thermal structure can be achieved in various subduction zones. These studies imply that the position of volcanic front is controlled by inclined upwelling flow, which can be formed at a similar position in various subduction zones. However, it is not theoretically clarified why the flow pattern in the mantle wedge can be similar with varying age and angle of subducting slab. Since there are no petrologic constraints to rationalize the formation of volcanic front so far, more theoretical investigations on the dynamics of mantle wedge flow is needed.

5.4. Temperature distribution in the mantle wedge

In our model, we assumed that the temperature in the mantle wedge exceed the dry solidus of depleted peridotite near the central portion of the inclined low-velocity zone (~1300 °C just below the volcanic front; Fig. 5) based on recent petrologic studies on arc basalts (Ueki and Iwamori, 2007). This estimation is too high as compared with the mantle wedge temperature estimated by numerical modeling (e.g., Drummond and Defant, 1990; Iwamori, 1998; Peacock, 2003). This discrepancy mainly derives from uncertainties in the rheological properties of mantle wedge incorporated in numerical calculations, as demonstrated by van Keken et al. (2002) and Kelemen et al. (2003). Our understanding of the rheological and other physical properties of mantle materials is not yet adequate to rigidly constrain the temperature in the mantle wedge.

We did not draw high temperature anomaly below the backarc-side volcanism (i.e., Chokai volcanic zone) in our model (Fig. 6), because the seismic velocity structure (Fig. 4a) doesn’t show significant anomalies beneath the backarc-side volcanoes. This can be explained by localization of melt migration. The occurrence of low-
frequency microearthquakes just below the Chokai volcano (Fig. 4) is thought to be caused by migration of liquid phases (Hasegawa et al., 1991). This suggests that partial melts are migrating upward there (Hasegawa and Nakajima, 2004). Therefore we interpret that magmas of the backarc-side volcanoes are segregated from the inclined partial melting zone and migrate upward in small length scales that cannot be detected by seismic tomography.

5.5. Implication of slab melting

If slab melting is a general feature of the subduction zone magmatism, it has an important implication for deep mantle recycling of crustal material. As partial melting of subducting ocean crust proceeds, the composition of its residue approaches bimineral eclogite (comprised solely of garnet + clinopyroxene) owing to the loss of silica-rich components as partial melts (Kogiso et al., 2004). Since bimineral eclogite is on the thermal divide in the peridotite-basalt melting regime (O’Hara, 1968; Kogiso et al., 2004), the residue composition remains bimineral until partial melting ceases. Therefore, bimineral eclogite can be the representative lithology of the crustal material subducting into deep mantle. If such bimineral eclogite is recycled in the deep mantle and involved in upwelling mantle plumes, it can generate nepheline-normative melts similar to alkaline ocean island basalts (OIB) that are dominant product in many hotspot volcanoes (Kogiso et al., 2003; Kogiso and Hirschmann, 2006). Thus, the idea that slab melting is a general phenomenon in subduction zone is consistent with OIB genesis that requires common occurrence of bimineral eclogite in their source regions as recycled crustal component.

6. Summary

Recent remarkable progress in seismic studies of NE Japan and petrologic studies of hydrous phase relations in the mantle enabled us to newly build a petrologic model for subduction zone magmatism from the viewpoint of the dehydration embrittlement hypothesis. Our model demonstrates that subducting slab inevitably undergoes partial melting in the basaltic portion. Hydrous minerals in mantle wedge are stable only in shallow (~120 km) part of the wedge corner, and no dehydration reactions occur at deeper areas in the mantle wedge. Aqueous fluids are supplied into the mantle wedge chiefly by temperature-dependent decomposition reactions of serpentine, talc, brucite and chlorite in subducting slab. Partial melting occurs in a wide area of mantle wedge, from just above subducting slab to just below volcanic front. The formation of volcanic front is controlled by distribution of partial melts in mantle wedge, which is governed by dynamics of mantle flow and melt migration. Petrologic constraints do not provide a rationale for the constancy of slab depth beneath volcanic front.

Acknowledgments

We are extremely grateful to Junichi Nakajima and Saeko Kita for providing us with their up-to-date seismic data and related figures. We deeply thank Prof. Hasegawa for his outstanding seismic studies, which stimulated us to review subduction zone magmatism. The model proposed here has been developed through extensive discussions in the subduction zone meetings held by Prof. Hasegawa’s and Maruyama’s groups. We thank Profs. Hasegawa, Matsuzawa, Umino, Zhao, and other members who attended the meetings and for constructive and helpful discussion. Discussions with Katsuya Kaneko and Mamoru Kato were helpful to improve our model. The manuscript has been improved with constructive comments by two anonymous reviewers.

References


