Magma Distribution in Island Arc Mantle in Three Dimensions

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Abstract : Distribution of partial melt (magma) in the upper mantle is investigated in detail from the seismic tomography of the mantle wedge beneath northeastern Japan. The comparison of the fine velocity structure with the laboratory velocity data on a partially-molten mantle rock yields estimates of three-dimensional distribution of melt. The results indicate that the cause of island arc volcanism in northeastern Japan is the upwelling of hot mantle materials (volcanic plumes) from beneath. The source of volcanic magma is diapir-like melting regions localized within the volcanic plumes. Extensive volcanic activity at the volcanic front is due to the presence of the vast melting zones right beneath the Moho discontinuity. Those melting zones may cause melting of lower crustal materials and produce felsic magma. Melt stays underneath the Moho, where crystallization fractionation may proceed. Melt exists at greater depths in the back-arc region, which may cause across-arc variations of chemical compositions of the volcanic rocks in northeastern Japan. We suggest that magma migration in the ductile lower crust may cause low-frequency microearthquakes, and magma penetration into the brittle upper crust may produce mid-crustal S-wave reflectors.

Key words : Magma distribution; three dimensions; seismic activity; northeastern Japan.

Introduction. The seismic velocity structure of the northeastern Japan arc has been extensively studied by, for example, Zhao et al. and Hasegawa et al. Their results have generally shown low velocity zones in the mantle wedge beneath the volcanic front to the west, and extremely low velocities right beneath the volcanoes. Hasegawa et al. pointed out that low-frequency microearthquakes occur in the lower crust right above the low velocity regions in the uppermost mantle, and that mid-crustal S-wave reflectors exist between the volcanoes and the low velocity regions. These observations indicate the close relationship of magmatism with low-frequency microearthquakes and S-wave reflectors.

We have used laboratory velocity data of dry mantle peridotite determined at high pressure and temperature to estimate the fraction of partial melt and temperature in the low velocity zone. The temperatures of the uppermost mantle derived from the velocity data were consistent with those from high heat flow values in the volcanic front to the back-arc regions. In these regions, therefore, we may apply laboratory results on dry peridotite to estimating the degree of partial melt in the mantle wedge.

Method of melt fraction estimates. Here we present a three-dimensional mapping of partial melt zones in the mantle wedge of northeastern Japan. We use the three-dimensional P-wave velocity structure determined by Zhao et al. They used 14045 P-wave arrival times including first arrivals and later arrivals of converted waves. Seismic velocity discontinuities as well as three-dimensional variations in velocity were determined in their study. Melt fractions ($M_p$) and temperatures ($T$) of the mantle wedge are obtained by comparing the velocity structure with the laboratory velocity data. We use the P-wave velocity data on dry peridotite determined up to 1 GPa and 1300°C; i.e., the effect of partial melt on upper mantle velocity has been measured. In order to extrapolate the laboratory results to greater depths (to 110 km depth), we calculate P-wave velocities ($V_{pm}$) at mantle solidus temperature ($T_m$) to 10 GPa, by using elasticity data of mantle minerals and employing a third-order finite strain theory. For this calculation, we follow the method described by Duffy and Anderson. The
results of P-wave velocity in peridotite at solidus temperature calculated by Sato\textsuperscript{5}\textsuperscript{)} are shown in Fig. 1a, together with the P-wave velocity perturbations (0%\texttextsuperscript{−}6%) given by Zhao et al.\textsuperscript{1)}

The homologous temperature dependence of the laboratory velocity data has indicated that we may extrapolate the laboratory results to higher pressures by simply taking the pressure effect on $T_m$ and $V_{pm}$ into account.\textsuperscript{4}\texttextsuperscript{−}6}\textsuperscript{)} Using the laboratory velocity data showing the velocity drops as a function of the volume percent of melt, we obtain the lines of constant melt fraction\textsuperscript{6}\textsuperscript{)} as also shown in Fig. 1a. The line of $V_{pm}$ corresponds to the line of $M_f=0$ vol.\% and $T/T_m=1$. Fig. 1b shows the lines of constant homologous temperature as a function of depth.\textsuperscript{6}\textsuperscript{)} From the velocity perturbations given by Zhao et al.,\textsuperscript{1)} Figs. 1a and b, therefore, yield the degree of partial melt and the homologous temperature, respectively. Further, the mantle solidus temperature has been determined at high pressure,\textsuperscript{9}\textsuperscript{)} so the temperatures of the mantle wedge are obtained. Because of the errors in laboratory velocity and melt fraction data, the presence of less than 1 vol.\% melt is not certain in this study. More detailed descriptions of temperature estimates of the upper mantle have been given elsewhere.\textsuperscript{4}\texttextsuperscript{−}6}\textsuperscript{)}

**Results and discussion.** Fig. 2 shows the results of three-dimensional mapping of partial melt zones in the mantle wedge beneath northeastern Japan. Below ~110 km depth, melt fraction is less than 1 vol.\% and the presence of melt is not certain. At 110\texttextsuperscript{−}100 km depth, a melting region (\textsuperscript{\textlesseq}1 vol.\%) appears and extensive melting occurs at around 90 km, 65 km and 40 km depths. Diapir-like melting regions of a few tens of kilometers exist along the middle of the mantle wedge. Most extensive melting occurs in the uppermost mantle beneath the volcanic front. Temperatures of the melting regions are 200\texttextsuperscript{−}300°C higher than the normal mantle temperatures, and ~1270°C, ~1360°C and ~1460°C at 40, 65 and 90 km depths, respectively.\textsuperscript{6}\textsuperscript{)}

The contours of -3\% velocity perturbation\textsuperscript{1)} are also shown in Fig. 2. Within the contours, velocity perturbations are below -3\%, and thus higher temperatures than averages are expected. These high temperature regions indicate the upwelling of hot mantle materials from beneath. Two major upwelling regions exist below ~50 km depth and branch off at the uppermost mantle, and eventually underplate the Moho right beneath the volcanoes. The results indicate that melting zones localized in the upwelling hot mantle materials cause volcanic activity in the northeastern Japan arc.

Beneath the volcanoes, mid-crustal S-wave reflectors as well as partial melt zones exist, and low-frequency microearthquakes occur in the crust as also shown in Fig. 2. The close relationship of magma source regions with S-wave reflectors and microearthquakes indicates that magma ascent from the uppermost mantle to the ductile lower crust may cause low-frequency microearthquakes, and magma penetration into the brittle upper crust may produce the mid-crustal reflectors. Magma movement in the brittle upper crust may increase stress (or at least change the state of stress) in the crust, and may contribute to the occurrence of crustal earthquakes including destructive earthquakes. Interestingly, large crustal earth-
quakes (M≥6) also occur around the volcanoes and the melting zones (Fig. 2).

Generation and ascent of magma as inferred from Fig. 2 are summarized as follows (see also Fig. 3). Upwellings of hot mantle materials from beneath cause pressure-release melting at ~110 km depth in the northeastern Japan arc. Localized diapir-like melting regions of a few tens of kilometers exist in the upwelling regions. A part of magma released from the upwelling melting regions may cause volcanic activity at the back-arc side of northeastern Japan. Fractional crystallization may proceed within the magma stagnated right underneath the Moho. The stagnant magma may cause melting of lower-crustal materials and produce felsic magma. A part of volcanic rocks in the Japan arc will be formed by lower-crustal melting. Some magma will segregate from the melting zone, and ascent through the ductile lower crust, causing low-frequency microearthquakes. Magma penetration into the brittle upper crust may cause the opening of
the fault planes and/or cracks, forming mid-crustal reflectors, and finally melt ascends to magma reservoirs. Continuous supply of magma from the melting zones right underneath the Moho causes the surface volcanic activity of the island arc. However, most of the magma will cool down under the ground and form the island arc crust.

The local existence of melting regions may account for the lifetime of the island arc volcanoes. Once a melting zone cools down, volcanic activity will be ceased. However, a new volcanic activity will start again after another diapir in the mantle wedge rises up to the Moho discontinuity. A typical lifetime of arc volcanoes is a few hundred thousand years. In this time, the diapirs rise by a few tens of kilometers (for the plate velocity of ~10 cm/yr); this is consistent with an average distance between the diapirs.

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Fig. 3. Generation and ascent of magma in the mantle wedge beneath northeastern Japan (R: mid-crustal S-wave reflector, C: Conrad, M: Moho, S: upper plane of subducted slab, triangles: active volcanoes, solid circles: hypocenters of low-frequency microearthquakes, squares: hypocenters of large crustal earthquakes, hatched circles: regions of localized partial melt, shading area: lower crustal melting and metamorphism, thin dashed lines with arrow: possible magma ascent pathway). Temperatures in the back-arc region are normally ~1000°C at 40 km depth to ~1200°C at 90 km depth. Localized hot melting regions with upwelling volcanic plumes exist beneath volcanoes and downwards to the west, where temperatures are 200~300°C higher than the normal mantle temperatures.

References