Review

Seismic imaging of mantle wedge corner flow and arc magmatism

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Abstract: I reviewed studies on the inhomogeneous seismic structure of the mantle wedge in subduction zones, in relation to corner flow and its implications for arc magmatism. Seismic studies in Tohoku clearly imaged the descending flow portion of the corner flow as a thin seismic low-velocity layer right above the slab. Slab-derived H$_2$O is fixed to the layer as hydrous minerals, which are brought down by the slab and eventually decompose. The released H$_2$O rises and encounters the ascending flow, formed to fill the gap caused by the descending flow. The combination of H$_2$O addition and adiabatic decompression causes partial melting within the ascending flow. For many subduction zones, seismic tomography has distinctly imaged the ascending flow of the corner flow as a seismic low-velocity and/or high-attenuation layer in the mantle wedge inclined nearly parallel to the slab. These observations indicate that the volcanic front in subduction zones is formed both by the ascending flow and the addition of slab-derived H$_2$O.

Keywords: corner flow, arc magmatism, mantle wedge, H$_2$O, seismic tomography

1. Introduction

A subduction zone is a plate boundary at which two plates converge and a relatively heavy oceanic plate sinks below a light continental plate. The highest seismic and volcanic activities occur in subduction zones. The subducting plate is also responsible for the descending flow part of the mantle convection within the Earth; thus, the subduction zone is important to understand the material circulation inside the Earth.

The oceanic plate is formed at a mid-ocean ridge. Because of the active hydrothermal circulations at the ridge, seawater is fixed as hydrous minerals to the shallow part of the oceanic plate.$^{1,2}$ Seawater is also fixed to the plate as hydrous minerals along transform faults near the mid-ocean ridges because of the fault movements and subsequent penetration of seawater along the faults.$^{3,4}$ After its formation at the mid-ocean ridge, the oceanic plate moves horizontally under the ocean floor over the period of millions of years to over 100 million years, finally reaching a subduction zone. Sediments accumulate while moving under the ocean floor and a sediment layer containing seawater is formed at the top of the oceanic plate. Thermal cracking has been proposed as a possible mechanism for the hydration of the plate prior to subduction; seawater enters the cracks caused by thermal stress associated with the cooling of the oceanic plate and hydrous minerals are formed along the cracks.$^{5,6}$ In addition, the oceanic plate that reaches the trench is bent downwards in the outer-rise region, forming normal faults. Some normal faults reach the mantle of the plate,$^{7}$ seawater enters along the faults and hydrous minerals are formed inside the plate.$^{8–12}$ Moreover, H$_2$O is fixed to the oceanic plate as hydrous minerals when the plate passes immediately above the mantle plumes or superplumes during its horizontal movement under the ocean floor.$^{13}$ Magma present in the plumes or superplumes intrudes into the oceanic plate and H$_2$O contained in magma is fixed to the plate. The H$_2$O is thus incorporated into the plate through several processes and a large amount of H$_2$O is stored in the oceanic plate in the form of hydrous minerals before its subduction.$^{14–16}$

The subduction of the oceanic plate forms secondary convection in the mantle wedge of the upper plate.$^{17}$ Viscous coupling occurs between the
subducting plate (slab) and the mantle wedge above it, causing mantle materials directly above the slab to potentially be dragged down in the direction of slab subduction and high-temperature and low-viscosity materials to rise from the deeper portion of the mantle wedge in the back-arc side to fill the gap. This process is the secondary convection in the mantle wedge formed by the slab subduction and is called corner flow. The shape of the ascending flow part of the corner flow depends on the physical conditions, such as the viscosity of the mantle wedge, the difference in viscosity between the slab and the mantle material immediately above, and the subduction angle of the slab.$^{18–20}$ However, in either case, the mantle wedge on the back-arc side has a high temperature of over 1,000 °C across its wide area because of this ascending flow.

As the slab subducts, hydrated minerals in the slab decompose and release $\text{H}_2\text{O}$ due to the increase in temperature and pressure$^{21–24}$ although some amount of $\text{H}_2\text{O}$ is retained in the slab and recycled to the deep mantle in old and fast subduction zones.$^{25}$ The released $\text{H}_2\text{O}$ migrates upward because it has a lower density than the surrounding rocks and part of it moves to the mantle wedge directly above. Water reaching the mantle wedge lowers the melting point of the surrounding peridotite and melt is generated near the center of the mantle wedge at which the temperature is elevated by the ascending flow.$^{26–29}$ The generated melt is transported to just beneath the Mohorovičić discontinuity (Moho) by the ascending flow in the mantle wedge. The melt accumulates beneath the Moho and then part of it intrudes into the crust while undergoing crystal differentiation, forming a magma reservoir. The magma supplied from the magma reservoir finally reaches Earth’s surface, causing volcanic eruptions. This is how hot magma is generated and volcanoes are formed in subduction zones in which cold oceanic plates subduct. However, there has been no systematic and comprehensive review on the details of the important processes presumed to be taking place in the mantle wedge of the subduction zone, such as the distribution of $\text{H}_2\text{O}$ released from the slab in the mantle wedge as a result of chemical reactions with surrounding rocks and the transportation paths followed by the melt and $\text{H}_2\text{O}$ to reach the Earth’s surface.

Recent seismic tomography studies in several subduction zones have clearly shown the ascending flow portion of the corner flow in the mantle wedge as a seismic low-velocity and/or high-attenuation layer. Information on the heterogeneous structure of the mantle wedge based on such seismic observations have revealed constraints in constructing a model for the magma generation and ascent in subduction zones.$^{30–33}$ This study is a review of the inhomogeneous structure of the mantle wedge in various subduction zones of the world, obtained by seismic observations such as seismic tomography. An overview of this inhomogeneous structure will contribute to our understanding of the process of magma generation and ascent in subduction zones.

2. Descending flow

Water expelled from the slab rises to the mantle wedge and reacts with mantle materials to form hydrous minerals such as serpentine, chlorite, and hornblende.$^{27,28}$ In subduction zones with an old oceanic plate such as Tohoku in northeast Japan, a layer containing $\text{H}_2\text{O}$ thus fixed is formed immediately above the slab, which is then dragged down by the subducting slab. This temporary $\text{H}_2\text{O}$-containing layer is carried to a depth of 150 to 200 km, where hydrated minerals in the layer dehydrate and decompose.$^{14,28,34}$ This is the descending flow portion of the corner flow formed in the mantle wedge by slab subduction. The depth of dehydration and decomposition depends on the thermal structure of the subduction zone; thus, it is different for each subduction zone. Even in the same subduction zone, different depths will be obtained if different models are used to estimate the thermal structure.

This layer containing serpentine and chlorite, which is expected to be formed just above the slab, should have a slower seismic velocity than the surrounding mantle wedge, allowing it to be detected as a seismic low-velocity layer. However, because the low-velocity layer is not thick, high spatial resolution is required for its detection by seismological methods. Currently, the Japanese islands, especially Tohoku, are the only subduction zones that satisfy this condition; they are covered by a high-quality and high-density seismic observation network. A high-resolution seismic tomography study and a receiver function analysis in Tohoku based on the data from the network detected this layer as a seismic low-velocity layer.$^{35,36}$

Beneath Tohoku, the old Pacific plate subducts from the east. In the crust of the subducting Pacific slab, a belt-like concentrated seismicity (upper plane seismic belt) is present at a depth of ~80 km, nearly parallel to the slab’s upper surface contour line.$^{37}$ This depth roughly agrees with the expected depth of
phase transformation of crustal materials to eclogite,\textsuperscript{22)} indicating that the upper plane seismic belt is formed by fluid-induced embrittlement.\textsuperscript{24,37–42)} Thus, the amount of H\textsubscript{2}O expelled from the crust by dehydration is particularly large at the depth at which the upper plane seismic belt is formed. A considerable part of the expelled H\textsubscript{2}O is expected to migrate upward and form a low-velocity layer in the mantle wedge right above, which is dragged down by the slab and carried to the deep part of the mantle wedge, indicating that the low-velocity layer should be located just above the slab at depths deeper than \(\sim 70\) km.

Tsuji \textit{et al.} (2008),\textsuperscript{36)} using the double-difference tomography method of Zhang and Thurber (2003),\textsuperscript{43)} estimated the detailed seismic velocity structure within the Pacific slab and the mantle wedge in the central part of Tohoku. As a result, the crust of the subducting Pacific slab was clearly imaged as a seismic low-velocity layer down to 80 km, the depth at which the crustal material is expected to change to eclogite\textsuperscript{22)} (Fig. 1). This low-velocity layer, the slab crust, is no longer a low-velocity layer at depths > 80 km corresponding to the phase change. In addition, a low-velocity layer was clearly imaged in the mantle wedge immediately above the slab at depths of 70–120 km (Fig. 1). This low-velocity layer corresponds to the layer containing serpentine and chlorite formed directly above the slab. According to the simulation results by Iwamori (1998)\textsuperscript{28)} and Horiuchi and Iwamori (2015),\textsuperscript{34)} this low-velocity layer is expected to persist down to a depth of 150–200 km. However, the low-velocity layer was only visible down to \(\sim 120\) km depth (Fig. 1) because the resolution of the double-difference tomography does not extend down to 150–200 km.

Kawakatsu and Watada (2007)\textsuperscript{35)} conducted receiver function analysis to obtain the crust and upper mantle structure under Tohoku and detected the upper and lower surfaces of the subducting Pacific slab and the slab Moho as velocity discontinuities. They further detected a noticeable low-velocity layer in the depth range of 70–130 km just above the slab, which corresponds to the layer containing serpentine and chlorite formed directly above the subducting slab. In the receiver function analysis, the low-velocity layer was detected down to a depth slightly deeper than that detected by the double-difference tomography. The seismic low-velocity layer, thus detected immediately above the slab both by the double-difference tomography and the receiver function analysis, is considered to correspond to the descending flow portion of the corner flow.

3. Ascending flow

3.1 Tohoku subduction zone. The ascending flow portion (return flow) of the corner flow was also first detected in Tohoku by seismic tomography as a seismic low-velocity layer which is inclined nearly parallel to the subducting Pacific slab.\textsuperscript{44,45)} Although it is not clear, the inclined low-velocity layer in Tohoku was also observed in an earlier seismic tomography study\textsuperscript{46)} (Fig. 2a). The low-velocity layer corresponding to the ascending flow is thicker than the low-velocity layer corresponding to the descending flow and thus can be more easily imaged by seismic tomography. Tomographic studies by Hasegawa \textit{et al.} (1991)\textsuperscript{44)} and Zhao \textit{et al.} (1992)\textsuperscript{45)} clearly showed the existence of the inclined low-velocity layer (Fig. 2b), and these were followed by subsequent seismic tomography studies that used gradually accumulated observation data.\textsuperscript{47–49)} Seismic attenuation tomography studies performed more recently show that the low-velocity layer is also a high-attenuation layer inclined almost parallel to the subducting slab.\textsuperscript{50–52)}
Figure 3 shows the vertical cross-sections of S-wave velocity perturbation along six lines perpendicular to the arc. In all cross-sections along lines a–f, the Pacific slab that sinks below the land area is clearly imaged as a prominent S-wave high-velocity layer. In the mantle wedge above it, there is an S-wave low-velocity layer inclined almost parallel to the subducting slab and extending from a depth of 100–150 km to the Moho just below the volcanic front. This inclined low-velocity layer is visible not only in the cross-sections of a, b, d, and f passing through active volcanoes but also in the cross-sections of c and e not including active volcanoes. In other words, a sheet-like low-velocity layer inclined almost parallel to the slab is distributed in the mantle wedge of Tohoku. This sheet-like low-velocity layer corresponds to the ascending flow portion of the corner flow. Since it consists of mantle materials that have risen from high-temperature regions deep within the mantle, the interior of this inclined ascending flow is hotter than the surroundings, and therefore should have low viscosity.

The layer containing serpentine or chlorite directly above the slab corresponding to the descending flow will dehydrate and decompose at 150–200 km depth. If released H\(_2\)O is conveyed directly above, it will eventually encounter the inclined ascending flow at a depth of 100 to 150 km. Observational evidence for this is not available from the seismic images. In any case, the supply of H\(_2\)O to the ascending flow acts to lower the solidus temperature. Comparison of the seismic attenuation structure in the inclined low-velocity layer with experimental data suggests that the temperature in the low-velocity layer (i.e., the ascending flow) is higher than the wet solidus of peridotite, indicating that partial melting is occurring in this layer. In fact, by comparing the P- to S-wave velocity reduction ratio estimated from seismic tomography with the Takei (2002) diagram, Nakajima et al. (2005) showed that inclusions with ~0.05 to 5 vol.% melts and aspect ratios of ~0.001 to 0.1 are contained in the inclined low-velocity layer (Fig. 4).

Nakajima and Hasegawa (2004) and Nakajima et al. (2006) obtained the S-wave anisotropy structure in this region by S-wave splitting analyses and showed that fast direction of S-wave polarization in the mantle wedge on the back-arc side is nearly parallel to the maximum inclination direction of the slab. This direction of anisotropy almost coincides with the direction of the ascending flow. These observations indicate that the inclined low-velocity and high-attenuation layer in the mantle wedge under Tohoku is a high-temperature and low-viscosity ascending flow containing melt, whereby the melt is efficiently carried to the vicinity of the Moho directly underneath the volcanic front.

The existence of the inclined low-velocity layer approximately parallel to the subducting slab detected by seismic tomography at depths shallower than ~150 km was confirmed by numerical simulations of secondary convection accompanied by the slab subduction. Eberle et al. (2002) conducted numerical simulations of the corner flow using temperature-dependent viscosity and found an inclined low-velocity layer with a P-wave velocity several percent slower than the surroundings. This low-velocity layer is nearly parallel to the subducting slab, ~50 km away from the upper surface of the slab and is distributed at depths shallower than ~125 km,
reproducing the inclined low-velocity layer detected in the mantle wedge beneath Tohoku.

Seismic tomography also shows how magma in the ascending flow, which reached the Moho directly under the volcanic front, passes through the crust and finally reaches the volcanoes on the Earth’s surface. Figures 5a and b show across-arc vertical cross-sections of the S-wave velocity perturbation along two lines crossing through two volcanoes, Iwate and Kurikoma, respectively. These images were obtained by seismic tomography, in which only the crust and the uppermost mantle were targeted to increase the resolution. The images correspond to the enlarged views of the crust (and uppermost mantle) of the vertical cross-sections of Figs. 3b and d, respectively. Some magma in the ascending flow, which reached the vicinity of the Moho directly under the volcanic front, penetrates into the crust while undergoing crystal differentiation. It then reacts with surrounding crustal materials and a part

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**Fig. 3.** Across-arc vertical cross-sections of S-wave velocity perturbation in Tohoku. Figures (a) through (f) show cross-sections along lines a through f in the inset map. S-wave velocity perturbation is shown by the color scale at the bottom. White and red circles show ordinary earthquakes and deep, low-frequency earthquakes, respectively. Red triangles and bars at the top denote active volcanoes and the land area, respectively.

**Fig. 4.** Melt-filled pore shapes and volume fraction of melt at three depth levels within the ascending flow of the corner flow in the mantle wedge beneath Tohoku. (a) Aspect ratio $\alpha$ and (b) volume fraction of melt-filled pores $\varphi$ within the inclined low-velocity layer in the mantle wedge along three across-arc profiles A, B, and C, shown in the inset map of Fig. 3. Shown in (a) are the range of $\alpha$ corresponding to the grain boundary tubules with dihedral angle $\theta = 10–80^\circ$ and the range of $\alpha$ corresponding to the Mavko (1980) tube geometry with $\varepsilon = 0–\infty$, using the results of Takei (2002). The hatched area in (a) shows the range of $\alpha$ expected for the texturally equilibrated partially molten rocks ($\theta \approx 20–60^\circ$).
of it rises further, eventually reaching the Earth’s surface and forming volcanoes. Figure 5 shows the S-wave low-velocity regions extending continuously from just below the Moho to the volcanoes on the surface. When magma cools and solidifies in the crust, H₂O is released and moves upward. In this way, magma and H₂O originating from the slab will be supplied continuously to the shallow crust along the volcanic front or the Backbone Range. The presence of H₂O is also supported by deep low-frequency earthquakes at depths near the Moho and distinct S-wave reflectors in the mid-crust along the volcanic front or the Backbone Range.

Based on these seismological observations, Hasegawa and Nakajima (2004) estimated the formation and ascent processes of arc magma and the transportation path of H₂O from the slab to the arc crust (Fig. 6a). The rise of the hot mantle materials from the deep part of the mantle wedge in the back arc and the addition of H₂O generates a melt of about 0.05 to 5 vol.-% in the inclined ascending flow. The generation of the melt is caused by the effects of adiabatic decompression and the addition of H₂O. The effect of H₂O addition plays an important role in melt generation because the inclined low-velocity layer is clearly observed at depths shallower than ~150 km.

In this manner, H₂O originally released from the subducted slab merges with the melt. The ascending flow containing the melt ultimately encounters the arc Moho just below the volcanic front. Since there is a density difference between the mantle wedge and the crust, a large amount of melt stays right below the Moho.

Fig. 5. Across-arc vertical cross-sections of S-wave velocity perturbation along lines crossing (a) the Iwate volcano and (b) the Kurikoma volcano in central Tohoku. S-wave velocity perturbation is shown by the color scale at the bottom. Black dots and red circles show ordinary earthquakes and deep low-frequency earthquakes, respectively. Red lines show distinct S-wave reflectors. Black lines denote seismic velocity discontinuities. Red triangles and black bars at the top of each figure denote active volcanoes and active faults, respectively.

Fig. 6. Schematic figure of (a) across-arc vertical cross-section of the crust and upper mantle beneath Tohoku, illustrating the descending and ascending flows in the mantle wedge and the transportation paths of H₂O from the subducting slab to the arc crust and (b) 3D expression of the crust and upper mantle beneath Tohoku, illustrating the ascending flow with varying thickness in the mantle wedge. The ascending flow of the corner flow is shown in pink, and the descending flow is shaded with hatching in (a). Blue arrows denote fluid flow, resulting from both dehydration of the subducting slab and solidification of magma.
along the volcanic front. The volume fraction of melt inclusions contained in the low-velocity zone spreading directly underneath the Moho along the volcanic front is estimated to be about 1%31) (Fig. 4b). Melt further rises from this point and penetrates into the crust, eventually reaching the Earth’s surface and creating volcanoes (Fig. 6a).

Hasegawa and Nakajima (2004)32) detected along-arc variation in magma generation and showed that the along-arc variation is involved in the formation of volcanoes on the back-arc side, such as the Chokai and Iwaki volcanoes. They focused on the inclined low-velocity layer in the mantle wedge by a specialized tomographic inversion and imaged it under higher spatial resolution. In their inversion, S-wave velocities of the mantle wedge portion alone were estimated and those of crust and slab were fixed to the values obtained by their previous study.49) Figure 7a shows the obtained S-wave velocity perturbation along the inclined low-velocity layer. The variation in velocity reduction in the low-velocity layer is clearly recognized in the strike direction of the arc. The topography map in Fig. 7b shows that the locations of locally large velocity reductions in the low-velocity layer at depths of 30–150 km in the mantle wedge coincided with those of the topography highs continuously distributed from the Backbone Range to the back arc on the surface. Quaternary volcanoes (red triangles) are distributed intensively in such areas with a topography high, striking transverse to the arc.65),66) Deep low-frequency earthquakes (open circles) in the depth range of 25–40 km occur directly above the region of large velocity reductions in the ascending flow in the mantle wedge, probably caused by the rapid movement of crustal fluid.44),57),67)

Analysis of the above results indicates clear spatial correlations among (1) the distribution of S-wave velocity in the inclined low-velocity layer of the mantle wedge in the depth range of 30–150 km, (2) the distribution of deep low-frequency earthquakes that occur in the depth range of 25–40 km, (3) the distribution of Quaternary volcanoes, and (4) distribution of topography highs from the Backbone Range to the back arc on the earth surface (Fig. 7). The crust and upper mantle structure and the ascending flow in the mantle wedge of Tohoku estimated from these observations are schematically

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Fig. 7. (a) S-wave velocity perturbation taken along the inclined low-velocity layer in the mantle wedge beneath Tohoku, and (b) topography of Tohoku.32) S-wave velocity perturbation and topography are shown by the color scale at the bottom of each figure. Red triangles, white circles, and thick lines denote Quaternary volcanoes, deep low-frequency earthquakes, and active faults, respectively.
illustrated in Fig. 6b.32) The two-dimensional cross-sectional schematic view in Fig. 6a is extended to three dimensions in Fig. 6b. The ascending flow in the mantle wedge takes the form of a single sheet with a thickness that varies locally depending on location. The volcanic front is formed at the location where this inclined ascending flow finally encounters the Moho. As the shallow area near the Moho is reached, the ascending flow velocity slows down. The melt contained therein then temporarily stays in the wide area right below the Moho along the volcanic front.

In regions of the sheet-like ascending flow where the layer is locally thick and the melt amount is large, there are cases in which the melt is partly segregated, leaving the inclined ascending flow before it reaches the Moho. The segregated melt then rises straight up in the form of a plume. Once it reaches the Moho, it stays temporarily just underneath it. Some of the melt further rises and penetrates into the crust, forming volcanoes and topography highs. This process explains how the areas of concentrated Quaternary volcanoes and topography highs extending from the volcanic front to the back arc are created.

### 3.2 Other subduction zones in the world.

As discussed in Section 3.1, the ascending flow portion of the corner flow was clearly observed in Tohoku as an inclined low-velocity layer nearly parallel to the subducting slab. The mantle wedge structure has also been estimated by seismic tomography in many subduction zones of the world. Table 1 summarizes the cases for which the ascending flow portion has been detected as an inclined low-velocity and/or high-attenuation layer.

In the Japanese islands, a nationwide dense seismic observation network has been deployed; thus, the inclined low-velocity layer has been clearly imaged by seismic tomography. Figure 8 shows across-arc vertical cross-sections of P-wave velocity perturbation for all Japanese islands.68) Under the Japanese islands, the Pacific plate is subducting from the east along the Kuril Trench, Japan Trench, and Izu-Ogasawara Trench. The age of the Pacific plate just before its subduction becomes older from the north to the south and is older than about 110 Ma in those regions. In these subduction zones of the old plate, not only in Tohoku but also in Hokkaido (cross-sections A, B, and C in Fig. 8) and the Izu-Ogasawara arc (cross-sections H and I in Fig. 8), inclined low-velocity layers nearly parallel to the subducting slab are distinctly visible and distributed from depths of ~180 km and ~250 km, respectively, to the vicinity of the Moho directly underneath the volcanic front.

Figure 8 also includes Tohoku (cross-sections E and F), and each of them clearly shows an inclined low-velocity layer in the mantle wedge as Fig. 3. A recent seismic attenuation tomography study in Hokkaido also showed that the inclined low-velocity layer is the inclined high-attenuation layer.69)

In central Japan, adjacent to the south of Tohoku, seismic tomography analysis using the data from the ocean bottom seismographs installed in the Sea of Japan was performed and the inclined

| Table 1. Descending and ascending flows of the corner flow imaged by the seismological method |
|-----------------------------------------------|-------------------|------------------|------------------|--------|
| (a) Descending flow                           |                   |                  |                  |       |
| Tohoku                                        | low-V layer       | 70–130           | ~130             | 35, 36 |
| Hokkaido                                      | low-V & low-Q layer | 30–150        | ~130             | 44, 45, 49, 51, 52 |
| Central Japan                                 | low-V layer       | 30–300           | ~115             | 68, 69, 93, 96, 97 |
| Izu-Ogasawara                                 | low-V layer       | 30–250           | ~132             | 70, 98 |
| Kyushu                                        | low-V layer       | 30–100           | ~135             | 68    |
| Mariana                                       | low-V & low-Q layer | 20–125       | ~152             | 72, 73 |
| Tonga                                         | low-V & low-Q layer | 25–180       | ~109             | 75, 76 |
| New Zealand                                   | low-V & low-Q layer | 30–120       | ~100             | 32, 77 |
| Kamchatka                                     | low-V layer       | 30–150           | ~93              | 79    |
| East Aleutians                                | low-V layer       | 30–100           | ~55              | 81    |
| Alaska                                        | low-V layer       | 30–150           | ~47              | 82    |
| Marianas                                      | low-V & low-Q layer | 20–125       | ~152             | 72, 73 |
| Tongas                                        | low-V & low-Q layer | 25–180       | ~109             | 75, 76 |
| New Zealand                                   | low-V & low-Q layer | 30–120       | ~100             | 32, 77 |
| Kamchatka                                     | low-V layer       | 30–150           | ~93              | 79    |
| East Aleutians                                | low-V layer       | 30–100           | ~55              | 81    |
| Alaska                                        | low-V layer       | 30–150           | ~47              | 82    |
low-velocity layer was found offshore of Noto Peninsula continuously distributed down to a depth of ~300 km.70) This area is located near the junction between the northeast Japan arc and Izu-Ogasawara arc, and is adjacent to the western end of the line G in the inset map of Fig. 8, covering an area 100–200 km north from there. This observation indicates that the ascending flow in the mantle wedge exists even at a depth of 300 km.

The Philippine Sea plate is subducting from the south beneath west Japan. The age of the Philippine Sea plate just before its subduction is different across the Kyushu-Palau Ridge; 15–27 Ma on the Shikoku Basin side in the northeast and more than about 50 Ma in the southwest side.71) Arc volcanoes formed by the subduction of the Philippine Sea plate are clearly recognized in Kyushu only. Even in this area, which is a subduction zone of a relatively young plate, the inclined low-velocity layer is clearly imaged by the nationwide high-density seismic observation network. As shown in cross-sections L and M in Fig. 8, the low-velocity layer is continuously distributed from a depth of ~100 km to the volcano on the surface.

In Mariana, which continues to the south from Izu-Ogasawara, the oldest Pacific plate subducts from the east. Here, the upper plate is also the oceanic plate with an ongoing active back-arc spreading. Although the volcanic arc is formed parallel to the Mariana Trench, the land area is narrow, making it difficult to construct a dense stationary seismic observation network. Temporary seismic observations using a large number of ocean bottom seismographs have been carried out recently and seismic tomography studies based on those data have revealed an inhomogeneous structure of the mantle wedge in this area that was previously not known.72,73) A low-velocity zone, corresponding to the ascending flow, is distributed from the depth of ~125 km to just below the volcanic front on the surface (Fig. 9). Its dip angle is very high, almost parallel to the Pacific plate subducting at a very high...
angle in this region. Another low-velocity zone is distributed from \( \sim 150 \text{ km} \) depth to the surface directly underneath the back-arc spreading axis.\(^{73)}\) Seismic attenuation tomography based on the ocean bottom seismograph data showed that these low-velocity zones are high-attenuation zones.\(^{72)}\)

Tonga is known as a subduction zone with the highest activity of deep earthquakes in the world. The old Pacific plate sinks under this area and back-arc spreading is proceeding. Since there are only small islands in the area and the land area is narrow, it is difficult to construct a seismic observation network to identify the detailed heterogeneous structure of the mantle wedge. However, the heterogeneous structure down to the upper mantle was obtained using the data from temporary observation networks including many ocean bottom seismographs. The obtained structure shows that there is a large low-velocity zone in the region from Tonga to the Lau Basin and the Fiji Islands and P- and S-wave velocity ratio (Vp/Vs) is particularly high directly underneath the back-arc spreading axis.\(^{74)}\) A distinct low-velocity layer inclined approximately parallel to the slab is distributed from \( \sim 180 \text{ km} \) depth to right below the volcanic front on the surface\(^{75),76)}\) (Fig. 10).

The old Pacific plate subducts obliquely from the east under the North Island of New Zealand and the Taupo volcanic belt is present in the middle of the arc. A dense seismic observation network is deployed in this area and many studies have been conducted on the seismic structure of the crust and the upper mantle. Reyners et al. (2006)\(^{33)}\) estimated the detailed upper mantle structure by merging the data from stationary seismic stations and temporary stations and detected the inclined low-velocity zone in the mantle wedge (Fig. 11a). They also found that the Vp/Vs ratio in that zone is slightly larger (\( > 1.80 \)). The magma generation and ascent model (Fig. 11b) in the North Island of New Zealand proposed by Reyners et al. (2006)\(^{33)}\) was very similar to the model for Tohoku by Hasegawa and Nakajima (2004)\(^{32)}\) (Fig. 6). A high-attenuation zone was also imaged in the central part of the mantle wedge by seismic attenuation tomography studies in this arc.\(^{77),78)}\)

Under the Kamchatka Peninsula where the old Pacific plate subducts, a clear volcanic front has formed from the middle to the south of the peninsula. However, there are no volcanoes in the northern part of the peninsula and thus no volcanic front. According to seismic tomography studies in this region,\(^{79)}\) an inclined low-velocity zone continuously distributed from \( \sim 150 \text{ km} \) depth to just below the volcanic front was observed in the southern part of the peninsula (Fig. 12). In contrast, in the northern part of the peninsula without volcanic activity, no Pacific slab has been identified directly beneath it\(^{80)}\) and no ascending flow due to slab subduction has formed. Therefore, the ascending flow of the corner flow formed by slab subduction is required to generate arc volcanic activity.
Fig. 10. Across-arc vertical cross-section of P-wave velocity perturbation in Tonga. P-wave velocity perturbation is shown by the color scale at the bottom. White circles denote earthquakes. Triangles at the top denote active volcanoes. CLSC and ELSC represent the locations of the central Lau spreading center and the eastern Lau spreading center, respectively.

Fig. 11. (a) Across-arc vertical cross-section of P-wave velocity and (b) 3D expression of the crust and upper mantle schematically illustrating the ascending flow in the mantle wedge beneath the North Island of New Zealand. In (a), P-wave velocity is shown by the color scale at the bottom. Regions with spread function >3.75 are masked but contoured. Crosses denote earthquakes. Triangles and arrows at the top denote active volcanoes and strands of the active North Island Dextral Fault Belt, respectively. In (b), grey arrows in the mantle wedge represent the corner flow. The ascending flow of the corner flow is shown in pink. Blue arrows denote fluid flow, resulting from both dehydration of the subducting slab and solidification of magma. Red stars denote earthquakes.
The Pacific plate subducts obliquely under the Aleutian Islands. Since the area of the islands is small and the number of routine seismic stations is low, it is difficult to clearly image the mantle wedge structure in this area. However, the eastern portion of the Aleutian Islands is an exception and the mantle wedge structure was estimated using data from a temporary seismic network with observation stations on the back-arc side.81) The estimated structure shows that the inclined S-wave low-velocity layer is imaged at depths of 30–100 km (Fig. 13). This is similar to the inclined low-velocity layer in the mantle wedge imaged under Tohoku.

The Pacific plate subducts beneath Alaska at a very low angle in its shallow portion, and the distance from the trench to the volcanic front is about 570 km, which is anomalously remote. The mantle wedge structure was estimated by seismic tomography using data obtained from the seismic observation network deployed in this area.82) Zhao et al. (1995)82) detected a P-wave low-velocity layer, corresponding to the ascending flow of the corner flow (Fig. 14). This low-velocity layer is inclined nearly parallel to the subducting Pacific slab and is almost continuously distributed from ~150 km depth to just below the volcanic front on the surface.

4. Discussion

As described in Section 2, the descending flow portion of the corner flow formed by the slab subduction has been detected by seismic tomography and receiver function analysis as a seismic low-velocity layer immediately above the slab. However, to date, it has been detected only in Tohoku and not in other subduction zones of the world (Table 1). This is because the low-velocity layer corresponding to the descending flow is not very thick and high-resolution seismic images are required for detection, but these are not available in many subduction zones. Tohoku is covered by a high-quality and high-density seismic observation network and the activity of intraslab earthquakes is very high, enabling us to use a large amount of earthquake data and to obtain high-resolution seismic images.
The situation is slightly different for the ascending flow portion of the corner flow. As described in Section 3, the inclined low-velocity layer corresponding to the ascending flow has been detected in many subduction zones (Table 1). In some subduction zones, the inclined low-velocity layer is also a high-attenuation layer. In Tohoku, the temperature estimated from the observed seismic attenuation exceeds the solidus temperature and partial melting occurs in the ascending flow. The estimation of P- and S-wave velocity reduction ratio indicates that \( \sim 0.05 \) to 5 vol.\% melt is contained in this ascending flow. These observations can explain how high-temperature magma is generated and arc volcanoes are formed in subduction zones where a cold oceanic plate subducts.

Although the inclined low-velocity layer corresponding to the ascending flow has been detected in many subduction zones, there are many other subduction zones at which it has not yet been detected because of the low resolution of seismic images. Sufficient resolution is required to properly detect the ascending flow, although it is not as difficult to detect as the descending flow. In particular, high-resolution imaging of the mantle wedge on the back-arc side is necessary, since the ascending flow is inclined from the Moho just under the volcanic front towards the back-arc side in the mantle wedge. For this purpose, a seismic network is required to sufficiently cover the area of the back arc, but there are not many subduction zones that satisfy these requirements.

Koulakov (2013)\(^{83}\) estimated the seismic velocity structure under the northern part of Sumatra, below which the Australian plate subducts, and found a nearly vertical low-velocity zone distributed from \( \sim 100 \) km depth to the Toba Caldera on the surface. He interpreted this nearly vertical low-velocity zone as the rising path of magma generated by the slab-derived \( \text{H}_2\text{O} \). This rising path is not parallel to the slab dip direction. However, the mantle wedge on the back-arc side was not imaged in his seismic tomography. There are currently no data for the seismic rays passing through the mantle wedge on the back-arc side. If there are sufficient seismic rays passing through the back-arc side of the mantle wedge and the back-arc side were to be precisely imaged like in Tohoku, the inclined low-velocity layer almost parallel to the slab might be detected. Further investigations including the deployment of a sufficient number of observation stations on the back-arc side of this arc are required.

As shown in Table 1, the ascending flow of the corner flow has been found only in the subduction zones with plate ages greater than \( \sim 40 \) Ma, except for in Kyushu. In Kyushu, although the plate age before the subduction is shown as 27 Ma in Table 1, the slab age just below its volcanic front or back-arc side is considered to be older than \( \sim 50 \) Ma. This is because the Philippine Sea slab is subducting at a very high angle, the deeper extension of the Kyushu-Palau Ridge greatly bends to the north, and the slab immediately below the volcanic front or its back-arc side is located on the south side of the Kyushu-Palau Ridge.\(^{24}\) Thus, all the subduction zones at which the ascending flow has been found are those with slab ages larger than \( \sim 40 \) Ma. In contrast, in much younger subduction zones, such as southwest Japan, Nicaragua, and Cascadia, the inclined low-velocity layer corresponding to the ascending flow has not been detected to date.

These young subduction zones may show differences in magma generation within their mantle wedge from the subduction zones with moderate to old slab age.\(^{84},85\) Seismic tomography studies in Nicaragua, below which the Cocos plate (\( \sim 18 \) Ma old) subducts, show a nearly vertical layer with P-wave low-velocity and high Vp/Vs ratio distributed continuously from \( \sim 180 \) km depth right above the steeply dipping slab to just below the volcanic front on the surface.\(^{86},87\) This layer is not parallel to the subducting slab. In Cascadia, below which the young Juan de Fuka plate (7–11 Ma old) subducts, the activity of intraslab earthquakes is very low and the seismic structure of the mantle wedge has not been accurately estimated. Electrical resistivity structure recently obtained by a magnetotelluric exploration across central Washington State in the United States, shows the existence of a low-resistivity zone continuously distributed from \( \sim 90 \) km depth directly above the slab to just below the volcano on the surface.\(^{88}\) This low-resistivity zone is also almost vertical and not parallel to the slab dip direction. These nearly vertical low-velocity or low-resistivity zones may show the pathway of the melt which has been generated by \( \text{H}_2\text{O} \) expelled from the slab and rises almost vertically to the volcanic front on the surface.

In moderate to old subduction zones, \( \text{H}_2\text{O} \) expelled from the slab to the mantle wedge is collected in a layer containing hydrous minerals directly above the slab and dragged down by the subducting slab to some depth, where it is dehydrated and decomposed.\(^{27}\) The \( \text{H}_2\text{O} \) then rises vertically and eventually encounters the inclined ascending flow of
the corner flow directly above. Since H$_2$O is added to the hot ascending flow, melt is produced and the viscosity within the ascending flow reduces; thus, the flow is localized. The viscosity subsequently reduces further because the temperature increase is substantial. This positive feedback works to efficiently transport the melt to the Moho directly underneath the volcanic front. In contrast, in young subduction zones, the depth at which the slab releases H$_2$O is very shallow$^{21,22,89}$ and the vertically rising released H$_2$O does not encounter the inclined ascending flow of the corner flow. It rises by buoyancy and if it meets an area with a temperature higher than the solidus temperature during its ascent, melt is generated and volcanism occurs on the surface. The nearly vertical low-velocity zone and low-resistivity zone detected directly below the volcanic front in Nicaragua and Cascadia, respectively, might represent examples of vertical melt ascent path formed in this manner.$^{85}$ Therefore, in this case of Nicaragua or Cascadia, flux melting is more important than decompression melting in the formation of the melt.

It should be noted, however, that if the mantle wedge on the back-arc side is not properly imaged, the inclined ascending flow parallel to the slab cannot be detected. The resolution of imaging of the mantle wedge structures on the back-arc side obtained to date is not sufficiently high. Further investigations in young subduction zones are required by increasing the resolution of images of the mantle wedge structure on the back-arc side.

The situation is slightly different in southwest Japan, which is another young subduction zone with plate ages of 15–27 Ma. In this subduction zone, a few but active volcanoes are distributed along the coast of the Japan Sea in the Chugoku district. Iwamori (1992)$^{90}$ assumed that the cause of this volcanic activity is the hydrated plume in the upper mantle just below the coast of the Japan Sea, based on the spatial variations in the chemical composition of volcanic rocks. In contrast, Kimura et al. (2005)$^{91}$ suggested that the volcanoes in the Chugoku district may be attributed to the melting of the crust of the Philippine Sea slab going north, based on the observations that volcanic activity gradually moves northward and volcanic rocks containing adakite are found on the coast of the Japan Sea after 1.7 Ma. A seismic tomography study by Nakajima and Hasegawa (2007)$^{92}$ showed that a large low-velocity zone is distributed from a depth of 300–400 km just above the Pacific slab to just beneath the volcanoes on the surface, surrounding the northern limit of the Philippine Sea slab. This observation seems to support the hydrated plume model. However, a recent seismic tomography using both teleseismic and regional earthquake data shows that the subducting Philippine Sea slab exists at a location ~200 km north of the coastline of the Japan Sea, reaching a depth of ~400 km.$^{93}$ If the Philippine Sea slab is sinking to such a depth, the possibility that the volcanoes in the Chugoku district are caused by the corner flow in the mantle wedge cannot be denied. In any case, an inclined low-velocity layer parallel to the slab has not been found to date and further research is needed to increase the image resolution for the mantle wedge on the back-arc side in this region.

5. Concluding remarks

Plate subduction produces secondary convection (corner flow) in the mantle wedge. In this study, I reviewed the heterogeneous structure of the mantle wedge in subduction zones obtained mainly by seismic tomography to understand the relation between corner flow and arc magmatism. In subduction zones in which the heterogeneous structure of the mantle wedge, including its back-arc side, is precisely estimated, the ascending flow portion of the corner flow has been clearly imaged as a low-velocity and/or high-attenuation layer inclined nearly parallel to the slab and distributed almost continuously from a depth of 100–300 km to the Moho directly under the volcanic front. In Tohoku, partial melting occurs in the ascending flow due to the reduction in pressure and the addition of H$_2$O and ~0.05 to 5 vol.% melt is contained in the ascending flow. These observations indicate that the ascending flow formed by slab subduction and addition of H$_2$O expelled from the slab are responsible for forming the volcanic front in subduction zones. The high-resolution seismic structure of subduction zones has contributed to the understanding of the formation and the ascent process of arc magma and the transportation path of H$_2$O released from the slab, reaching the arc crust. Further improvements in the resolution of seismic images and model upgrades will make it possible to set stronger constraints on the process of generation and ascent of arc magma and the material circulation in subduction zones.

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Profile

Akira Hasegawa was born in 1945 in Gunma Prefecture. He graduated from Tohoku University Faculty of Science in 1967, then went to the Graduate School of Science of the same university. He majored in solid earth geophysics, focusing on observation seismology. He received his MSc in 1969 and Ph.D. in 1977. Since his graduation, he has worked as a research associate (1971–1977), an associate professor (1977–1989), and a professor (1989–2008) at the Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University. Currently he is a professor emeritus at Tohoku University. In his doctoral thesis, he investigated the double-planed deep seismic zone and the plate structure in the northeast Japan subduction zone. Since then, he has been consistently working on the generation mechanism of earthquakes in subduction zones, particularly in northeast Japan, based on data obtained by a high quality seismic observation network that he constructed with his colleagues. He has conducted pioneering fundamental work on subduction zone tectonics, including discovery of the double-planed deep seismic zone, detection of the mechanically induced convection within the mantle wedge, and contribution to deeper understanding of the generation mechanisms of interplate, intraslab and shallow inland earthquakes and the origin of arc magmas in subduction zones. He is a recipient of the Imperial Prize and the Japan Academy Prize in 2017.