Convergence of aqueous fluid at the corner of the mantle wedge: implications for a generation mechanism of deep low-frequency earthquakes

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Abstract

Recent seismic observations have shown that low-frequency earthquakes occur in nonvolcanic regions in subduction zones in southwest Japan and Cascadia, and it is suggested that an aqueous fluid released from the subducting lithosphere is necessary for the occurrence of these earthquakes. In a mantle wedge under a subduction zone, a permeable network is likely created by hydrofracturing due to continuous fluid release from the subducting lithosphere. The migration of aqueous fluid through a permeable network is governed by the pressure gradient resulting from the viscous mantle flow that is induced by the subducting oceanic lithosphere. Calculations of the streamlines of the aqueous fluid in the mantle wedge under the subduction zones show that the fluid released from the subducting crust migrates toward the corner of the mantle wedge. The convergence of the aqueous fluid toward the corner of the mantle wedge results in the accumulation of the aqueous fluid near the wedge corner. Due to the propagation of fluid-filled cracks under the effect of buoyancy, the accumulated fluid may easily migrate upward in the overlying lithosphere and along the plate interface. The propagation of fluid-filled cracks from the region containing the accumulated fluid is likely to be the cause of deep low-frequency earthquakes occurring near the corner of the mantle wedge in these subduction zones.

Keywords: dehydration, nonvolcanic tremor, low-frequency earthquake, subduction zone, fluid

1. Introduction

Fluids released from the subducting oceanic lithosphere play an important role in magma generation and seismicity in subduction zones. The migration of an aqueous fluid released from the subducting oceanic crust to the overlying mantle wedge depresses the mantle solidus and causes partial melting, which is considered to be the cause of arc magmatism (Tatsumi, 1989). Recently, deep low-frequency earthquakes have been observed in the nonvolcanic regions of southwest Japan (Obara, 2002) and Cascadia subduction zones (Kao et al., 2005). Low-frequency earthquakes commonly occur in volcanic areas and are considered to be caused by the migration of magma and/or hydrothermal fluids (Chouet, 1996). In subduction zones, an aqueous fluid is released by the dehydration of hydrous minerals in the subducting oceanic crust due to an increase in temperature and pressure, and the occurrence of low-frequency earthquakes in these subduction zones has been suggested to be related to the migration of aqueous fluids (Kao et al., 2005; Obara, 2002; Seno and Yamasaki, 2003). Recent studies show that low-frequency earthquakes comprise a portion of deep nonvolcanic tremors in the southwest Japan subduction zone (Shelly et al., 2006). Such earthquakes are inferred to represent a fluid-enabled shear slip on the plate boundary (Kodaira et al., 2004); the shear slip requires fluid supply from the dehydrating subducting lithosphere.

In the subduction zones in southwest Japan and Cascadia, the epicenters of low-frequency earthquakes are distributed on and above an isodepth contour of 30–40 km at the upper surface of the subducting oceanic lithosphere, which corresponds to the Moho depth in these regions; the hypocenters of the earthquakes are located near and above the corner of the mantle wedge (Kao et al., 2005; Katsumata and Kamaya, 2003) (Fig. 1). Then, the low-frequency earthquakes observed in these areas occur above a narrow band of the dehydrating oceanic crust along this isodepth contour. In the subducting oceanic crust, an aqueous fluid is expected to be released continuously from various depths of dehydrating crust (Schmidt and Poli, 1998). The relationship between low-frequency earthquakes and the dehydration reactions occurring in the subducting oceanic crust is still unclear.

Dehydration reactions occurring in the subducting oceanic crust depend on the temperature and pressure conditions. Hydrous minerals in the oceanic crust decompose under increased temperatures and pressures and release an aqueous fluid into the mantle. Most of the dehydration reactions proceeding in the subducting oceanic crust are completed by the depth at which the basalt-eclogite transition occurs. It is suggested that under subduction zones, water is continuously released from the subducting crust and is migrating upward, forming hydrous minerals in the overlying crust and mantle (Iwamori, 2007; Kawakatsu and Watada, 2007). The mineralogically determined phase boundary between basalt (gabbro) and eclogite in the two-part model is shown in Fig. 2; the eclogite facies contains a small amount (<1%) of water (Hacker et al., 2003b). Each facies in this phase diagram is assumed to be bounded by discontinuous reactions of a single set of minerals of constant composition, but the approximate water content in the subducting crust can be estimated using the phase diagram (Iwamori, 2007). As shown in Fig. 2, hydrous minerals can survive under higher pressures in a colder subducting crust under the forearc region where major dehydration reactions occur in the subducing crust whose depth is shallower than about 60 km, indicating that the amount of aqueous fluid at depth depends on the temperature structure in the subducting crust.

It is suggested that the temperature structure under the subduction zone depends on mantle rheology and interplate contact length which are controlled by a complex thermomechanical equilibrium (Arcay et al., 2007). When a rheology structure is given in the mantle and crust, thermal structure is expected to be controlled mainly by the age of the lithosphere and the subduction velocity. In the southwest Japan subduction zone, the subduction velocity is nearly constant; however, the age of the subducting lithosphere varies from 15 to 30 Ma (Okino et al., 1999; Sdrolias et al., 2004). The temperature difference at the surface of the subducting lithosphere in the along-arc direction is expected to be approximately 110°C at the Moho depth; this difference is obtained using an empirical equation from a simple numerical model of the temperature structure under subduction zones (Furukawa, 1995), under the assumption that the subduction velocity and the frictional coefficient are 0.045 m/yr and 0.02 (Furukawa, 1999; Wang and Suyehiro, 1999), respectively. The calculated temperature range at the surface of the subducting lithosphere in the southwest Japan subduction zone is shown in Fig. 2; the temperature range is consistent with the previous estimates of the temperature structure for the youngest part of the subducting lithosphere (Wang et al., 1995) and the depth at which the basalt-eclogite transition occurs in the older subducting crust (50–60 km) in the southwest Japan subduction zone (Fukao et al., 1983; Hori et al., 1985). This figure shows the temperature profile obtained by Hacker et al. (2003), which is for the subducting lithosphere of approximately a median age (Okino et al., 1999; Sdrolias et al., 2004) and the isoviscous mantle; and the profile is located within the estimated range.

The obtained temperature variation in the along-arc direction indicates that the depth range of the major dehydration reactions occurring in the subducting crust also varies as shown in Fig. 2, although the low-frequency earthquakes observed in the southwest Japan subduction zone have occurred near the Moho depth. When low-frequency earthquakes are closely related to a high fluid content in the subducting crust, mechanisms to increase the fluid content near the Moho depth are required. In the mantle wedge having a percolation network, the flow of fluids released from the subducting oceanic crust is expected to be driven by buoyancy and the pressure gradient caused by viscous mantle flow that is induced by the subducting lithosphere (Spiegelman and McKenzie, 1987). In this study, the migration paths of an aqueous fluid released from the subducting oceanic crust into the mantle wedge are estimated, and the relationship between the migration of an aqueous fluid to the mantle wedge and low-frequency earthquakes in subduction zones is discussed.

2. Migration of aqueous fluid in the mantle wedge

An aqueous fluid released from the subducting oceanic crust is considered to infiltrate into the overlying mantle. Hydrous minerals are formed by the reactions of mantle minerals with the aqueous fluid in the mantle wedge; the hydrous mantle is carried downward in the mantle flow induced by the subducting lithosphere. The hydrous minerals decompose at a depth where the dehydration conditions are satisfied, and they release an aqueous fluid. The released fluid lowers the solidus of mantle rocks, resulting in partial melting in the mantle wedge and arc volcanism (Iwamori, 2007; Tatsumi, 1989). Seismic studies have revealed low-velocity regions near the corner of the mantle wedge in the southwest Japan subduction zone (Honda and Nakanishi, 2003; Kamiya and Kobayashi, 2000) and seismic reflectors above the subducting plate below the depth of major dehydration reactions in the subducting crust in the northeast Japan subduction zone (Kawakatsu and Watada, 2007), indicating the presence of hydrous minerals formed by the infiltration of an aqueous fluid from the subducting lithosphere. On the other hand, it is suggested from numerical simulations considering the temperature-dependent rheology that calculated temperature structures above the subducting plate are too high to have major hydrous minerals stable in the mantle layer just above the subducting plate (Arcay et al., 2005); in this case, the seismic reflectors just above the subducting plate could indicate the existence of hydrous melts generated by the addition of aqueous fluid from the dehydrating crust. In both cases, the aqueous fluid released from the subducting lithosphere at various depths under the forearc region is likely to migrate easily through the percolation network from the dehydrating crust into the mantle wedge.

When the dihedral angle is smaller than about 60°, an intergranular fluid is connected and it can migrate through the interconnected network. Laboratory experiments suggest that the dihedral angle between the aqueous fluid and mantle silicates is greater than ~60° at relatively lower temperatures (<800–1000°C) and pressures (<2–4 GPa) (Mibe et al., 1999); it is then difficult for the fluid to migrate through the intergranular network unless the volume fraction of the fluid is high (3%) (Davies, 1999; Gaetani and Grove, 2003; von Bargen and Waff, 1986). Conditions of low temperature and pressure are expected just above the dehydrating subducting lithosphere in the depth range considered in this study. For the smaller volume fractions, it is unlikely that the aqueous fluid migrates into the mantle wedge through the intergranular network.

It is widely recognized that hydraulic fracturing is the dominant mechanism for fluid migration in the crust. Widespread fluid infiltration is considered to occur in metamorphic terranes, and fractures induced by dehydration reactions are considered to be an important factor influencing fluid flow during metamorphism (Cox and Etheridge, 1989; Etheridge et al., 1984; Hoogerduijn Strating and Vissers, 1991). It is inferred that magma migrates through a fracture network in partially molten rocks formed by partial melting (Watt et al., 2000). Pore pressure is expected to increase due to a progressive supply of fluid released by dehydration reactions or by partial melting (Ko et al., 1997) and due to a compaction of pore space, which is caused by the stress difference between the mantle matrix and the fluid (Byerlee, 1993; Sleep and Blanpied, 1992). Then fluid overpressures are generated; brittle fracturing occurs and a fracture network is generated (Sleep, 1988). High-pressure experiments performed by various mantle conditions show that fracturing occurs with a small amount of fluid (<1%) at higher pressures (3 GPa) and temperatures (1000°C) under deviatoric stresses (Zhang et al., 2004). In the forearc mantle wedge, it is probable that hydraulic fracturing occurs and a fracture network is formed; fluids can percolate through the fracture network in the mantle wedge.

The subducting oceanic lithosphere in the subduction zones in southwest Japan and Cascadia is young and its temperature is high, and the seismicity of the mantle wedge in these subduction zones is very low (Hacker et al., 2003b). In contrast, high seismicity is observed near the corner of the mantle wedge in subduction zones, in which an older, cooler lithosphere subducts such as the northeast Japan subduction zone (Yoshii, 1979); the mantle materials near the corner of the mantle wedge are brittle and not entrained in the mantle flow induced by subduction (Furukawa, 1993a). In low-seismicity zones where a younger, warmer lithosphere subducts, the mantle materials near the corner of the mantle wedge undergo ductile deformation. From geodetic studies (Aoki and Scholz, 2003), it is inferred that interplate seismic coupling decreases gradually at depths between 20 and 40 km and no seismic coupling is present below the depth range in the southwest Japan subduction zone, supporting the assumption that the forearc mantle wedge is ductile. It is suggested that the depth of the interplate boundary is controlled by the mantle rheology and a complicated thermomechanical equilibrium and becomes shallower for higher subduction velocity (Arcay et al., 2007). In the southwest Japan and Cascadia subduction zones, however, the depth of the interplate boundary is considered to be shallower than that in the northeast Japan subduction zone with a higher subduction velocity, and the mantle wedge is likely to flow entirely due to the drag of the subducting lithosphere.

It is considered that the mantle wedge under the subduction zone in which a young oceanic lithosphere is subducting is ductile and mantle flow is induced in the entire mantle wedge by the subducting lithosphere. In this study, the flow of fluids released from the subducting oceanic crust into the mantle wedge is estimated using a model of permeable flow in viscously flowing media.

3. Model of fluid flow in mantle wedge

Permeable fluid flow in the mantle was modeled for magma migration (McKenzie and O'Nions, 1991; Spiegelman and McKenzie, 1987). Spiegelman and McKenzie (1987) estimated magma migration paths under the arcs and ridges and discussed the formation of the volcanic front. McKenzie and O'Nions (1991) calculated the relationship between the chemical composition of magma and percolation paths of magma in the mantle; they also estimated the distribution of magma in the mantle. It is assumed in these studies that the permeable flow of magma is driven by the piezometric pressure gradient. In this study, the previously proposed model was applied to the estimation of fluid migration paths in the mantle wedge.

When the mantle wedge is assumed to be an incompressible permeable medium into which fluids infiltrate, fluid flow is driven by the piezometric pressure gradient (P) caused by the buoyancy of the fluids and the shear in the mantle wedge, which is caused by the subducting lithosphere. In the mantle wedge, mantle materials above the subducting lithosphere are dragged down by subduction, which causes a negative pressure gradient toward the corner of the mantle wedge. Mantle materials just below the overlying lithosphere flow toward the corner of the mantle wedge to compensate for the downward flow above the subducting lithosphere. The pressure gradient caused by the viscous mantle flow is a driving force for fluid flow in the permeable network in the mantle. The buoyancy force resulting from the density difference between fluids and the solid mantle also causes the pressure gradient in the permeable channels of fluids in the mantle wedge. The fluid flow in the permeable channels in the mantle wedge is driven by the piezometric pressure gradient caused by the viscous force in the viscously flowing mantle and by the buoyancy force.

The control of porous fluid flow by the pressure gradient has been formulated in a previous study on the migration of magma in the mantle (Spiegelman and McKenzie, 1987):

$$\nabla P = \eta \, \Delta V + (1\text{-}\varphi) \, \Delta\varrho \, g \, \hat{z}. \quad (1)$$

Here, η and V are the viscosity and flow velocity of the mantle, respectively, φ is the porosity, $\Delta\varrho$ is the density difference between fluids and the mantle, g is the acceleration due to gravity, and $\hat{z}$ is a vertical unit vector directed downward. In this equation, the compaction-dilatation behavior of the solid matrix, driven by fluid buoyancy, is neglected.

Dimensional analyses indicate that the piezometric pressure is controlled by a length scale:

$$L = \{\eta \, V_0 / [(1\text{-}\varphi) \, \Delta\varrho \, g]\}^{0.5}, \quad (2)$$

where V_0 is the subduction velocity (Spiegelman and McKenzie, 1987). The percolation velocity for the fluid flowing in the porous mantle under buoyancy is given by Darcy's law as

$$v_0 = k\,(1-\varphi)\,\Delta\varrho\, g \,/\, (\varphi\, \mu), \tag{3}$$

where k is the permeability and μ is the viscosity of the fluids. In this study, the physical parameters considered in these equations are assumed to be constant.

With no-slip boundaries and a moving lower boundary with the velocity V_0, the stream function of the fluid flow can be expressed in the nondimensional form (Spiegelman and McKenzie, 1987) as

$$\Psi^f = -\frac{v_0}{V_0}\left[\frac{2\left\{\theta_0 \sin\theta_0 \sin\theta + \left(\theta_0 \cos\theta_0 - \sin\theta_0\right)\cos\theta\right\}}{r\left(\theta_0^2 - \sin^2\theta_0\right)} - r\cos\theta\right] + \Psi^s, \tag{4}$$

where r is the distance from the corner of the mantle wedge, θ is the angle from horizontal, θ_0 is the corner angle of the mantle wedge (Fig. 1), and Ψ^s is the stream function of the mantle flow obtained analytically using the two-dimensional corner flow model (Batchelor, 1967).

The depth extent of the region in which the fluid converges depends on the values of v', which controls the mode of the fluid flow, and L. In this study, the physical parameters of mantle materials and aqueous fluid in the mantle wedge used in the above equations are estimated to calculate the depth extent of the region in which the fluid converges in the mantle wedge.

The permeability of the continental crust has been estimated in metamorphic terranes; the estimated permeability decreases exponentially with depth and the asymptotic value is

10^{-19} to 10^{-18} m^2 in the deeper part of the crust (~30km) (Ingebritsen and Manning, 1999; Manning and Ingebritsen, 1999). As previously mentioned, in the southwest Japan subduction zone, major dehydration reactions occur at depths shallower than approximately 60 km; in this study, the asymptotic permeability value is used for the mantle wedge.

The relationship between permeability and porosity has been proposed; permeability (k) decrease due to the compaction of pores is formulated from experimental data as $k \propto \phi^n$, where ϕ is the porosity and n is a constant (David et al., 1994). A permeable network model predicts a power law with $n \sim 3$ at porosity values greater than a critical value (ϕ_{cr}), which is consistent with experimental data; at porosities lower than ϕ_{cr} the permeability decreases drastically due to the disconnection of the network (Zhu et al., 1995). In the mantle wedge, the relationship between porosity and permeability is not clearly known. Laboratory experiments on a crystalline rock (Westerly granite) in the brittle regime show that the permeability of the rock is approximately 10^{-19} to 10^{-18} m^2 for a porosity of 0.5–1.0% and the permeability decreases steeply below a porosity of 0.5%. This result agrees with the results of the network model of a permeable network (Brace et al., 1968; Zhu and Wong, 1999). The permeability value is similar to that expected for the deeper crust described above. A porosity of 0.5–1.0% is considered for the mantle wedge in this study.

The viscosity and density of an aqueous fluid vary with temperature and pressure. The temperature under the subduction zones in southwest Japan and Cascadia has been estimated to be 500–800°C near the corner of the mantle wedge above the depth at which the basalt-eclogite transition occurs(Gutscher and Peacock, 2003; Hacker et al., 2003b). As mentioned earlier, materials in the mantle wedge in these subduction zones are likely to be in the ductile regime, and the temperature in this case is expected to be higher (>600–700°C) (Furukawa, 1993a; Kirby, 1983). In this study, a temperature range of 700–800°C is considered near the corner of the mantle wedge. For this temperature range, the solubility of silicate in aqueous fluids is very low (Stalder et al., 2001); in this study, a viscosity and density of 10^{-4} Pa·s (Audetat and Keppler, 2004) and 900 kg/m^3 (Wagner and Pruss, 2002), respectively, of the aqueous fluids are used. The density of the solid mantle is assumed to be 3300 kg/m^3. Further, in this study, the mantle wedge under the forearc region is considered; a continuous release of fluids from the subducting oceanic crust is expected and a percolation network is probably formed there, as previously mentioned. Water is soluble in mantle rocks, but even a very low amount of dissolved water (a few hundred ppm) is sufficient to significantly weaken the mantle (Hirth and Kohlstedt, 1996). Therefore, the wet viscosity of the mantle is used in this study; from high temperature and pressure experiments, the wet viscosity at the estimated temperatures is estimated to be 10^{21} Pa·s (Karato et al., 1986).

4. Results

Previous studies (McKenzie and O'Nions, 1991; Spiegelman and McKenzie, 1987) have shown that near the corner of the mantle wedge, fluids released from the subducting crust migrate toward the wedge corner. There are two modes of fluid migration paths from the above equations (Fig. 3). Using the nondimensional length (L) as a measure, for a velocity ratio v' (= v_0/V_0) greater than unity, the length of the segment of the subducting crust from which fluids migrate toward the corner of the mantle wedge becomes greater (Fig. 3a) than that for v' smaller than unity (Fig. 3b). In this model, when the segment of the subducting lithosphere from which fluids converge extends to a depth greater than that of the basalt-eclogite transition, most of fluids released from the subducting crust converge toward the wedge corner.

The streamlines of the aqueous fluid in the mantle wedge calculated using the parameter values estimated above are those for the case of a longer segment from which an aqueous fluid converges toward the corner of the mantle wedge, as shown in Fig. 3a. The subduction velocity and subduction angle are set to 0.045 m/yr and 30°, respectively, in this calculation. The streamlines of the aqueous fluid released from the shallower part of the subducting oceanic crust converge toward the corner of the mantle wedge under the effect of the increasing shear stress gradient directed toward the corner of the mantle wedge, while fluids released from the deeper part of the subducting crust rise to the Moho depth before reaching the corner of the mantle wedge. The length of the subducting oceanic crust that releases an aqueous fluid that converges toward the corner of the mantle wedge is approximately 6L for a subduction angle of 30° (Fig. 3a). With a decrease of the subduction angle, this length increases to approximately 8L at a subduction angle of 15°. In this study L is calculated to be approximately 8 km; this length corresponds to a depth of approximately 60 km (at a subduction angle of 30°), assuming a Moho depth of 35 km (Kao et al., 2005; Katsumata and Kamaya, 2003). This depth is nearly the same as that of the basalt-eclogite transition that occurs for the colder subducting lithosphere in the southwest Japan subduction zone. This indicates that most of the aqueous fluid released from the subducting oceanic crust into the mantle wedge converges toward the wedge corner.

When the dimensionless velocity v' (= v_0/V_0) is greater than unity, the streamlines of this converging flow display the same pattern (Fig. 3a). If v_0 is considerably smaller than V_0, the region in the mantle wedge in which fluid paths converge toward the wedge corner becomes considerably small (Fig. 3b). Using the parameter values estimated above, the dimensionless velocity value is calculated to be 3–16. In the equation of v_0, the permeability in the mantle wedge is the most uncertain variable. When the permeability value is one order of magnitude lower than the value used above, the migration velocity of the fluid becomes smaller than the subduction velocity. The region in which the aqueous fluid migrates from the subducting oceanic crust to the corner of the mantle wedge becomes smaller; the downdip length of the region in the subducting lithosphere is approximately 2L, as shown in Fig. 3b, which corresponds to a depth of approximately 45 km.

5. Discussion

5.1 Fluid migration as a cause of low-frequency earthquakes

As mentioned earlier, low-frequency earthquakes observed in the subduction zones in southwest Japan and Cascadia are considered to be caused by fluid-related processes. The propagation of fluid-filled cracks from the region containing the accumulated fluid near the corner of the mantle wedge is likely to be the cause of the occurrence of low-frequency earthquakes, and the hypocenters of the earthquakes are then distributed near the corner of the mantle wedge. When the Moho depth is nearly constant, the epicenters of these earthquakes are located along an isodepth of the seismic zone in the subducting lithosphere.

In the Cascadia subduction zone, deep tremors have been observed within a limited horizontal band at a depth exceeding 40 km, and it is suggested that fluid-related processes are responsible for the generation of deep tremors (Kao et al., 2005). Fluid-filled cracks propagating upward from the region containing the accumulated fluid near the corner of the mantle wedge may be the cause of these earthquakes, just as volcanic tremors are caused by the migration of magmas (Chouet, 1996). The plate interface may provide a pathway for the migration of fluids, thereby reducing the effective normal stress at the plate interface and affecting the generation processes of interplate slow-slip events (Dragert et al., 2001).

5.2 Fluid accumulation near the corner of the mantle wedge

The region of the mantle wedge where an aqueous fluid released from the subducting crust converges toward the wedge corner is estimated to extend up to a depth of approximately 60 km in this study. This depth is greater than that of the basalt-eclogite transition in the subducting crust estimated in the subduction zones in southwest Japan and Cascadia, as shown in Fig. 2. This indicates that most of the aqueous fluid released from the subducting crust converges toward the wedge corner, resulting in a high volume fraction of fluid near the wedge corner.

When the uncertainty of permeability is considered, the depth extent of the region in which the fluid converges in the mantle wedge becomes shallower (approximately 45 km) and the amount of accumulated aqueous fluid may decrease due to lower permeability. For the temperature profiles of the warmer subduction zones in southwest Japan and Cascadia, as shown in Fig. 2, the water content decreases by approximately 1.5% at the depth of 40–45 km at which the basalt-eclogite transition occurs (Hacker et al., 2003a). The aqueous fluid released at this depth range can migrate toward the corner of the mantle wedge because of the shallower depth of the basalt-eclogite transition. For the low-temperature profile of the southwest Japan subduction zone, the depth of 45–60 km at which the basalt-eclogite transition occurs is greater than that of the region in which fluid converges in the mantle wedge due to low permeability, and the metamorphic facies with a relatively higher water content of >3% could be stable below the depths of the region in which fluid converges in the mantle wedge.

The phase diagram shown in Fig. 2 is based on the assumption that each facies is bounded by discontinuous dehydration reactions, but the dehydration reactions are expected to be continuous due to the solid solutions and many dehydration reactions in the subducting crust (Iwamori, 2007; Schmidt and Poli, 1998), as previously mentioned. Assuming that the water content in the phase diagram (Fig. 2) represents the average value in each metamorphic facies and the water content decreases continuously under the conditions of each metamorphic facies, a decrease of >1% in water content is expected in the depth range from the Moho to a depth of approximately 45 km for the low-temperature subducting crust in the southwest Japan subduction zone. The water content in this depth range for the low-temperature profile may decrease; however, it does not become lower than half the water content for the high-temperature profiles. The water content between the Moho and the basalt-eclogite transition region is greater than 2% for the case of a greater downdip length of the fluid converging region. In the southwest Japan subduction zone, the amount of fluid converging toward the wedge corner could vary by a factor of two in the along-arc direction.

In dehydrating systems, a fluid can migrate when pressures resulting from dehydration reactions are sufficient to induce hydraulic fracturing; then fluid pressures become lower and the dehydration reactions are accelerated (Miller et al., 2003). In the subducting crust where dehydration reactions occur, this feedback mechanism is active and a fluid is expected to be released continuously under pressure and temperature conditions for each metamorphic facies below the Moho depth; further, a relatively high pore pressure is likely to be maintained up to the depth to the basalt-eclogite transition. From seismic studies, it is inferred that in the southwest Japan subduction zone, the subducting oceanic crust with a higher Poisson's ratio extends to a depth of 50–60 km (Honda and Nakanishi, 2003; Kodaira et al., 2004). In the subducting oceanic crust in the Cascadia subduction zone, the seismic velocity profile shows a gradual increase in seismic velocity with depth (Preston et al., 2003). These results are consistent with the result that an aqueous fluid is continuously released in the subducting oceanic crust.

It is suggested that in the subduction zones in southwest Japan and Cascadia, more than 1% of water contained in the subducting crust can migrate toward the corner of the mantle wedge as an aqueous fluid due to the piezometric pressure gradient in the mantle wedge. The aqueous fluid is considered to converge and accumulate near the corner of the mantle wedge, as shown in Fig. 4. The volume of the accumulated aqueous fluid is probably sufficient for it to migrate upward in the overlying crust and cause low-frequency earthquakes for both modes shown in Fig. 3. As suggested from seismic velocity structures in the mantle wedge, a higher concentration of the aqueous fluid near the corner of the mantle wedge results in a higher content of hydrous minerals (Kamiya and Kobayashi, 2000).

5.3 Migration of fluid-filled cracks

When an aqueous fluid migrates to the mantle wedge where ductile flow is induced, and when the fluid accumulates near the corner of the mantle wedge, fluid-filled cracks are formed; these cracks propagate upward due to the buoyancy in the overlying lithosphere. This phenomenon is similar to the intrusions of magma. In linear elastic fracture mechanics, cracks will propagate when the stress intensity factor K is greater than the fracture toughness K_c. For a planar crack, $K = \Delta P(\pi\, c)^{0.5}$, where excess pressure $\Delta P = \Delta\varrho\, g\, c$, c is the crack half-length, $\Delta\varrho$ is the density contrast, and g is the acceleration due to gravity. Laboratory experiments have shown that K_c is on the order of 1 $\mathrm{MPa \cdot m^{0.5}}$ (Atkinson, 1984). Assuming the density contrast between the mantle and the aqueous fluid to be 2400 kg/m^3, we obtain $c > \sim 10$ m. When the crack length becomes larger than a few tens of meters, cracks filled with an aqueous fluid could propagate upward from the fluid-containing region near the corner of the mantle wedge. This implies that the fluid that is accumulated near the corner of the mantle wedge can easily migrate in the lithosphere and the plate interface.

The buoyancy-driven propagation of fluid-filled cracks has been formulated in previous studies (Heimpel and Olson, 1994; Nunn, 1996; Spence and Turcotte, 1990). For teardrop-shaped cracks, the propagation speed (w) is obtained as follows:

$$w = \frac{\pi c}{192\mu}\left(\frac{1-\nu}{G}\right)^2 K_c^2\left(\Delta\rho g - \frac{K_c}{c\sqrt{\pi c}}\right), \tag{5}$$

where ν is Poisson’s ratio and G is the shear modulus (Nunn, 1996). For G = 44 GPa and ν = 0.28 for gabbroic rocks, the propagation velocity is calculated to be 3 km/day. For fluid-filled cracks propagating upward along the plate interface, the velocity is approximately 1 km/day because of the inclined propagation paths along the plate interface. In the southwest Japan subduction zone, low-frequency earthquakes occur in a zone with a width of approximately 20 km in the dip direction on the plate interface. At the abovementioned velocities, fluid-filled cracks are expected to overpass the zone in three weeks. The frequency distribution of low-frequency earthquakes shows a pulse-like feature with a duration of 1–3 weeks (Shelly et al., 2006), which agrees with the duration of the overpassing of fluid-filled cracks. A very high and nearly lithostatic pore pressure is probably required for the generation of low-frequency earthquakes, and an episodic upward propagation of fluid-filled cracks from the region containing the accumulated fluid in the mantle wedge could trigger low-frequency earthquakes at the plate interface near the corner of the mantle wedge.

5.4 Effects of the mantle rheology and melting

The viscosity of mantle materials depends on temperature, pressure, and other physicochemical parameters, and it varies in the mantle wedge. When a temperature-dependent viscosity is considered, the mantle flow is dominated mainly in the region just above the subducting plate and the overlying lithosphere tends to be thinner near the corner of the mantle wedge due to a larger viscosity contrast (Furukawa, 1993b; van Keken et al., 2002). When the water softening is also considered, the viscosity reduction associated with hydration smoothes out the viscosity contrast, and the overlying lithosphere tends to be ablated especially near the corner of the mantle wedge; the mantle flow is induced in a larger part of the mantle wedge (Arcay et al., 2005). The flow pattern for the weak water softening is approximately similar to that of the isoviscous mantle near the corner of the mantle wedge, although the thickness of the overlying lithosphere increases with the distance from the trench.

When the water softening is stronger, the overlying lithosphere is ablated extensively near the corner of the mantle wedge and temperature in the forearc mantle becomes very high to cause wet melting (Arcay et al., 2005). In the forearc region, however, observed heat flow is low (Blackwell et al., 1982; Furukawa and Uyeda, 1989; Furukawa et al., 1998; Lewis et al., 1988). The temperature structure under the forearc region is well constrained from the surface heat flow (Conder, 2005; Furukawa, 1999), and the temperature in the forearc mantle should not be very high (Furukawa, 1993a; van Keken et al., 2002). The overlying lithosphere could be ablated due to water softening (Arcay et al., 2005), but the ablation may not be so extensive. The temperature in the forearc mantle is probably well below the wet solidus considering the observed heat flow distribution, and the pattern of the temperature structure could be similar to that estimated for weak water softening (Arcay et al., 2007).

When buoyant fluids exist in an intergranular network in the mantle, fluids are expected to accumulate due to the compaction of the mantle matrix, where the compaction is caused by a ductile flow that is driven by the density difference between the fluids and the solid mantle (Richard et al., 2007). This compaction mechanism is considered to occur when magma segregates from the mantle matrix (Sramek et al., 2007; Wiggins and Spiegelman, 1995); magma-filled cracks could be formed and propagate upward due to the buoyancy of magma (Rubin, 1998; Sleep, 1988). This buoyancy-driven compaction is expected to occur in the case of a low mantle viscosity (e.g. $<10^{20}$ Pa·s (Richard et al., 2007)). In the mantle wedge under the forearc region considered in this study, the temperature is lower than that in the mantle under the volcanic belt, as menioned above. In this study, higher viscosity (10^{21} Pa·s) corresponding to the lower temperatures is used, and the buoyancy-driven compaction is not considered in this study. If the forearc lithosphere is ablated effectively due to water softening, temperature above the dehydrating crust is sufficiently high to cause wet partial melting. It is suggested that water released from the subducting crust is absorbed by magma, but magma should migrate upward and the viscosity structure in the mantle above the subducting crust changes little (Arcay, et al., 2007).

A fracture network formed by hydrofracturing is considered to be an effective migration path for the fluids released from the subducting crust. The direction of cracks formed under deviatoric stresses tends to be parallel to that of the maximum compressional stress, and permeability may increase in the preferred direction of cracks. In the mantle wedge just above the subducting lithosphere, fluid flux toward the corner of the mantle wedge could be smaller due to the anisotropy of permeability, which is caused by the preferred orientation of cracks (Dahm, 2000). In the upper part of the mantle wedge, on the contrary, fluid flux could be larger toward the wedge corner, in particular for the variable viscosity mantle (Furukawa, 1993b). The fluid paths may be skewed and the region in which fluids converge toward the wedge corner could be smaller due to the anisotropy of permeability. The anisotropy of permeability is a crucial factor for the estimation of fluid migration paths in the mantle wedge and should be evaluated. The degree of the anisotropy of permeability in the mantle wedge is not yet clearly known, and the effect of the anisotropy of permeability is not considered in this study.

The distribution of the hypocenters of low-frequency earthquakes in the southwest Japan subduction zone shows that there is an area without hypocenters, in which the subduction angle changes abruptly in the along-arc direction and the subducting seismic slab is highly distorted (Obara et al., 2004). A low supply of fluids from the subducting crust with an acidic composition is suggested to be the cause of the absence of low-frequency earthquakes in this area (Seno and Yamasaki, 2003). In this area, the fossil spreading ridge is subducting and enriched basalts have been sampled from the fossil ridge (Sato et al., 2002); however, it appears unlikely that a thick acidic layer exists under this ridge. In this area, the induced flow in the mantle is probably three-dimensional due to the abrupt change in the subduction angle, and the along-arc velocity component of the mantle flow may be dominant. Then, it may be difficult for an aqueous fluid to migrate toward the corner of the mantle wedge, which could result in the absence of low-frequency earthquakes in this area.

6. Conclusions

In the mantle wedge under a subduction zone, the migration of fluids through a permeable network is proposed to be controlled mainly by the piezometric pressure gradient resulting from the viscous mantle flow that is induced by the subducting oceanic lithosphere and fluid buoyancy. The migration paths of the aqueous fluid released from the subducting oceanic crust are estimated using the previous piezometric pressure model for magma migration; this model shows that the aqueous fluid will converge from the subducting oceanic crust toward the corner of the mantle wedge. In the subduction zones in southwest Japan and Cascadia, the depth of the subducting oceanic crust that releases the aqueous fluid that migrates toward the corner of the mantle wedge is estimated to be approximately 60 km. Most of the water contained in the subducting crust is considered to be released above depths of approximately 60 km in these subduction zones, and most of the aqueous fluid released from the subducting oceanic crust can converge toward the corner of the mantle wedge. The aqueous fluid is likely accumulated near the corner of the mantle wedge due to the convergence of the migration paths. When the permeability in the mantle, which is the most uncertain parameter used in this model, is one order of magnitude lower than 10^{-19} to 10^{-18} m^2, the depth of the fluid converging region in the mantle wedge is estimated to be shallower by approximately 15 km. In this case, the amount of aqueous fluid converging toward the wedge corner could be less. In both cases, more than 1% of the water contained in the subducting crust is inferred to converge toward the corner of the mantle wedge in the subduction zones in southwest Japan and Cascadia. In the southwest Japan subduction zone, the amount of aqueous fluid accumulated near the corner of the mantle wedge may vary in the along-arc direction by a factor of two due to the variation in the depth range of the major dehydration reactions occurring in the subducting crust.

The volume of the fluid accumulated near the wedge corner may be sufficient for the fluid to migrate upward due to the buoyancy in the overlying lithosphere and along the plate interface by the crack propagation mechanism. The propagation of fluid-filled cracks is likely to generate low-frequency earthquakes in the overlying lithosphere similar to the generation of volcanic tremors. Fluid-filled cracks will migrate upward along the plate interface, which makes the frictional state of the plate interface near the corner of the mantle wedge conditionally stable due to higher pore pressures. Then, low-frequency earthquakes are likely to be generated near the corner of the mantle wedge in the subduction zones in southwest Japan and Cascadia.

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Figure captions

Fig. 1. Geometry and coordinate system of the subduction model. The gray lines denote the streamlines of the mantle flow induced by the descending oceanic lithosphere. The hatched circle represents the source region of low-frequency earthquakes.

Fig. 2. Temperature profiles (thick gray lines) at the upper surface of the subducting lithosphere. The hatched area denotes the temperature variation expected due to the age difference of the subducting lithosphere in the southwest Japan subduction zone. The phase boundaries of the metamorphic facies in the subducting oceanic crust are also shown according to the water content of each facies. The number represents the water content (wt%). The thick line denotes the basalt-eclogite boundary for the two-mode model of gabbro and eclogite. Solidus lines are shown by broken lines (after Hacker et al., 2003).

Fig. 3. Streamlines of fluids released from the subducting oceanic crust into the mantle wedge (solid lines) and the induced flow in the mantle wedge (broken lines). In the hatched region, the aqueous fluid converges toward the corner of the mantle wedge. (a) $v_0/V_0 = 8$ ($k = 5\times10^{-21}$ and $\phi = 0.01$). The downdip length d of the hatched region on the subducting crust is approximately 6L for a subduction angle of 30º. (b) $v_0/V_0 = 0.08$ ($k = 5\times10^{-19}$ and $\phi = 0.01$). The downdip length d is approximately 2L. The depth is calculated assuming that the Moho depth is 35 km.

Fig. 4. Schematic model of fluid migration near the corner of the mantle wedge. The

aqueous fluid released by the dehydration reactions in the subducting hydrous oceanic crust (light gray area) migrates toward the corner of the mantle wedge due to the piezometric pressure gradient (solid lines). The aqueous fluid accumulates near the corner of the mantle wedge (dark gray area) and migrates through the plate interface and/or upward into the overlying lithosphere due to buoyancy (dark gray arrows). The gray broken lines denote the mantle flow induced by the subducting lithosphere.

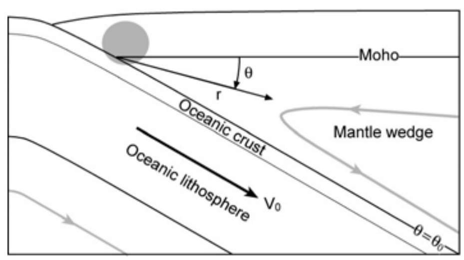
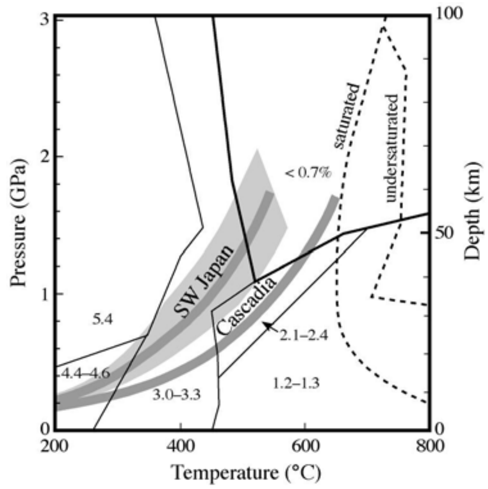

Moho
θ
r
Oceanic crust
Mantle wedge
Oceanic lithosphere
V_0
$\theta=\theta_0$

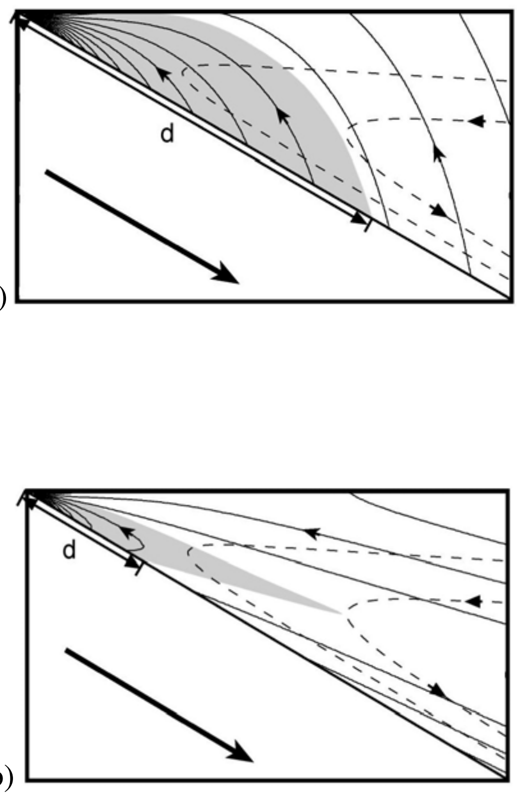
Fig. 1



Pressure (GPa)
Depth (km)
Temperature (°C)
SW Japan
Cascadia
saturated
undersaturated
< 0.7%
5.4
4.4–4.6
3.0–3.3
2.1–2.4
1.2–1.3

Fig. 2

(a)



(b)

Fig. 3

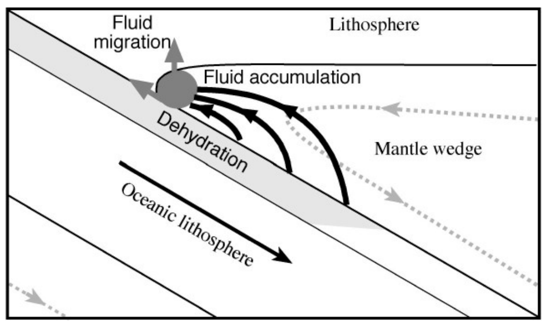

Fluid
migration
Lithosphere
Fluid accumulation
Mantle wedge
Dehydration
Oceanic lithosphere

Fig. 4