Hydrous minerals in the mantle wedge and the maximum depth of subduction thrust earthquakes

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Abstract. In many subduction zones the downdip limit of thrust earthquakes approximately coincides with the intersection of the subduction thrust with the forearc mantle. This limit may be explained by aseismic hydrous minerals present in the mantle wedge. During subduction, fluids released from the subducting slab infiltrate the overlying forearc mantle forming serpentine + brucite, especially in cool subduction zones. At the slab interface itself, talc-rich rocks form in the mantle by the addition of silica transported by rising fluids and by mechanical mixing of mantle and siliceous rocks. In the laboratory, serpentine generally exhibits stable-sliding aseismic behavior. The behavior of talc, a layered hydrous silicate, and brucite, a layered hydroxide, has not been investigated, but their structures also suggest weak stable-sliding behavior. We suggest all three layered hydrous minerals promote aseismic behavior and that their presence controls the downdip limit of thrust earthquakes in many subduction zones.

Introduction

Great destructive thrust earthquakes are a characteristic of most subduction zones, especially beneath continents. The downdip rupture limit represents the closest approach of the seismic source region to landward population centers and is thus an important factor in assessing earthquake hazards. In anomalously warm subduction zones, like Cascadia and SW Japan, the downdip limit of the seismogenic zone (the maximum depth of thrust earthquakes and aftershocks) is relatively shallow (10-20 km) and appears to be controlled by interface temperature ~350-450 °C [*Hyndman and Wang*, 1993; *Hyndman et al.*, 1997]. In contrast, the downdip limit of the seismogenic zone in most continental subduction zones occurs at 40±5 km depth [e.g., *Tichelaar and Ruff*, 1993] and appears to coincide with the depth to the forearc Moho where the subducting slab first intersects the mantle of the overriding plate [*Ruff and Tichelaar*, 1996]. The correspondence between the Moho and downdip limit of thrust earthquakes in the Alaskan and most of the Chilean subduction zones has been demonstrated by *Oleskevich et al.* [1999]; data for the Aleutian subduction zone are discussed below. That the seismogenic zone should end at the Moho is surprising because normal mantle rocks are considerably stronger than crustal rocks [e.g., *Kirby*, 1983]. Dry mantle rocks should be seismogenic at the low temperatures characteristic of forearcs.

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Aqueous fluids released from subducting slabs can profoundly alter the overlying mantle [*Peacock*, 1990]. Subducting sediments and altered oceanic crust contain large amounts of H_2O in pore spaces and in hydrous minerals that is expelled by porosity collapse at shallow depths and by numerous progressive metamorphic dehydration reactions from the trench to depths >200 km [e.g., *Peacock*, 1993a; *Schmidt and Poli*, 1998]. *Hyndman et al.* [1997] proposed that serpentinization of the forearc mantle, caused by the upward infiltration of fluids derived from the subducting slab, could control the downdip limit of the seismogenic zone. In this paper we examine the hypothesis that the downdip limit of subduction thrust earthquakes is controlled by hydrous serpentine minerals, talc, and brucite, that form in the forearc mantle wedge.

Forearc Mantle Petrology

The forearc mantle is composed of depleted ultramafic rocks consisting primarily of olivine and orthopyroxene with lesser amounts of clinopyroxene and Cr-spinel. Harzburgites (olivine + orthopyroxene rocks) and dunites (olivine-rich rocks) are the most abundant ultramafic rocks in suprasubduction zone ophiolites [e.g., *Pearce et al.*, 1984]. Hydration of depleted mantle can be described using the simple MgO-SiO_2-H_2O system. The addition of H_2O to the mantle wedge will stabilize a variety of different hydrous minerals including serpentine (antigorite, chrysotile, lizardite), talc, and brucite, which depend on temperature (T), pressure (P), and bulk composition (e.g., SiO_2 content) [*Evans*, 1977; *Manning*, 1995] (Fig. 1). Serpentine is expected to be the most abundant hydrous mineral in the forearc mantle wedge because $SiO_2/(MgO+SiO_2)$ for serpentine (0.40-0.41) lies between forsterite (0.33) and enstatite (0.50). Antigorite is the stable serpentine mineral in ultramafic rocks metamorphosed under blueschist- and greenschist-facies conditions [*Evans*, 1977] and is stable to 620 °C at 1 GPa [*Ulmer and Trommsdorff*, 1995] (Fig. 2). Lizardite and chrysotile are stable in the lower-grade zeolite and pumpellyite facies at $T <$ 250 °C at 1 GPa [*Evans*, 1977].

In addition to serpentine, hydrated forearc mantle will contain other minerals (Fig. 1). Brucite coexists with serpentine in olivine-rich compositions [$SiO_2/(MgO+SiO_2) < \sim 0.4$] whereas talc coexists with serpentine in pyroxene-rich compositions [$SiO_2/(MgO+SiO_2) > \sim 0.4$]. Serpentine minerals can accommodate small amounts of Al, but the hydration of ultramafic protoliths containing substantial amounts of Al will form chlorite. Diopside is the stable Ca-mineral in ultramafic rocks at $T < \sim 500$ °C; tremolite is stable at higher temperatures [*Evans*, 1977]. Fe partitions into serpentine,

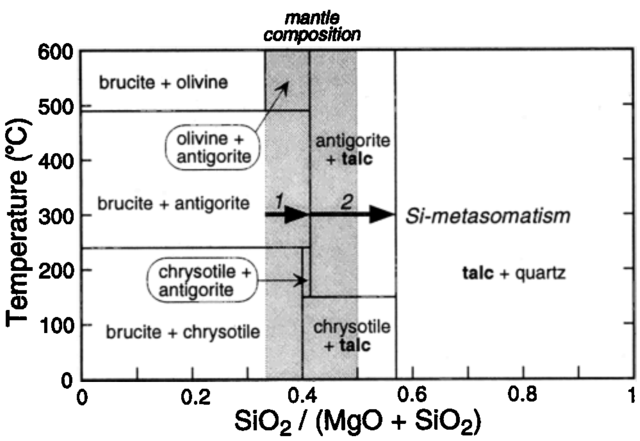

Figure 1. Stable mineral assemblages in fully hydrated rocks at 1 GPa as a function of T and $SiO_2/(MgO+SiO_2)$. Shaded region depicts composition of mantle (olivine + orthopyroxene) rocks. Large arrow illustrates formation of talc resulting from infiltration of silica-saturated fluids at 300 °C via reactions (1) and (2).

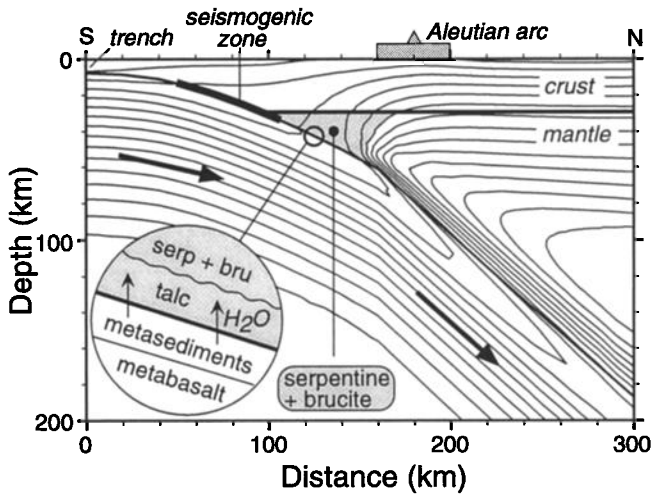

Figure 3. Cross section through the Aleutian subduction zone (Umnak Island) showing thermal structure, calculated using a 2-dimensional finite element model [*Peacock and Wang*, 1998], and potential region of forearc mantle serpentinization (shaded region). Inset shows metasomatic talc layer expected to form in the mantle wedge at the contact with the subducting slab. Contour interval = 100 °C.

brucite, and talc to a limited extent, but the serpentinization process invariably produces magnetite [e.g., *O'Hanley*, 1996]. Thus cold serpentinized mantle might be detected by magnetic anomalies caused by magnetite.

Subduction-zone forearcs are characterized by low heat flow (0.025-0.05 W m^{-2}) reflecting the removal of heat from the overriding plate by the cold subducting oceanic lithosphere. Calculated P-T conditions for subduction-zone forearcs lie well within the serpentine stability field [*Peacock*, 1996] (Figs. 2, 3). In cool subduction zones, such as Alaska, the Aleutians, and NE Japan, the subducting slab intersects the forearc Moho at ~30-40 km at calculated temperatures of 150-250 °C (Fig. 2). In these cases, infiltration of H_2O into the ultramafic hanging wall will form chrysotile/lizardite/antigorite + brucite. For unusually warm subduction zones, such as Cascadia and SW Japan, the temperature at the intersection of the slab with the forearc Moho is ~500 °C and fully hydrated mantle will consist of antigorite + forsterite.

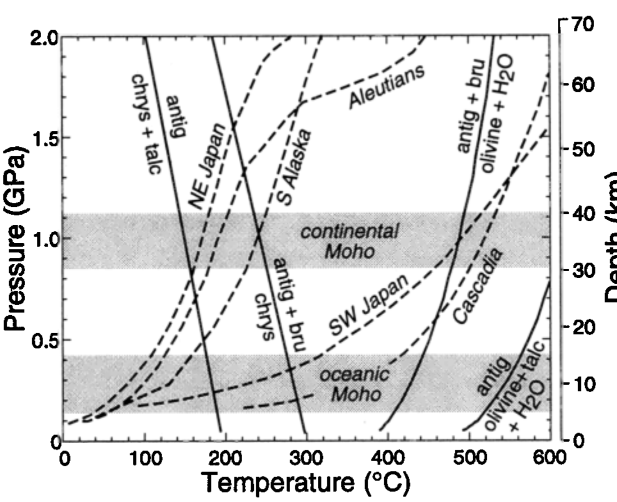

Figure 2. Pressure-temperature diagram depicting MgO-SiO_2-H_2O mineral reactions (solid lines) and calculated P-T conditions along the subduction shear zone for selected subduction zones (dashed lines): Alaska [*Oleskevich et al.*, 1999]; Aleutians [*this study*]; Cascadia [*Hyndman and Wang*, 1993]; NE Japan [*Peacock and Wang*, 1998]; SW Japan [*Wang et al.*, 1995]. Antigorite breakdown reactions calculated using *Holland and Powell*'s [1998] thermodynamic database; chrysotile reactions from *Evans* [1977]. Antig, antigorite; bru, brucite; chrys, chrysotile.

Geological and geophysical observations demonstrate that aqueous fluids released from subducting oceanic crust infiltrate the overlying mantle wedge causing extensive serpentinization. Active serpentinite mud volcanoes observed in the Mariana forearc provide direct evidence for hydration of the forearc mantle by slab-derived fluids [*Fryer*, 1996]. Unusually low seismic velocities observed in forearc mantle [e.g., *Suyehiro et al.*, 1996; *Fliedner and Klemperer*, 1999] suggest serpentinization may be common. On Santa Catalina Island (California) the ultramafic hanging wall of a paleo-subduction zone is extensively hydrated [*Bebout and Barton*, 1989]. The base of the ultramafic section of ophiolites is commonly serpentinized by fluids derived from underthrust rocks [*Coleman*, 1977; *Peacock*, 1987; *Harper et al.*, 1990].

Calculations based on estimated fluid fluxes suggest that over several tens of million years enough H_2O is released from subducting oceanic crust to hydrate the entire forearc mantle wedge [*Peacock*, 1993b]. The amount of serpentinization will be controlled by the amount of H_2O that actually chemically interacts with the forearc mantle. In these low permeability rocks, fluid flow is probably fracture controlled, much fluid may escape to the surface, and serpentinization is probably very heterogeneous.

Formation of Talc at the Slab-Mantle Interface

Quartz-saturated aqueous fluids, derived from subducting sediments and oceanic crust, will produce talc in the overlying forearc mantle. Sediments are subducted to mantle depths in most subduction zones including those with large accretionary prisms [e.g., *von Huene and Scholl*, 1991]. Metamorphosed siliceous oozes and mudrocks contain quartz, and fluids in equilibrium with these rocks will be quartz saturated [*Manning*, 1996]. Whereas most mid-ocean ridge basalts are olivine normative, metamorphosed basalts commonly contain modal quartz coexisting with low-silica minerals such as chlorite [*Peacock*, 1993a]. Aqueous fluids in equilibrium with oceanic crust metamorphosed to blueschist-facies assemblages thus will be saturated with respect to quartz.

Quartz-saturated fluids infiltrating the silica-undersaturated mantle wedge add SiO_2 to the base of the mantle wedge by means of two metasomatic reactions (Fig. 1) [e.g., *Peacock*, 1987; *Manning*, 1995]. First brucite, if present, reacts with aqueous silica in the fluid to form serpentine:

$$3\ Mg(OH)_2\ \text{(brucite)} + 2\ SiO_2\ \text{(aq.)} = Mg_3Si_2O_5(OH)_4\ \text{(serpentine)} + H_2O\ \text{(fluid)} \quad (1)$$

Serpentine then reacts with aqueous silica in the fluid to form talc:

$$Mg_3Si_2O_5(OH)_4\ \text{(serpentine)} + 2\ SiO_2\ \text{(aq.)} = Mg_3Si_4O_{10}(OH)_2\ \text{(talc)} + H_2O\ \text{(fluid)} \quad (2)$$

At a given P and T, reactions (1) and (2) both buffer the silica content of the fluid. For example, at $P = 1$ GPa and $T = 300$ °C, fluid in equilibrium with serpentine + brucite contains $10^{-4.15}$ moles of SiO_2 per kg H_2O, fluid in equilibrium with talc + serpentine contains $10^{-2.15}$ moles of SiO_2 per kg H_2O, and fluid in equilibrium with quartz contains $10^{-1.55}$ moles of SiO_2 per kg H_2O [*Manning*, 1997]. Quartz-saturated fluids infiltrating serpentine + brucite rocks will be scrubbed of virtually all silica by reaction (1) until all brucite is consumed. Talc then begins to form via reaction (2) and 75% of the silica in the infiltrating quartz-saturated fluid will be removed.

The amount of talc formed depends on the time-integrated fluid flux, the P-T conditions, and the original composition of the mantle rocks [e.g., *Peacock*, 1987; *Manning*, 1995]. Subduction for tens of million years will produce a talc-rich zone several meters to several tens of meters thick using published estimates of fluid fluxes [e.g., *Peacock*, 1990]. Silica solubility increases strongly with T and the relatively high temperatures associated with the early stages of subduction or young subducting lithosphere should promote rapid formation of talc in the thrust zone [*Manning*, 1995].

Geological studies of paleo-subduction zones demonstrate that talc does indeed form in the mantle at the contact with underlying subducted rocks. At the base of the Trinity peridotite (northern California), a 4-m-thick zone of metasomatic talc-rich serpentinite formed in dunite as a result of silica-rich fluids derived from underthrust metabasalts [*Peacock*, 1987]. Talc-rich serpentinite occurs locally near the basal thrust of the Josephine ophiolite (northern California) and the thrust zone is marked by a 1-meter thick talc-tremolite schist [*Harper et al.*, 1990]. On Santa Catalina Island high-pressure blueschist-, greenschist-, and amphibolite-facies metamorphic rocks are overlain by a 100+ meter thick ultramafic melange containing talc both in veins and in the matrix of the melange [*Platt*, 1975; *Bebout and Barton*, 1989]. The matrix of the ultramafic melange contains 55 wt % SiO_2 reflecting large-scale Si-metasomatism (fluid infiltration) and mechanical mixing processes along the slab-mantle interface at 25-45 km depth [*Bebout and Barton*, 1989].

Frictional Behavior of Hydrated Mantle

Serpentine, talc, and brucite possess perfect layer-parallel cleavage and are relatively soft. Brucite consists of a layer of octahedral Mg^{2+} ions between two layers of OH^- ions. Serpentine consists of alternating brucite and tetrahedral SiO_4 layers. In talc, a brucite layer is sandwiched between two tetrahedral SiO_4 layers. Serpentine minerals have a Mohs hardness (H) of 2.5-3.5, brucite $H = 2.5$, and talc is one of the softest minerals, with $H = 1$. Indeed, talc is used as a lubricant in industrial processes.

In the laboratory serpentinite generally exhibits stable sliding (velocity strengthening, aseismic) behavior. Antigorite gouge exhibits velocity strengthening behavior at $T = 25$-194 °C [*Moore et al.*, 1997]. At 25 °C, chrysotile gouge exhibits velocity strengthening behavior at plate tectonic velocities, but velocity weakening behavior at velocities > ~0.5 mm s^{-1} [*Moore et al.*, 1997]; at higher T the velocity strengthening behavior extends to higher velocities. The results for lizardite gouge are less easily interpreted, but follow the same general trends as chrysotile [*Moore et al.*, 1997]. Experiments conducted by *Reinen et al.* [1991] on antigorite suggest that increasing normal stress promotes velocity strengthening behavior. The downdip limit of subduction thrust earthquakes, therefore, may be controlled by the formation of serpentinite in the forearc mantle as proposed by *Hyndman et al.* [1997]. However, talc-rich rocks which form at the mantle-slab interface may be the most important factor promoting aseismic behavior. To our knowledge, the velocity strengthening/weakening behavior of talc and brucite has not been investigated experimentally under forearc mantle conditions, but their layered structure indicates they are probably aseismic.

Eastern Aleutian Subduction Zone

The eastern Aleutian Islands are an excellent example of a subduction zone where hydrous minerals in the forearc mantle may control the downdip limit of great thrust earthquakes (Fig. 3). In the eastern Aleutian Islands, wide-angle seismic data show the forearc Moho lies at a depth of 25-35 km [*Fliedner and Klemperer*, 1999]. The great 1957 Aleutian earthquake occurred in this region and the downdip limit of aftershocks extended to 30-40 km depth [*Sykes*, 1971]; to the west the great earthquakes of 1965 and 1986 had similar downdip rupture limits. *Tichelaar and Ruff* [1993] estimated the downdip limit of thrust earthquakes in the central Aleutians at 35-41 km with a slight shallower depth limit in the east where three large thrust earthquakes in the vicinity of Umnak Island occurred at 19-29 km depth.

A large part of the Aleutian forearc mantle lies within the P-T stability field of serpentine + brucite (Fig. 3). Mesozoic-Cenozoic subduction generated large amounts of fluids from the subducted slab that serpentinized the overlying mantle and may have produced talc-rich rocks at the slab interface. Extensive serpentinization of the Aleutian forearc is consistent with a trench-parallel magnetic anomaly [*Godson*, 1991] and unusually low average P-wave velocity of 7.7 km s^{-1} in the mantle wedge [*Fliedner and Klemperer*, 1999]. Similar evidence for forearc mantle serpentinization is observed in other subduction zones. In oceanic subduction zones, the forearc Moho lies at depths of only 5-15 km and mantle serpentinization occurs at shallow depths which may explain the lack of great thrust earthquakes in subduction zones such as Mariana.

Conclusions

The infiltration of H_2O into the forearc mantle wedge transforms dry, strong olivine + pyroxene ultramafic rocks into weak, hydrous mineral assemblages consisting of serpentine minerals, talc, and brucite. The downdip limit of subduction-zone earthquakes appears to occur where the subducting slab intersects the forearc mantle. We propose the formation of serpentine + brucite rocks in the mantle wedge and metasomatic talc at the slab-mantle interface controls the downdip limit of subduction-zone earthquakes.

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