Seismic evidence for widespread serpentinized forearc upper mantle along the Cascadia margin

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ABSTRACT

Petrologic models suggest that dehydration and metamorphism of subducting slabs release water that serpentinizes the overlying forearc mantle. To test these models, we use the results of controlled-source seismic surveys and earthquake tomography to map the upper mantle along the Cascadia margin forearc. We find anomalously low upper-mantle velocities and/or weak wide-angle reflections from the top of the upper mantle in a narrow region along the margin, compatible with recent teleseismic studies and indicative of a serpentinized upper mantle. The existence of a hydrated forearc upper-mantle wedge in Cascadia has important geological and geophysical implications. For example, shearing within the upper mantle, inferred from seismic reflectivity and consistent with its serpentinite rheology, may occur during aseismic slow slip events on the megathrust. In addition, progressive dehydration of the hydrated mantle wedge south of the Mendocino triple junction may enhance the effects of a slab gap during the evolution of the California margin.

Keywords: serpentinite, mantle, forearc, Moho, Cascadia.

INTRODUCTION

A shear-wave velocity model across the central Oregon forearc, volcanic arc, and backarc based on teleseismic arrivals presents a dramatic image of the eclogitization of the subducting Juan de Fuca slab and the serpentinization of the overlying forearc upper mantle (Bostock et al., 2002). Heat-flow modeling (e.g., Bostock et al., 2002) indicates that the forearc upper mantle is likely colder than typical continental upper mantle, making serpentinization the most likely explanation for reduced forearc upper-mantle velocities (Fig. 1). In addition to lowering seismic velocities in the upper mantle, serpentinization can appreciably reduce the amplitude of both wide-angle and near-vertical reflections from the Moho. For the first time we summarize seismic reflection, refraction, and tomography observations of the upper mantle along the Cascade margin to test the hypothesis that the forearc upper mantle there has been serpentinized.

SEISMIC OBSERVATIONS

We compiled upper-mantle (Pn) velocities, near-vertical-incidence reflection images of the continental Moho, and wide-angle reflections from the top of the upper mantle (PmP) along the margin from Vancouver Island to California. We distinguish between PmP reflections from the Moho of the subducting slab (PmP Juan de Fuca plate reflections) and those from the North American upper mantle (PmP North American plate reflections). We discuss and show the locations of PmP Juan de Fuca plate reflections because they form the western boundary of the anomalous forearc upper mantle as well as document that the seismic surveys were capable of imaging PmP if it existed.

With reference to a one-dimensional velocity model (Rondenay et al., 2001), the western tip of the forearc upper mantle wedge exhibits an anomalous, inverted velocity contrast between the upper mantle and the overlying continental crust, placing high over low velocities (Fig. 1). Farther east, lowering of the forearc upper-mantle velocities results in little or no velocity contrast across the Moho (Fig. 1). For both regions the weak or inverted Moho contrast predicts reduced amplitudes for both wide-angle and near-vertical Moho reflections than typical for the continental Moho. A more typical velocity contrast for the continental Moho in the Oregon backarc (Fig. 1) might

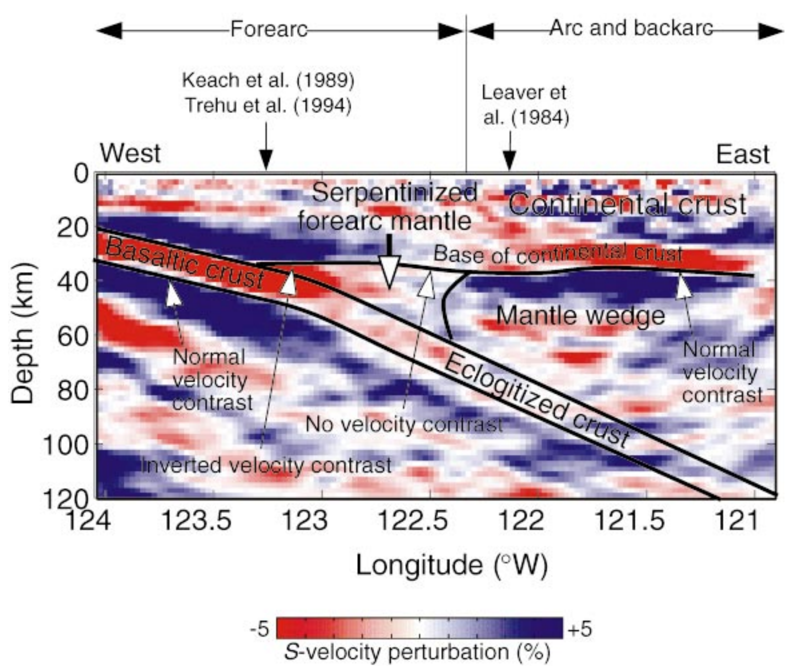

Figure 1. Interpreted teleseismic shear-wave velocity model in central Oregon, showing low-velocity region of forearc upper mantle above high-velocity eclogitized oceanic crust (modified from Bostock et al., 2002). Velocities are perturbations to one-dimensional reference model (Rondenay et al., 2001). Arrows point to locations of intersecting controlled-source seismic surveys summarized here.

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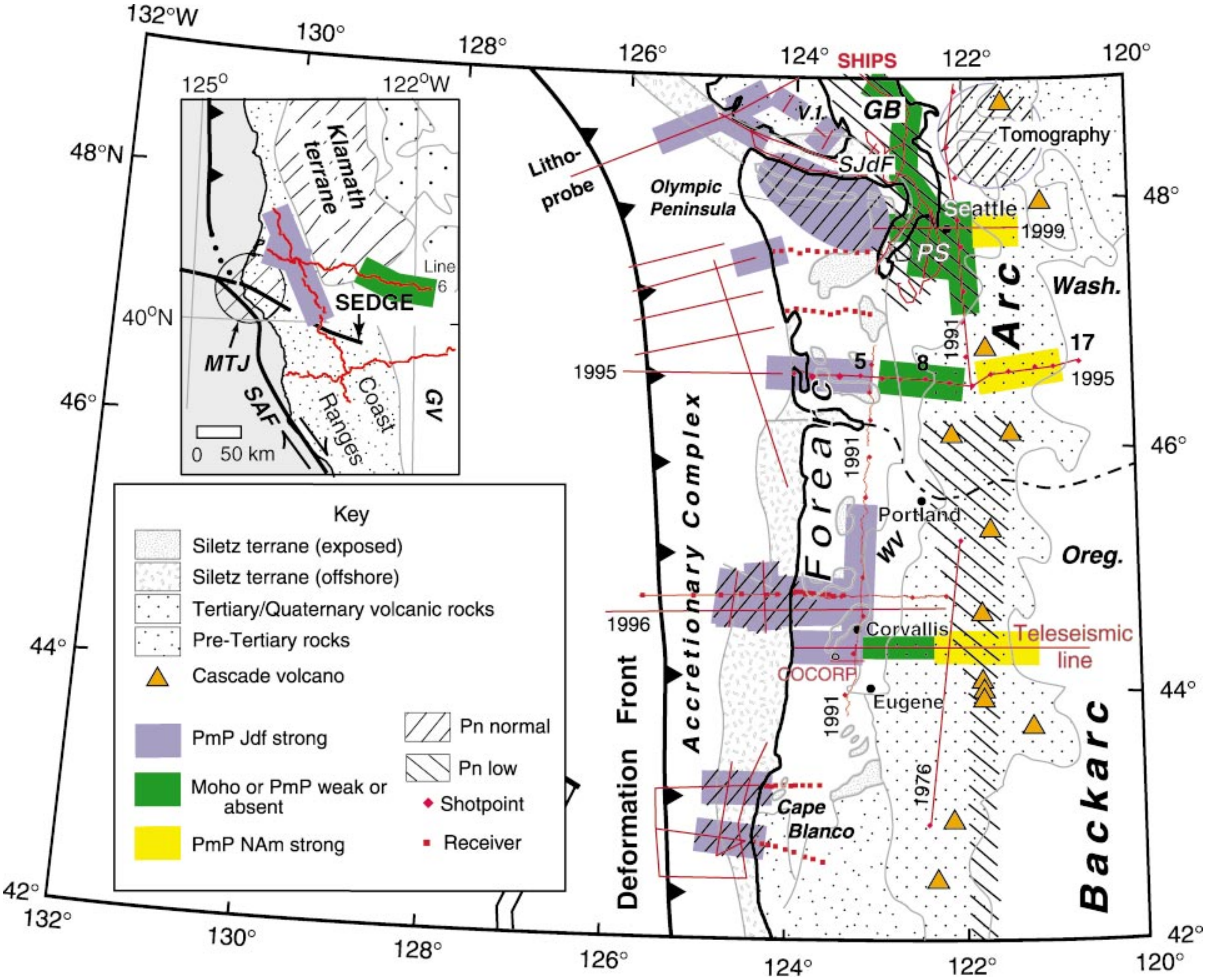

Figure 2. Location of teleseismic line and seismic surveys (red lines) providing upper-mantle observations in Cascadia. These observations are color coded as explained in key. Seismic surveys are labeled by names and dates cited in text. Circle labeled tomography summarizes unpublished tomography results by R.S. Crosson. Typical upper-mantle velocities are between 7.9 and 8.2 km/s. Abbreviations: GB—Georgia Basin; GV—Great Valley; MTJ—Mendocino triple junction; PS—Puget Sound; SAF—San Andreas fault; SEDGE—southern edge of subducted Gorda plate; SJdF—Strait of Juan de Fuca; V.I.—Vancouver Island; WV—Willamette Valley; PmP Jdf—Juan de Fuca plate reflections; PmP NAm—North American plate reflections.

be expected to produce more typical PmP North American plate reflections.

Southwestern Vancouver Island

Lithoprobe wide-angle and seismic reflection studies image a strong Moho reflection from the Juan de Fuca plate beneath the southwestern end of Vancouver Island (Hyndman et al., 1990). These lines map a typical upper mantle (Fig. 2).

Southern Georgia Basin, Strait of Juan de Fuca, and Puget Sound

In the southern Georgia Basin, at the southeastern end of Vancouver Island, and in the Puget Lowland, earthquake tomography by Zhao et al. (2001) down to 60 km reveals a low-velocity forearc upper mantle at ~46 km depth (Fig. 2). Zhao et al. (2001) interpreted the low velocities as evidence for 15%–20% serpentinization of the upper mantle.

In central Puget Sound, unpublished earthquake tomography by R.S. Crosson reveals anomalously low upper-mantle velocities that range from 7.2 to 7.4 km/s. This tomography reveals no evidence for a typical 8 km/s velocity in the upper mantle in this location, although a typical upper-mantle velocity is found underneath the subducting oceanic crust in the Olympic Peninsula and to the northeast of the low-velocity upper mantle (Fig. 2).

Eastward-dipping Moho reflections are observed on the east-trending Seismic Hazards Investigation in Puget Sound (SHIPS) line from the Strait of Juan de Fuca to the mouth of Puget Sound (Tréhu et al., 2002), but Moho reflections cannot be traced farther south and east into the sound (M.A. Fisher, 2001, written comm.; D. Graindorge, 2002, written comm.). In the Puget Sound, Moho reflections from the forearc upper mantle are not observed in the north-trending SHIPS multichannel seismic reflection line extending from Tacoma into the southern Georgia Basin (M.A. Fisher, 2001, written comm.).

Snelson (2001) presented a low-fold stack from the east-trending 1999 SHIPS seismic reflection-refraction line in Puget Lowland (Fig. 2). This stack reveals weak Moho reflections at near vertical incidence on the far western end of the line in the Olympic Mountains, coincident with large-amplitude, wide-angle PmP midpoints (Tréhu et al., 2002). Similarly, the stack shows weak Moho reflections on the eastern end of the line (Fig. 2). The stack shows no evidence of Moho reflections in the Puget Lowland (Snelson, 2001).

Olympic Peninsula

Tréhu et al. (2002) and Creager et al. (2002) reported PmP reflection midpoints from the subducting slab beneath the Olympic Peninsula and Strait of Juan de Fuca (Fig. 2) from the SHIPS experiment. The midpoints map a region having a typical velocity contrast between subducting crust and subducting upper mantle (as in the western end of Fig. 1). No PmP midpoints from the forearc upper mantle are mapped by SHIPS beneath Puget Lowland.

Eastern Washington Forearc

Miller et al. (1997) investigated a 1991 north-south seismic refraction profile along the eastern Washington forearc showing that the Moho exhibits weak contrast between 7.4 km/s lower-crustal and 7.6 km/s upper-mantle velocities. Miller et al. (1997) stated that in the eastern Washington forearc (Fig. 2), Moho arrivals are difficult to pick on any given record, Pn is not clearly observed, and PmP North American plate reflections are only observed on the northern and southern ends of the 1991 north-south line.

Southwestern Washington

A 1995 seismic transect crossing southern Washington (Parsons et al., 1998) identified variable wide-angle reflection amplitudes from the Moho with a pattern similar to that identified by Bostock et al. (2002). Shotpoints in the forearc produced weak PmP North American plate reflections and stronger slab PmP Juan de Fuca plate reflections (Fig. 3, shotpoint 5). In contrast, several shotpoints in the Cascades produced slab PmP JdF reflections but no continental PmP North American plate reflections (Fig. 3, shotpoint 8). Farther east beneath the Columbia Plateau, PmP reflections were again observed (Fig. 3, shotpoint 17). Figure 2 updates the PmP midpoint coverage shown by Parsons et al. (1998).

Oregon Forearc and Volcanic Arc

Tréhu et al. (1994) reported a 1991 north-south Oregon line, sited in the forearc over the subducted slab, showing strong wide-angle PmP Juan de Fuca plate reflections from the subducting oceanic slab (Fig. 1). These PmP Juan de Fuca midpoints plot northward of the teleseismic transect (Fig. 2). Gerdom et al. (2001) presented PmP Juan de Fuca plate observations along the Oregon margin obtained during a 1996 study. The COCORP reflection line in the Willamette Valley (Keach et al., 1989), located just south of the teleseismic line (Fig. 2), shows prominent precritical reflectors between 30 and 40 km depth, from either the subducted oceanic crust or the serpentinized upper mantle (Fig. 1). Tréhu et al. (1994, footnote 18) stated that similar ''precritical reflections from depths of 35–40 km beneath the 1991 north-south profile are observed from several of the 1991 shot points.''

Leaver et al. (1984) presented a 1976 study of the western Oregon volcanic arc and reported a low upper-mantle velocity of 7.7 km/s in the Oregon Cascades (Figs. 1 and 2). Dehlinger et al. (1965) reported a normal Pn velocity west of the Cascades.

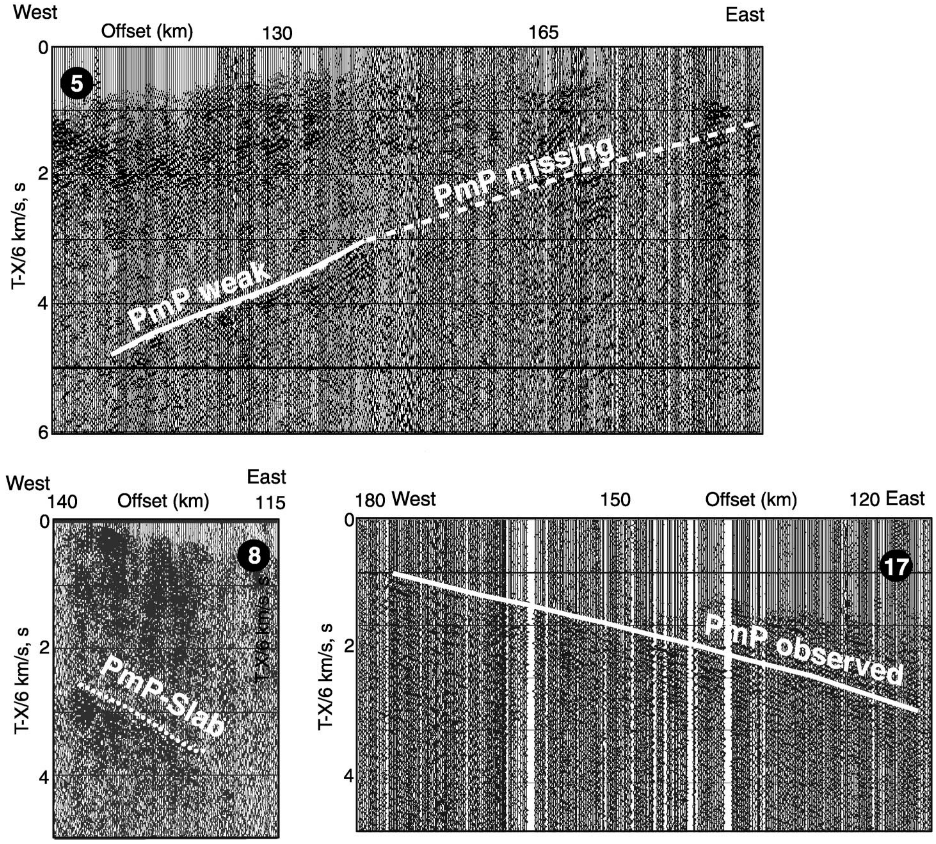

Figure 3. Previously unpublished refraction profiles showing characteristics of wide-angle upper-mantle reflections along east-trending 1995 line in southwest Washington (Parsons et al., 1998). Numbers on each profile give shotpoint number; locations are in Figure 2.

Cape Blanco, Oregon

Typical wide-angle PmP reflections and upper-mantle velocities for the subducting oceanic slab have been reported from the southern Oregon coast near Cape Blanco (Davis, 1995). No information on the forearc upper mantle at this latitude is currently available (Fig. 2).

Mendocino Triple Junction

Strong wide-angle PmP Juan de Fuca plate reflection arrivals and typical upper-mantle velocities are observed beneath the coastal forearc from the subducted Gorda slab north of the Mendocino triple junction (inset map in Fig. 2) (Beaudoin et al., 1996, 1998). No clear PmP or Pn arrivals are observed from the North America plate in spite of the fact that line 6 extends across the entire forearc with shotpoints distributed along the profile.

DISCUSSION

As summarized by Zhao et al. (2001), low upper-mantle velocities are reported in the forearc of the Mariana, Izu-Bonin, northeast Japanese (Zhao, 2001), Alaskan, Chilean (Graeber and Asch, 1999), and northern New Zealand arcs (Reyners et al., 1999). The repeated occurrence of a low-velocity forearc mantle suggests that the serpentinization of the forearc mantle is widespread in subduction zones and plays an important role in subduction dynamics.

Weak or missing PmP North American plate reflections along Cascadia suggest a weak velocity contrast across the continental Moho, as predicted by Figure 1. These weak reflections and/or low upper-mantle velocities characterize a narrow region along the continental margin from California to southern British Columbia (Fig. 2). Serpentinization is the most likely explanation for the reduced upper mantle velocities inferred from these seismic studies (Bostock et al., 2002). Dehydration and eclogitization of the subducting oceanic slab is most likely the source of water for the serpentinization of the forearc upper mantle (Peacock, 1993). Thus, a widespread hydrated upper mantle suggests that slab dehydration and eclogitization occur along the entire Cascadia margin and has several important implications for the subduction process and for earthquake hazards.

Accepting the interpretation that relatively high (7.2–7.6 km/s) velocities in the forearc overlying the subducted crust are indicative of anomalously low velocity, hydrated mantle, then prominent seismic reflectivity within this hydrated mantle (Keach et al., 1989; Tréhu et al., 1994) is indicative of shearing. Reflectivity within the upper mantle is uncommon and elsewhere has been observed along fossil shear zones (Cook, 2002). Aseismic shearing may occur during silent (slow) slip events on the Cascadia megathrust located downdip from the locked and transitional zones of the megathrust (Dragert et al., 2001). The anomalous forearc upper mantle mapped along the Cascadia margin (Fig. 2) is proximal to these slow slip events. For the low (~35 mm/yr) slip velocities expected along Cascadia (e.g., Flück et al., 1997), serpentine exhibits rate-strengthening, stable-sliding, aseismic behavior at room temperature in the laboratory (Reinen, 2000). A serpentinite rheology for the forearc upper mantle is consistent with slow aseismic slip along the megathrust.

Hydration of the forearc upper mantle provides an important deep reservoir of water for forearc volcanism or for lubricating crustal faults. This hydration, however, requires ongoing subduction to depress temperatures and to replenish water. Once subduction ceases along a segment of the Cascadia margin due to the northward propagation of the Mendocino triple junction (e.g., Furlong, 1993), upper-mantle temperatures return to normal, dehydrating the upper mantle. Water driven off by reheating of the upper mantle may explain forearc volcanism lagging the northward passage of the Mendocino triple junction (Fox et al., 1985). Progressive dehydration of the forearc upper mantle may enhance the effects of a proposed slab gap beneath the California forearc (e.g., Furlong, 1993).

If a hydrated forearc upper mantle results from slab dehydration and eclogitization (e.g., Peacock, 1993), Figure 2 suggests that these processes ought to occur along the entire Cascadia margin. Slab dehydration and embrittlement reactions have been proposed as a mechanism producing in-slab earthquakes (e.g., Kirby et al., 1996). Cascadia in-slab earthquakes, however, are limited to the Georgia Strait, Puget Lowland, and the Mendocino triple junction (Ludwin et al., 1991). These observations suggest that these proposed mechanisms alone cannot cause in-slab earthquakes, because such earthquakes are not observed in central Oregon, where ongoing slab eclogitization and mantle hydration is inferred (Fig. 1).

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