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The fate of the downgoing oceanic plate: Insight from the Northern Cascadia subduction zone

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ABSTRACT

In this study, we use teleseismic receiver function analysis to image the seismic structure of the Juan de Fuca oceanic plate during its subduction beneath the North American plate. Seismic data have been recorded at 58 seismic stations deployed along the northern Cascadia subduction zone. Harmonic decomposition of the receiver function data-set along a trench-normal profile allows us to image both the isotropic and the anisotropic structure of the plate (slab). Our images highlight the presence of a highly anisotropic region at 40–70 km depths across the Cascadia subduction zone. The detected seismic anisotropy is interpreted to be related to both metamorphic facies (e.g. blueschists) and fluid released during the dehydration of the subducting mantle. The processes of dehydration and metamorphism produce the variations of the seismic properties within each lithologic unit that constitutes the subducted slab, i.e. basalts, gabbro layer and upper mantle, as the oceanic plate sinks in the upper mantle. Such variations make it almost impossible to recognize the "plate boundary" as a characteristic "velocity-jump" at depth (neither positive nor negative) along the Cascadia subduction zone. Based on the comparative interpretation of both the isotropic and the anisotropic structures retrieved, we propose a 4-stage model of the evolution of the Juan de Fuca oceanic plate during its subduction beneath the North American plate.

1. Introduction

The sinking of the oceanic plate at the trench, given by its gravitational instability, is considered the driving force of plate tectonics. Such process has been widely documented both from direct observations of subducted oceanic lithosphere (e.g. seismic tomography, Tsuji et al., 2008) and theoretical studies (e.g. numerical and analogues modeling, Royden and Husson, 2006; Funiciello et al., 2008). During subduction, the oceanic plate follows a pressure–temperature (PT) path that results in its dehydration and the outputs derived from such process (e.g. fluids) play a key-role in geophysical processes occurring along the plate interface (Wassmann and Stöckhert, 2013). For example, water released from the subducted plate can modify the thermal state of the lithosphere, extracting heat from the oceanic crust and affecting the downdip extent of the potential rupture area (i.e. the seismogenetic zone, Cozzens and Spinelli, 2012). A simplified scheme depicts the evolution of the subducted oceanic plate, and related fluid release, in three main processes: (1) shallow marine sediments compaction; (2) metamorphism of the crust; and (3) breakdown of antigorite minerals and other hydrous phases, such as chlorite and talc, in the oceanic upper mantle. The first process occurs at shallow depths, where the oceanic plate underthrusts beneath the overriding plate, and water stored in pore space is mostly expelled (cf. Faccenda, 2014). The other two processes occur at variable depths, depending on the thermal state of the subducted plate, which, in turn, depends on the plate age and motion. As the oceanic plate subducts, the PT conditions of the subducted materials change resulting in the eclogitization of the oceanic crust and the dehydration of the oceanic upper mantle (Hacker et al., 2003). While these two mechanisms of fluid release are widely accepted as key-processes for the diffuse distribution of the water along the overlying mantle wedge, the depth at which they occur is highly variable between different subduction zones (van Keken et al., 2011). Theoretical models of oceanic plate metamorphism and fluid flow have been presented, based on thermal modeling of the subduction zone, but a number of key-factors needs to be considered, such as weakening of the subduction interface (Wada et al., 2008), localized hydration in the incoming plate (Wada et al., 2012) and alteration to the thermal state due to hydrothermal

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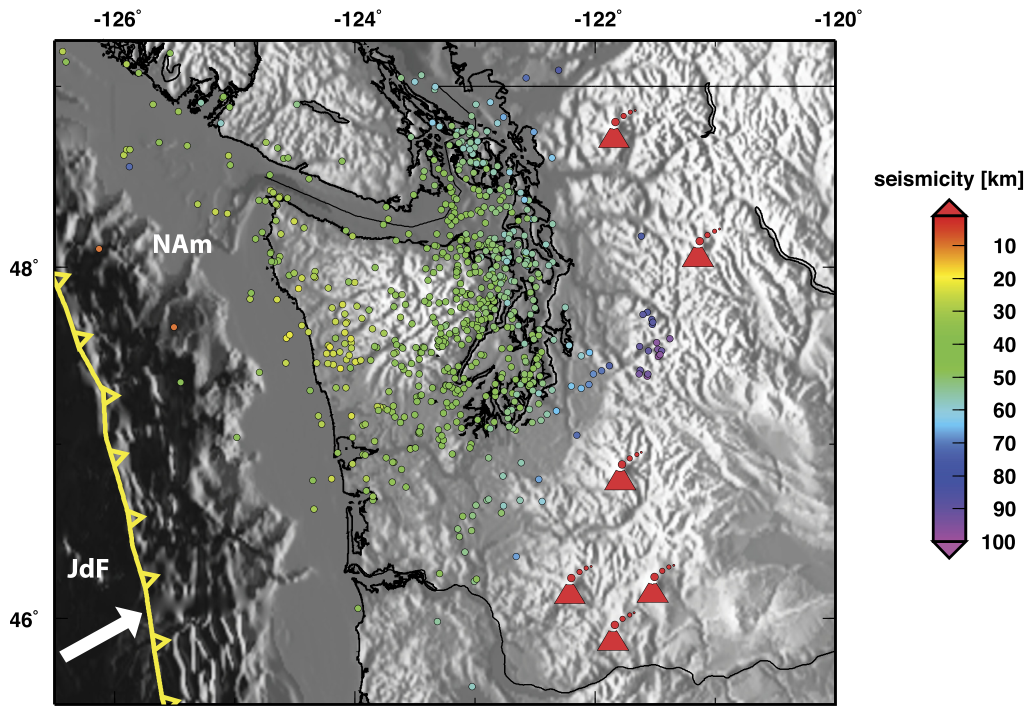

Fig. 1. Generalized map of study area. Plate convergence direction shown by a white vector, plate boundary indicated with a yellow line, and seismicity in the downgoing JdF plate from McCrory et al. (2006, 2012). Label "NAm" indicates the North American plate, "JdF" the Juan de Fuca plate. Red triangles indicate arc volcanoes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

circulation in the subducting crustal aquifer (Rotman and Spinelli, 2013). Such models are usually tested against the distribution of intermediate-depth earthquakes, which are likely to be generated by both the dehydration of the oceanic crust (Tsuji et al., 2008) and the upper oceanic mantle (Reynard, 2013) and against the analysis of metamorphic rock in exhumed crustal sections (Breeding et al., 2004). In recent years, seismic velocity models of subduction zones have also been used to discriminate between different thermal models and to evaluate the influence of different factors to alter the thermal equilibrium of the oceanic plate (Cozzens and Spinelli, 2012). The high density of seismic stations and the development of new methods for seismic data analysis increased the resolution of the images of the subsurface, allowing to be directly compared to thermal and petrological models for subduction zones.

The Cascadia subduction zone (Fig. 1) is an ideal location to explore the evolution and metamorphism of the subducted oceanic plate. Along the west coast of North America the young ($<$10 Ma) Juan de Fuca plate is subducting at approximately 4 cm/year (Gordon et al., 1990). Images of the Cascadia subduction zone structure at depth are primarily based on detailed seismic observations using various methodologies, even though there is a lack of prevalent Wadati–Benioff zone seismicity. Most recently results based on USArray Transportable and Flexible Array deployments have allowed for characterization of lithospheric structure of the convergent margin. Generalized models of the plate boundary (Fluck et al., 1997; McCrory et al., 2006, 2012) have utilized velocity models and hypocenter data to provide constraints on the slab morphology. Teleseismic tomography studies (e.g. Burdick et al., 2008, 2012; James et al., 2011; Obrebski et al., 2011; Roth et al., 2008; Schmandt and Humphreys, 2010, 2011; Sigloch et al., 2008; Sigloch and Mihalynuk, 2013) image the Juan de Fuca plate with fast P- and S-wave velocity perturbations down to at least the transition zone. The shallow slab and overriding plate structure have been imaged using various teleseismic converted wave imaging techniques (e.g. Receiver Function, RF) with increasingly higher resolution (e.g. Rondenay et al., 2001; Bostock et al., 2002; Abers et al., 2009; Audet et al., 2009; Hansen et al., 2013). A distinctive dipping low S-wave velocity zone (LVZ), which is interpreted as the subducted oceanic crust was first noted by Langston (1977, 1981) and since then more detailed studies of this LVZ structure have been mapped by other groups. One of the initial detailed studies using RF migration clearly image the subducted basaltic crust of the Juan de Fuca plate beneath central Oregon down to ∼45 km depth, where its signal then disappeared due to the onset of eclogitization (Bostock et al., 2002; Hyndman and Peacock, 2003). Similar results have been recently obtained using seismic data collected in central Washington State (Abers et al., 2009). These images also show a dipping low velocity zone that extends to 45 km depth and is interpreted as the subducted crust of the Juan de Fuca plate. More studies at other subduction zones have focused on the dipping low-velocity zones and have begun to understand that these low-velocity zones are comprised of multiple layers within the subducted oceanic crust. For Cascadia, the low-velocity zone seems to be composed of three layers, such as sediments, hydrated pillow basalts and dykes, and gabbros and other ultra-mafic rocks (Hansen et al., 2013). Despite the large number of studies focused on the Cascadia subduction zone, there are a number of important open questions about the shallow structure in the 40–100 km depth range, as testified by the controversy over the depth of the plate boundary beneath northern Washington, a fundamental parameter that influences the assessment of seismic hazard potential in the area (Audet et al., 2010).

We have used broadband seismic data from temporary and permanent network stations in Washington State to image the S-wave velocity structure of the Cascadia subduction zone in order to better understand the morphology of the downgoing Juan de Fuca plate to depths of approximately 75 km. We have applied the harmonic decomposition of receiver functions to map seismic anisotropy and infer the structure and evolution of the Juan de Fuca subducted slab beneath Cascadia. Our observations suggest that the seismic properties of the Juan de Fuca plate change