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Multi-mode conversion imaging of the subducted Gorda and Juan de Fuca plates below the North American continent

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ABSTRACT

Receiver function analysis and seismic tomography show tectonic structures dipping eastward in the mantle below the Cascadia volcanic arc (western US) that have been related to the subduction of the Gorda and Juan de Fuca oceanic micro-plates. Inconsistencies in the dip angle and depth extent of the slab between the two methods undermine the interpretation of the structure and processes at work. Receiver function imaging is biased by multiple reflection phases that interfere with converted phases, and produce spurious discontinuities in images. Here, we correct the interference using a multiple mode conversion imaging technique that efficiently removes artifacts under dipping structures. The method has the advantage of being applicable to large aperture arrays, and can image large-scale structures down to the transition zone. With this approach, the interfaces between the subducting and overriding plates and the oceanic Moho are imaged at shallow depths (<120 km) with a dip angle of ∼20°, consistently with former studies. In addition, several important features are imaged with the present method. Faint converters located between 100 and 400 km depth in the mantle wedge, and strong sub-horizontal seismic scatterers near 160 km depth, may highlight dehydration and metasomatism processes in the Cascadia subduction zone. A discontinuity located at ∼15 km depth in the lithospheric mantle of the subducted plates and associated with a negative impedance contrast is interpreted as the fossil fabric of the plates acquired at the spreading ridges.

1. Introduction

The Cascadia subduction zone is the manifestation of the convergence between the North American plate and the Juan de Fuca and Gorda oceanic micro-plates over the last 6–10 Myr. Seismic imaging of the slab and surrounding mantle beneath this area provides key information to resolve the relationship between continental volcanism and tectonics and the dynamics of the underlying mantle. Despite numerous seismic studies (Xue and Allen, 2007; Burdick et al., 2010; Obrebski et al., 2011; Bostock et al., 2002; Audet et al., 2010; Liu et al., 2012; McCrory et al., 2012), the position of the slab interface at depth and its seismic velocity structure remain controversial. Contrary to older and colder subduction zones such as the Pacific margins, the absence of a well-developed Wadati–Benioff zone in the subducted plate (McCrory et al., 2012) prevents resolving this discrepancy.

In regional tomographic models, the subducted oceanic lithosphere is tracked by eastward dipping fast velocity anomalies (e.g. Xue and Allen, 2007; Burdick et al., 2010; Obrebski et al., 2011). These studies show a steep subduction (∼50°) down to the mantle transition zone, whereas most receiver function (RF) analyses (Bostock et al., 2002; Audet et al., 2009, 2010; Liu et al., 2012) show the Juan de Fuca–Gorda plate gently dipping (∼15° to 30°) at shallow depths (<120 km). Part of this discrepancy results from differences in sensitivity of the two methods. Tomographic models can only constrain the large-scale bulk velocity structure of subducting plates (Grand and van der Hilst, 1997; Kárason and Van Der Hilst, 2000) whereas RF analysis resolves sharp velocity contrasts (Audet et al., 2009; Bostock, 2013) that produce conversions from P to S waves (Langston, 1979).

The reflectivity sequence obtained from classical P-to-S RF imaging in a subduction context is usually contaminated by multiple phases reverberated between the surface and the top of the subducted plate. These free-surface multiples can be accounted for using complex migration schemes that involve a general treatment of seismic scattering (e.g. Bostock and Rondenay, 1999; Bostock et al., 2001). However, these techniques strongly depend on the level of data coverage (Rondenay, 2009), which needs to be dense and uniform. To date, these approaches have only been applied to targeted local arrays of densely spaced stations,

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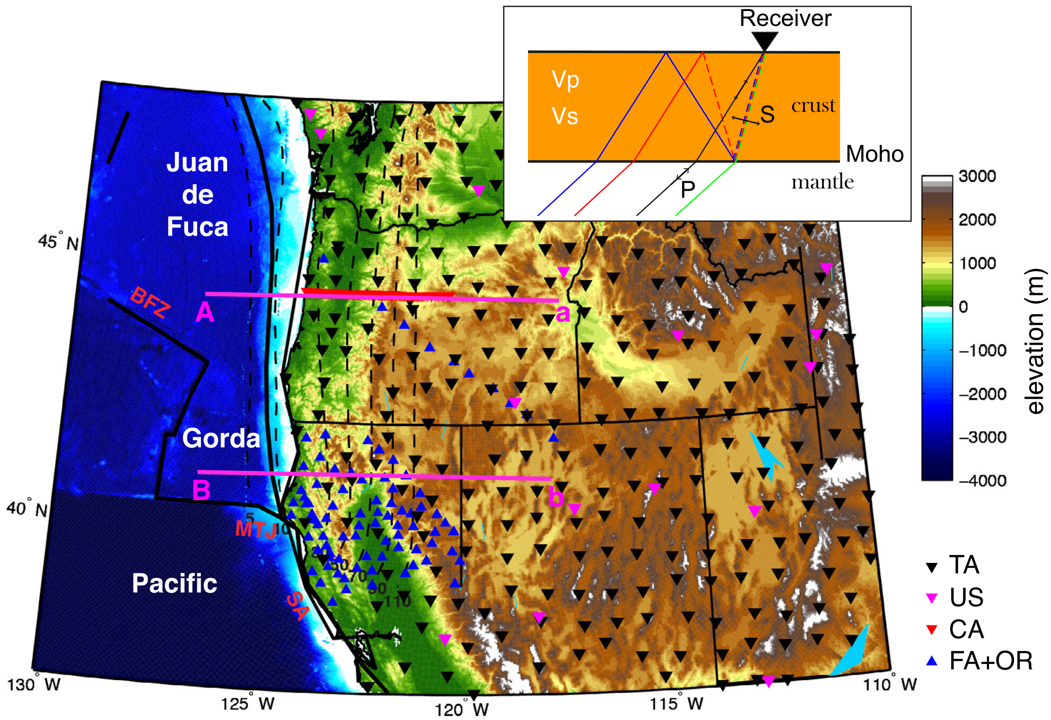

Fig. 1. Map of stations used in this study. Two seismic profiles are discussed in the text: A–a makes use of the dense Cascadia 93 linear array of stations (red triangles) in Central Oregon; B–b uses a combination of data from the Transportable Array (black triangles) and the Mendocino experiment (blue triangles) in northern California. Depth contours for the subducted Juan de Fuca Plate (McCrory et al., 2012) are indicated with north–south dashed lines. Acronyms: TA, Transportable Array; FA, FAME Mendocino Experiment; OR, Oregon Teleseismic Experiment; CA, Cascadia 93 experiment; US, permanent network. BFZ, Blanco fracture zone; MTJ, Mendocino Triple Junction; SA, San Andreas Fault. Inset: ray geometry of PS waves converted directly at the Moho (green) and reverberated with P–P–S (blue) and P–S–S (red) modes of vibrations within the crust. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

e.g. Alaska (Rondenay et al., 2008), Cascadia (Bostock et al., 2002; Abers et al., 2009), Costa Rica and Nicaragua (MacKenzie et al., 2010), western Hellenic (Suckale et al., 2009), and central Mexico (Kim et al., 2012).

In this paper, we use a multiple mode conversion imaging technique that explicitly takes into account the effect of free-surface multiples. It is conceptually simple, easy to implement, and can be applied to larger and sparser arrays to investigate large-scale mantle structures down to 400 km depth. The approach allows us to combine different arrays characterized by various inter-station distances. We complement a previous RF database (61,793 receiver functions) from the US Transportable Array (Tauzin et al., 2013) with two denser arrays of stations: the Cascadia 93 and Mendocino experiments located in central Oregon and northern California (Fig. 1). The wide aperture Transportable Array allows us to depict the western US structure down to the transition zone (TZ) at semi-continental scale. The denser arrays along the A–a and B–b profiles (Fig. 1) increase the number of waveforms by 3490 in central Oregon and by 17,632 in California, providing an up to five times increase in ray coverage of the mantle structure in these regions. These arrays provide a high-resolution image of the subduction system to the west of the North American continent with a better coherence of the slab signature than in the prior study of Tauzin et al. (2013).

This paper is divided into two parts. First, we present the method, establish its robustness on synthetic data for flat and dipping structures, and discuss its advantages compared with other techniques. Second, we reconstruct the reflectivity sequence below Cascadia and re-locate the subduction interface. Our seismic images reveal the existence of new reflectors, located at a depth of about 15 km within the lithospheric mantle of the Gorda and Juan de Fuca plates, and between 100 and 400 km depth in the mantle wedge above the plates. We interpret these signals in the light of regional tomographic models. The signal at ∼15 km depth in the lithospheric mantle of the subducted plates is likely associated with the fossil fabric of the plates acquired at the spreading ridges. The deeper converters are tentatively related to pervasive reflectivity from deep slab-dehydration and metasomatism in the mantle wedge of the Cascadia subduction zone.

2. Method

A receiver function (RF) is a waveform constructed by deconvolving the vertical component of a teleseimic P wave seismogram from its horizontal component (Langston, 1979). This removes the source and distant path effects in the seismograms and allows us to isolate the effect of the structure below the recording station (Langston, 1979). In this study, we build two datasets by low-pass filtering the broadband seismograms at 1 and 0.2 Hz, respectively. The RFs are then obtained from an iterative time domain deconvolution (Ligorría and Ammon, 1999). The back-projection of the RF waveforms allows us to illuminate the sources of scattering in the subsurface and produce depth seismic sections (see Rondenay, 2009 for a review).

2.1. Conventional CCP stacking

2.1.1. The P–S mode

The standard way to interpret receiver functions is by assuming that the energy in the observed signal is due to S waves converted from P waves at discontinuities beneath the recording station. The most common RF imaging method uses direct P-to-S (PS) conversion mode (Langston, 1979) and stacks the data by common conversion points (CCP) assuming conversions at horizontal discontinuities (e.g. Wittlinger et al., 2004). The output of this operation is a reconstructed depth reflectivity sequence, which gives