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Deep crustal fracture zones control fluid escape and the seismic cycle in the Cascadia subduction zone

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ABSTRACT

Seismic activity and non-volcanic tremors are often associated with fluid circulation resulting from the dehydration of subducting plates. Tremors in the overriding continental crust of several subduction zones suggest fluid circulation at shallower depths, but potential fluid pathways are still poorly documented. Using receiver function analysis in the Cascadia subduction zone, we provide evidence for a seismic discontinuity near 15 km depth in the crust of the overriding North American plate. This interface is segmented, and its interruptions are spatially correlated with conductive regions of the forearc and shallow swarms of seismicity and non-volcanic tremors. These observations suggest that fluid circulation in the overriding plate is controlled by fault zones separating blocks of accreted terranes. These zones constitute fluid escape routes that may influence the seismic cycle by releasing fluid pressure from the megathrust.

1. Introduction

Along the Cascadia subduction margin, the oceanic Gorda–Juan de Fuca (JdF) plate has underthrusted the continental North American (NA) plate over the last 6–10 Myr (Fig. 1). A first order and largely debated question concerns the recurrence as well as the spatial distribution of large earthquakes on the megathrust of this subduction zone (*e.g.* Hyndman, 2013). Paleo-seismological reconstructions of recorded subsidence in coastal intertidal marshes suggest a northward increase of recurrence intervals from ∼230 yr to ∼480 yr (Leonard et al., 2010). Modeling of coseismic subsidence of the 1700 A.D. great Cascadia earthquake (Wang et al., 2013) implies a seismic rupture in a single magnitude 9.0 event of much if not the whole length of the margin. The modeling revealed along-strike slip heterogeneities, with patches of higher-moment release separated by an area of lower-moment release near Alsea Bay in Oregon (∼44.4°N). This heterogeneous short-term frictional behavior on the megathrust is also predicted by a recent local gps geodetical study (Schmalzle et al., 2014). The modeled locked zones reveal a wider transition zone under central Oregon than in nearby regions of northern California, Washington, and the Vancouver island, further suggesting that the frictional behavior is segmented along the Cascadia margin. Aseismic slip events, non-volcanic tremors, and low-frequency earthquakes, are also the manifestation of the short-term frictional behavior on the subduction megathrust (Dragert et al., 2001; Rogers and Dragert, 2003; Shelly et al., 2006). Along-strike variations in the distribution and recurrence interval of episodic tremors and aseismic slips, in correlation with the location of forearc basins interpreted as the manifestation of megathrust asperities, have lead Brudzinski and Allen (2007) to speculate a possible link between the long- and short-term seismic cycles. The exact nature of this link still remains to be clearly demonstrated.

The strength of faults, and in particular that of the subduction megathrust where major earthquakes occur, is influenced by the build-up and release of pore-fluid pressure near the slab interface. Fluids originate from metamorphic dehydration reactions in the subducting plate (Hacker et al., 2003). In a partially sealed fault zone, water is extracted from minerals faster than it can be removed by porous flow. This increases the fluid pressure on the megathrust so that frictional earthquake failure occurs at low shear stress (Sleep and Blanpied, 1992). In this way, at the plate interface, fluid pressure is believed to control the occurrence of earthquakes, episodic tremors, and aseismic slip (Obara, 2002; Hacker et al., 2003; Rogers and Dragert, 2003; Audet et al., 2009). Diffuse seismic activity in the overriding plate has also been associated with fluid circulation (Kao et al., 2005; Reyners and Eberhart-Phillips, 2009) but neither the fluid paths

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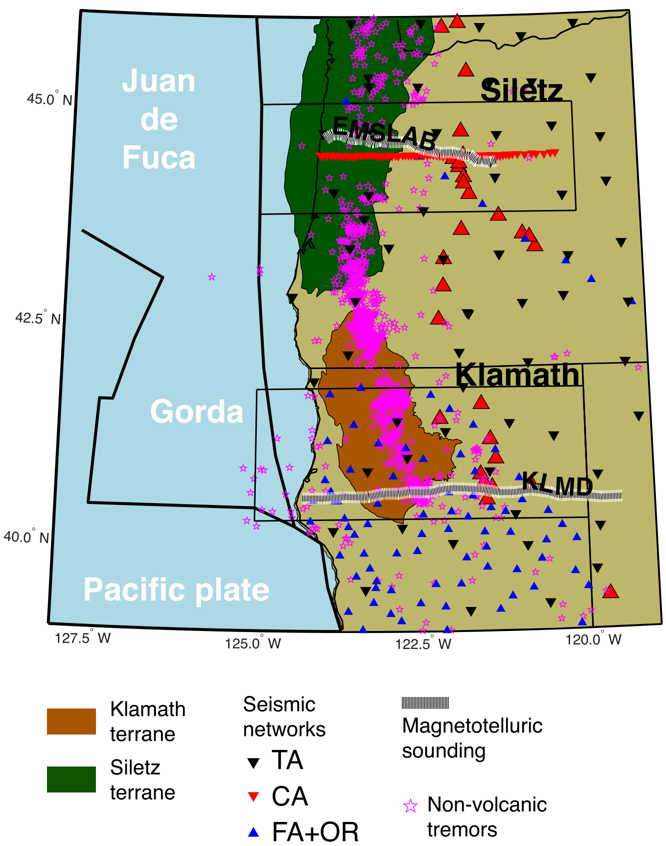

Fig. 1. The geodynamical and geological context of the studied area with the locations of the Siletz and Klamath geological terranes in Oregon and California (Ernst et al., 2008; McCrory and Wilson, 2013). Small triangles are three-component broadband seismological stations. The seismic networks used in this study are the Transportable Array (TA), the Mendocino and Oregon Teleseismic Experiments (FA+OR), and the Cascadia 93 experiment (CA). The areas sampled by the seismic data in Figs. 5 and 6 are indicated with the black frames. The hatched thick white lines correspond to the magnetotelluric survey lines of Wannamaker et al. (2014). The non-volcanic tremors (magenta stars) are from a catalog of Idehara et al. (2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nor the structural control of the overlying forearc geological terranes have truly been evidenced.

In Cascadia, the JdF plate subducts below island arc-subduction assemblages of volcanic rocks that provide the basement throughout much of the arc and forearc (Fig. 1). In central Oregon, the Siletz terrane basalts that are Paleocene to Eocene in age underlie the Coastal Range as well as the western part of the Willamette Basin. In northern California and southern Oregon, much of the forearc is covered by Mesozoic and Paleozoic metamorphic, volcanic, and plutonic basement blocks, the Klamath terranes. By their composition and morphology, these terranes are the usual suspects for controlling the strength variations and the seismic cycle on the megathrust (Brudzinski and Allen, 2007; Audet and Bürgmann, 2014; Wannamaker et al., 2014; Schmalzle et al., 2014). In this study, combining the information provided by high-resolution seismic imaging with electrical resistivity profiles from Wannamaker et al. (2014) sensitive to the amount and nature of fluids, we provide evidence for deep crustal fracture zones in the terranes of the Cascadia forearc. The extent of the fracture zones could control the permeability properties of the forearc, and may determine the presence of shallow non-volcanic tremors. Fluctuations in pore-fluid pressure due to heterogeneous distribution of fractures could also contribute to the segmentation of frictional behavior along the Cascadia margin.

2. Data and methods

We conducted a new analysis of receiver functions (RFs) from two previous studies including data from the Earthscope Transportable Array (Tauzin et al., 2013), and two denser arrays in central Oregon and northern California, the Cascadia 93 and the FAME Mendocino experiments (Tauzin et al., 2016). This comprehensive database of 82,885 RFs allows the dense coverage of a region of approximately 300 × 600 km^2 in the arc and forearc of the Cascadia subduction zone (Fig. 1).

The RFs are the records of P-to-S converted waves that reverberate in the structure beneath seismometers and are isolated from the primary incident teleseismic P-wave by deconvolution (Ammon, 1991). We computed the RFs after rotation of the recording components into the Z-R-T directions, using different low-pass filters at 1 and 0.2 Hz, and using an iterative time–domain deconvolution (Ligorrìa and Ammon, 1999).

We used a common conversion point stacking approach (CCP), which back-projects the seismic signal recorded on the RFs at the corresponding location of theoretical scatterers in the subsurface (*e.g.* Zhu, 2000; Wittlinger et al., 2004). We used the one-dimensional IASP91 velocity model (Kennett and Engdahl, 1991) for ray-tracing and time-to-depth conversion. In Oregon, where the dense Cascadia 93 network is available with inter-station distances of ∼5 km, we stacked the data sensitive to the structure within a distance of 20 km around the profile, and projected them onto the 2D vertical profile. In California where the Mendocino network is sparser (25 km average station spacing), we stacked and projected the data from stations within 100 km of the profile to benefit from data redundancy and improve the signal-to-noise ratio. These lateral distances of projection are reduced compared with our previous work at larger scale (Tauzin et al., 2013; Tauzin et al., 2016, used a ±250 km lateral distance of projection).

Our images are then built from multi-mode CCP stacking (Hetényi, 2007; Tauzin et al., 2016) by combining three images using the PS, PPS, and PSS modes of scattering (Fig. 2). By taking explicitly into account seismic phases reflected multiple times (*i.e.* second order scattering effects), this method removes artifacts from multiples and significantly improves the resolution and the signal-to-noise ratio (Bostock et al., 2002; Tauzin et al., 2016). The PS modes are conversions from P-waves to S-waves (Fig. 2a). PPS and PSS are multiple reverberated waves (Fig. 2b, c). The time-to-depth conversion of the multiples warps more the RF signal than does the back-projection for the PS signal. Therefore to turn the images to similar wavelengths, the data are filtered with low-pass corner frequencies at 1 Hz for PS, and 0.2 Hz for PPS and PSS (Tauzin et al., 2016). We also reversed in polarity the PSS image because PSS conversions have opposite amplitudes to the PS and PPS modes (Fig. 2c). The final multi-mode images in Fig. 2d are simply constructed by stacking the three images obtained from the different modes. To remove possible problems arising from stacking out phase modes, we proceed to a phase-weighted stack (Schimmel and Paulssen, 1997). The operation efficiently filters out the incoherent signal over the different modes (Tauzin et al., 2016).

Bin size is 2 km in horizontal direction and 1 km in vertical direction, similar to the study of Tauzin et al. (2016). The image is smoothed over 8 km horizontal and 3 km vertical distances (against 18 km and 8 km in Tauzin et al., 2016). We also muted the parts of the image where the combined coverage from Ps, PpPs, and PpSs phases is less than 10 rays. This processing allowed building and interpreting high-resolution images of the subducted JdF oceanic plate below the Cascadia forearc (Fig. 2d).

We interpreted the two multi-mode CCP images for central Oregon and northern California with a simple forward modeling