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Constraining the hydration of the subducting Nazca plate beneath Northern Chile using subduction zone guided waves

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ABSTRACT

Guided wave dispersion is observed from earthquakes at 180–280 km depth recorded at stations in the fore-arc of Northern Chile, where the 44 Ma Nazca plate subducts beneath South America. Characteristic P-wave dispersion is observed at several stations in the Chilean fore-arc with high frequency energy (>5 Hz) arriving up to 3 s after low frequency (<2 Hz) arrivals. This dispersion has been attributed to low velocity structure within the subducting Nazca plate which acts as a waveguide, retaining and delaying high frequency energy. Full waveform modelling shows that the single LVL proposed by previous studies does not produce the first motion dispersion observed at multiple stations, or the extended P-wave coda observed in arrivals from intermediate depth events within the Nazca plate. These signals can however be accurately accounted for if dipping low velocity fault zones are included within the subducting lithospheric mantle. A grid search over possible LVL and faults zone parameters (width, velocity contrast and separation distance) was carried out to constrain the best fitting model parameters. Our results imply that fault zone structures of 0.5–1.0 km thickness, and 5–10 km spacing, consistent with observations at the outer rise are present within the subducted slab at intermediate depths. We propose that these low velocity fault zone structures represent the hydrated structure within the lithospheric mantle. They may be formed initially by normal faults at the outer rise, which act as a pathway for fluids to penetrate the deeper slab due to the bending and unbending stresses within the subducting plate. Our observations suggest that the lithospheric mantle is 5–15% serpentinised, and therefore may transport approximately 13–42 Tg/Myr of water per meter of arc. The guided wave observations also suggest that a thin LVL (∼1 km thick) interpreted as un-eclogitised subducted oceanic crust persists to depths of at least 220 km. Comparison of the inferred seismic velocities with those predicted for various MORB assemblages suggest that this thin LVL may be accounted for by low velocity lawsonite-bearing assemblages, suggesting that some mineral-bound water within the oceanic crust may be transported well beyond the volcanic arc. While older subducting slabs may carry more water per metre of arc, approximately one third of the oceanic material subducted globally is of a similar age to the Nazca plate. This suggests that subducting oceanic lithosphere of this age has a significant role to play in the global water cycle.

1. Introduction

Subducting oceanic crust is widely thought to deliver large amounts of water to the mantle, some of which is thought to be released from the slab (causing intermediate depth earthquakes) and rise through the mantle wedge to cause arc volcanism. This release of water is thought to occur as hydrous mineral assemblages lose their bound water through metamorphic reactions due to increased temperature and pressure. Some water however is carried to greater depths by meta-stable oceanic crust and hydrated minerals in the subducting lithospheric mantle. Observations of the hydrated structure of the oceanic plate at intermediate depths, where dehydration processes take place, are however limited. This is largely due to the lack of resolution of conventional seismic imaging methods (e.g. seismic tomography) at these depths.

Subduction zone guided wave observations have the potential to probe the fine scale structure of the down-going plate, and hence constrain the onset of these dehydration reactions, due to the large amount of time these trapped waves spend interacting with the subducting slab. Observations of guided wave dispersion from a number of subduction zones around the Pacific suggest that upper plane intermediate depth earthquakes may be asso-

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ciated with low velocity hydrated minerals that have not transformed to eclogite in the subducted oceanic plate (Abers, 2000; Martin et al., 2003). Detailed analysis of guided wave observations from upper plane Wadati–Benioff zone (WBZ) events in Northern Japan suggest that low velocity hydrated mineral assemblages may persist to much greater depths than is predicted by thermal and petrological modelling of these dehydration reactions (Garth and Rietbrock, 2014a). Observations from lower plane WBZ seismicity in Northern Japan also suggest that these events may be directly associated with low velocity channels, caused by serpentinised outer rise normal faults that penetrate the subducting slab mantle (Garth and Rietbrock, 2014a, 2014b).

Outer rise faulting has been proposed as an effective method of hydrating the lithospheric mantle and accounting for the occurrence of lower plane WBZ seismicity through dehydration processes (e.g. Peacock, 2001). Seismic reflection profiles have shown the presence of outer rise faults penetrating the lithospheric mantle in Nicaragua (Ranero et al., 2003) and Central Chile (Grevemeyer et al., 2005) and an associated drop in heat flow due to the onset of serpentinisation is observed at the outer rise in both of these subduction zones (Grevemeyer et al., 2005). More recently the hydrated zone where these dipping outer rise normal faults penetrate the oceanic crust has been constrained in Nicaragua using electromagnetic methods (Naif et al., 2015), showing that the geometry of the hydrated structure is controlled by the outer rise faults. Geodynamic modelling of the formation of outer rise normal faults suggests that the extent to which these faults penetrate into the subducting plate may increase with depth within the subduction zone, as fluids are forced down as the subducting slab unbends (Faccenda et al., 2009, 2012). These models demonstrate the mechanism by which the lithospheric mantle may become hydrated, allowing lower plane WBZ seismicity to occur due to the associated dehydration reactions.

In Northern Chile outer rise faulting is apparent from the bathymetry of the oceanic plate close to the trench (Fig. 1). Constraints from refraction tomography and gravity inversion in the area suggest that at the trench an approximately 20 km thick layer of hydrated lithospheric mantle is present beneath the subducting oceanic crust (Ranero and Sallares, 2004). It is proposed that these outer rise normal faults (and other structures within the subducting plate) are reactivated in the WBZ (Rietbrock and Waldhauser, 2004; Ranero et al., 2005), suggesting that these fault zone structures persist to intermediate depths within the subduction zone.

Analysis of guided waves from intermediate depth earthquakes in Northern Japan has shown that low velocity hydrated fault zone structures persist to depths of up to ∼150 km and can therefore account for lower plane WBZ seismicity. Additionally, analysis of the P-wave coda from these events provides a constraint on the hydration of the subducted lithospheric mantle, showing that this part of the subducting slab is highly hydrated and carries approximately 90% of the water transported to the mantle (Garth and Rietbrock, 2014b).

This study concerns the South American subduction zone in Northern Chile, where the 44 Myr Nazca plate is subducted beneath the South American plate at approximately 78 mm/yr (van Keken et al., 2011). This much younger and therefore warmer subducting oceanic crust contrasts with the 130 Myr cooler oceanic crust subducting in Northern Japan (Garth and Rietbrock, 2014a, 2014b). Our results therefore provide a test of whether the low velocity features observed in Northern Japan are unique to older subducting oceanic plates or are more ubiquitous feature of subduction zones with a variety of ages and thermal properties. The results also provide crucial information about how much water is transported by the lithospheric mantle in 'younger' subduction zones and therefore provides vital evidence for estimating the overall water budget in the Earth's mantle.

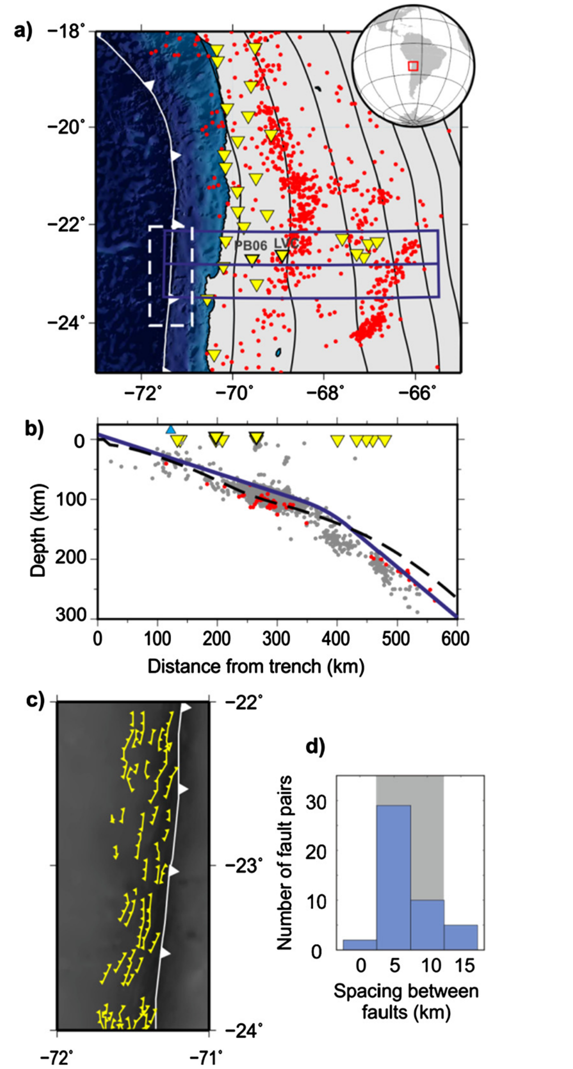

Fig. 1. Summary map and profile. **a)** The study area of Northern Chile. Well located background seismicity from the ISC earthquake bulletin from 2010–2014 (International Seismological Centre, 2014) is shown in red, and slab contours are shown from slab1.0 (Hayes et al., 2012). The IPOC broadband seismic network (GFZ German Research Centre for Geosciences, 2006), temporary stations used in Bolivia (West and Christensen, 2010), and IU station LVC are shown by the inverted yellow triangles. The stations used in the grid searches are highlighted and labelled. The blue box shows the profile location given in the bottom panel. **b)** Local seismicity located with temporary networks is shown in grey, and well located events from the ISC bulletin are shown in red. The slab geometry of slab1.0 (Hayes et al., 2012) is indicated by the dashed black line and the chosen model geometry is given by the blue line. The blue triangle shows the location of the coast. **c)** Bathymetry is shown in grey, with the outer-rise fault structures identified by Ranero et al. (2005) highlighted in yellow. The area plotted is shown by the dashed white box in a). **d)** A histogram showing the number of faults with specific fault spacing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Subduction zone guided waves have previously been observed in the study area from temporary seismic deployments (Martin et al., 2003, 2005; Martin and Rietbrock, 2006), and studies suggest that a relatively thin (<4.5 km thick) low velocity layer (LVL) persists to a depth of at least 160 km (Martin et al., 2003). Guided wave arrivals are seen as energy decouples from the slab due to the bend of the slab (Martin et al., 2003; Martin and Rietbrock, 2006), and at shallower depths due to contact with the low velocity over riding plate (Martin et al., 2005). In this paper we present new guided wave observations from the South American subduction zone, recorded on permanent broadband stations in Northern Chile. We explore the new resolution