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The lithosphere–asthenosphere boundary beneath the South Island of New Zealand

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ABSTRACT

Lithosphere–asthenosphere boundary (LAB) properties beneath the South Island of New Zealand have been imaged by Sp receiver function common-conversion point stacking. In this transpressional boundary between the Australian and Pacific plates, dextral offset on the Alpine fault and convergence have occurred for the past 20 My, with the Alpine fault now bounded by Australian plate subduction to the south and Pacific plate subduction to the north. Using data from onland seismometers, especially the 29 broadband stations of the New Zealand permanent seismic network (GeoNet), we obtained 24,971 individual receiver functions by extended-time multi-taper deconvolution, and mapped them to three-dimensional space using a Fresnel zone approximation. Pervasive strong positive Sp phases are observed in the LAB depth range indicated by surface wave tomography. These phases are interpreted as conversions from a velocity decrease across the LAB. In the central South Island, the LAB is observed to be deeper and broader to the northwest of the Alpine fault. The deeper LAB to the northwest of the Alpine fault is consistent with models in which oceanic lithosphere attached to the Australian plate was partially subducted, or models in which the Pacific lithosphere has been underthrust northwest past the Alpine fault. Further north, a zone of thin lithosphere with a strong and vertically localized LAB velocity gradient occurs to the northwest of the fault, juxtaposed against a region of anomalously weak LAB conversions to the southeast of the fault. This structure could be explained by lithospheric blocks with contrasting LAB properties that meet beneath the Alpine fault, or by the effects of Pacific plate subduction. The observed variations in LAB properties indicate strong modification of the LAB by the interplay of convergence and strike-slip deformation along and across this transpressional plate boundary.

1. Introduction

The South Island of New Zealand is a particularly intriguing transpressional boundary in which the strike-slip Alpine/Marlborough fault system is bounded by subduction to its north and south. The goal of this study is to place new constraints on the structure of the lithosphere beneath the South Island using Sp converted waves and to relate this structure to the tectonic history of the region, in particular the interplay of strike-slip motion and convergence.

In the South Island of New Zealand, the Alpine/Marlborough fault system divides the Pacific plate (on the southeast) from the Australian plate (on the northwest). Two subduction zones bound the strike-slip plate boundary segment, the Hikurangi subduction zone to the north where Pacific plate lithosphere subducts northwestward, and the Puysegur subduction zone to the south where Australian plate lithosphere subducts southeastward (Fig. 1) (Sutherland et al., 2000). Whereas the Alpine fault dominates much of the strike-slip boundary, in the northern South Island multiple strike-slip faults form the Marlborough fault zone, which lies above the edge of the Hikurangi subduction zone. The strike-slip fault system plays an important role in accommodating relative plate motions on the island (Anderson et al., 1993; Lamb et al., 2015; Wallace et al., 2007). While relative plate motion is mostly parallel to the strike-slip faults (35.5 mm/yr reported by Cande and Stock, 2004; 38.9 mm/yr reported by Beavan et al., 2007), the convergence of the two plates at the fault (∼6.5 mm/yr reported by Cande and Stock, 2004; 9.1 mm/yr reported by Beavan et al., 2007) is also significant. The northeast-striking Alpine fault dips at 40°–60° to the southeast in the central South Island and at 80°–90° in the southern South Island (Barth et al., 2013; Norris and Toy, 2014; Sutherland et al., 2000).

Questions of particular interest are how the combination of strike-slip motion and convergence at this plate boundary have

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altered the base of the lithosphere, and how the currently subducting Australian and Pacific plates connect to the upper plate lithosphere. Earlier studies found a high-velocity anomaly in the mantle southeast of the Alpine fault, beneath the high topography that forms the spine of the South Island (Lamb et al., 2015; Molnar et al., 1999; Stern et al., 2000). Interpretations for this feature include transpressional thickening of the upper plate (Molnar et al., 1999; Savage et al., 2007a; Stern et al., 2000) rollback of Pacific plate lithosphere (Lamb et al., 2015), or a connection to the extended margin of the Australian plate that partially subducted while translating with strike-slip motion since ∼25 Ma (Sutherland et al., 2000). However, with better sampling provided by recent deployments of seismic stations, recent tomography studies have instead found a high velocity zone consistent with thicker lithosphere that lies beneath the northwestern coast of the South Island, largely to the northwest of the Alpine fault, that could represent subducted Pacific lithosphere (Ball et al., 2016; Zietlow et al., 2016). Fry et al. (2014) also found a high velocity anomaly northwest of the Alpine fault, but their preferred interpretation is that it represents a remnant slab from Cretaceous subduction. Resolving this debate and determining lithospheric thickness across the South Island is important to testing geodynamic models of lithospheric deformation and instability in transpressional plate boundaries (e.g. Molnar and Houseman, 2004; Pysklywec et al., 2010).

In addition, while strike-slip fault geometries and plate motions are relatively well understood at the surface (Barth et al., 2013; Wallace et al., 2007), they are debated deeper in the crust (Lamb et al., 2015; Lay et al., 2016; Norris and Toy, 2014; Scherwath et al., 2003), and the form of the plate boundary in the deep mantle lithosphere is even less clear. Several lines of evidence have been interpreted as evidence for a distributed plate boundary at depth. Moho topography and crustal anisotropy across the Marlborough fault zone (Wilson et al., 2004) were used to infer a deformation zone of more than 60 km in width, and mantle anisotropy as constrained by shear-wave splitting (Karalliyadda et al., 2015; Molnar et al., 1999; Zietlow et al., 2014) and azimuthal variations in Pn velocities (Collins and Molnar, 2014) have been interpreted in terms of a strike-slip shear zone distributed over 100–200 km horizontally, although with the shear-wave splitting trade-offs exist between the width of the shear zone in the mantle lithosphere versus the asthenosphere (Zietlow et al., 2014). In contrast, Norris and Toy (2014) propose a steep and horizontally-localized ductile strike-slip zone that penetrates through crust and mantle lithosphere.

In this study, common conversion point (CCP) stacking of Sp receiver functions is used to image the LAB across the South Island to address these questions. Sp CCP stacking is effective at imaging shallowly-dipping interfaces, in particular those with dips of less than 15° (Lekić and Fischer, 2017). Most of the receiver function studies that have been conducted in the region (Bourguignon, 2009; Boyd et al., 2007; Salmon et al., 2013; Savage et al., 2007b; Spasojević and Clayton, 2008; Wilson et al., 2004) have employed Ps phases to image crustal structure, including dipping interfaces associated with the subducting Pacific plate (Boyd et al., 2007; Savage et al., 2007b). However, interference from crustal multiples can complicate the interpretation of mantle structure from Ps receiver functions. Sp and SKSp phases recorded by four South Island stations have provided evidence for shallow mantle discontinuities (Bourguignon, 2009). Here we take advantage of the good spatial sampling provided by broadband stations across the South Island, the New Zealand GeoNet network in particular, to construct a continuous image of LAB properties.

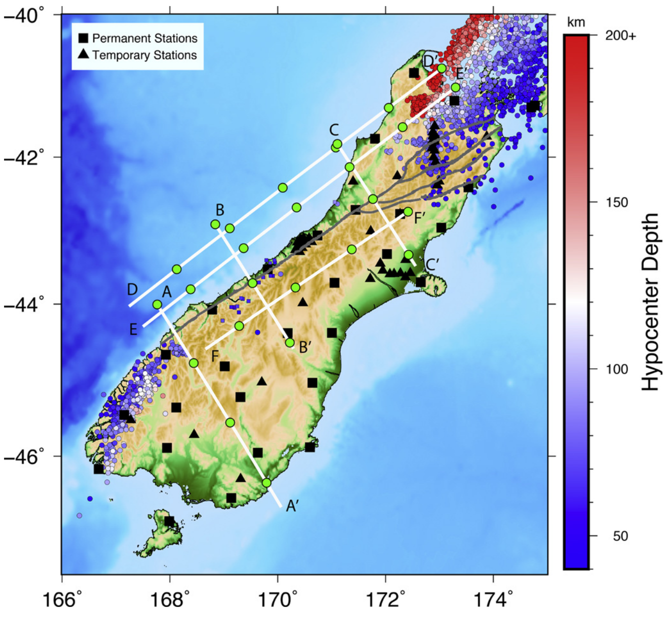

Fig. 1. Map of the study region covering the South Island, New Zealand. Broadband stations employed in this study are black squares (permanent) and triangles (temporary). The Alpine fault and Marlborough fault system are shown by gray lines (New Zealand Active Faults Database). Earthquakes through 2016 (depth greater than 50 km, magnitude greater than 3.5) from the New Zealand Catalogue of Earthquakes from GeoNet (Petersen et al., 2011) are shown by dots color-coded by depth. Mantle earthquakes in the central South Island (Boese et al., 2013) are marked by small squares. Bold white lines show locations of profiles discussed in this paper; the distance between the green circles on the profiles is 100 km. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Data

Data used in this study are Sp phases from broadband seismograms recorded from as early as 1992 to 2016 by seismometers on the South Island and the southern edge of the North Island (Fig. 1). Other phases such as SKSp were not employed. Data was analyzed from 72 stations, including 29 permanent stations of the New Zealand GeoNet National Seismograph Network (NZ) (Petersen et al., 2011), one from the IRIS Global Seismic Network (IU) (doi: https://doi.org/10.7914/SN/IU), and the remainder from five temporary networks (Jones and Sheehan, doi: https://doi.org/10.7914/SN/XB_2000; Sheehan et al., doi: https://doi.org/10.7914/SN/Y3_2009; Thurber and Savage, doi: https://doi.org/10.7914/SN/4A_2010; Thurber et al., doi: https://doi.org/10.7914/SN/ZT_2012; Wu, doi: https://doi.org/10.7914/SN/XU_1996). Broadband ocean-bottom seismometers have also been deployed around the South Island (e.g. Ball et al., 2016; Zietlow et al., 2016), but these data were not employed in this study due to lower signal-to-noise ratios, particularly on horizontal components. Earthquakes were required to have a source station distance range of 55°–85° and $M_w > 5.8$, resulting in 24971 event-station pairs which provided useful receiver functions. Given these criteria, the distribution of event back-azimuths is highly asymmetric, with most S phases arriving from 270°–345° (Fig. 2a).

3. Methods

In contrast to Ps phases, Sp receiver functions are not contaminated by crustal reverberations, leading to their widespread use in measuring LAB properties (e.g. Fischer et al., 2010). Sp conversion points from a given depth lie farther from the station than Ps conversion points. Given the event back-azimuths for the usable waveforms (Fig. 2a), sampling of mantle structure is particularly good beneath the western South Island and offshore regions to the