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Evidence for strong lateral seismic velocity variation in the lower crust and upper mantle beneath the California margin

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ABSTRACT

Regional seismograms from earthquakes in Northern California show a systematic difference in arrival times across Southern California where long period (30–50 s) SH waves arrive up to 15 s earlier at stations near the coast compared with sites towards the east at similar epicentral distances. We attribute this time difference to heterogeneity of the velocity structure at the crust–mantle interface beneath the California margin. To model these observations, we propose a fast seismic layer, with thickness growing westward from the San Andreas along with a thicker and slower continental crust to the east. Synthetics generated from such a model are able to match the observed timing of SH waveforms better than existing 3D models. The presence of a strong upper mantle buttressed against a weaker crust has a major influence in how the boundary between the Pacific plate and North American plate deforms and may explain the observed asymmetric strain rate across the boundary.

1. Introduction

The lithospheric structure beneath the California margin plays an important role in controlling how the plate boundary between Pacific plate and North American plate deforms. Geodetic studies (Chery, 2008; Schmalzle et al., 2006; Wdowinski et al., 2007) have shown an asymmetry in strain accumulation across the San Andreas Fault (SAF). The asymmetry is attributed to factors including laterally heterogeneous elastic properties in the upper crust (0–20 km) and varying elastic lithospheric thickness across the fault in the lower crust. Here, we present seismic observations that are consistent with the lateral transition in elastic properties across the SAF boundary, involving the lower crust and upper mantle structure beneath the California margin, as shown schematically in Fig. 1.

The seismic lithosphere or lid, as defined in Anderson (1995) is a zone of relatively high seismic velocity in the uppermost mantle, generally overlying a low velocity zone (LVZ) under oceans and cratons. The lid and underlying LVZ are different from the mechanically-defined lithosphere–asthenosphere boundary, although both are closely related, and the seismological layers are often used to outline mechanical structure (Stein and Wysession, 2009). Pure path (1D) models indicate that the Pacific plate has a thick (∼60 km) lid overlaying a strong LVZ extending to below a depth of 300 km (Gaherty et al., 1999; Tan and Helmberger, 2007). In contrast, the continental Western United States (WUS) structure is characterized by a relatively slower, thinner lid (10–20 km) along with a weaker mantle LVZ (Grand and Helmberger, 1984). Despite these large lateral differences, the vertical travel times through these two structures are quite similar. Thus, studies utilizing teleseismic phases with nearly vertical ray paths (e.g., most global tomographic models) have diffi-

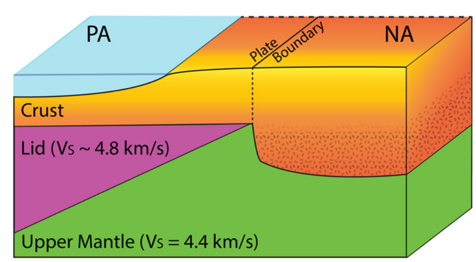

Fig. 1. A schematic drawing of our proposed model. The lid (defined in text), which is faster than its surrounding medium, grows in thickness from the plate boundary towards Pacific plate (PA). In order to better fit the arrival times for inland stations (details in Section 3), the crust below the North American plate (NA) is modeled with a thick, relatively low-velocity crust.

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culty resolving the lateral variation in shear wave velocity structure across the plate boundary.

Using regional S-SS differential travel times, Melbourne and Helmberger (2001) showed that there is lateral variation within the sub-crustal mantle characterized by the presence of a seismic lid beneath California with thickness increasing from 0 km in Eastern California to 55 km along the Pacific plate (see Fig. S1 in Supplementary material (SM)). As the Pacific plate with a thick lid has lower dextral strain compared to the North American plate with a thin lid, they propose that the lid structure may modulate the deformation across the plate boundary. However, the sampling sites of the lid thickness, denoted by the SS reflection points, are located along the coast of Baja California and therefore cannot precisely resolve the lid thickness beneath the main California coastal region.

Understanding how the plate boundary between Pacific plate and North American plate deforms requires an accurate image of the deep structure along the plate boundary. Seismic studies since the 1970s indicate large variability in velocity structure along this boundary. For example, Zandt and Furlong (1982) combined teleseismic travel-time data and thermal models to infer lithospheric-thinning along the San Andreas fault system in northern California. More recently, Wang et al. (2013) used surface wave tomography to map out lateral velocity variations to a depth of 300 km throughout the southwestern United States, finding similar lithospheric thinning to the east of the San Andreas fault in the Mendocino region as well as high velocity regions within the upper mantle at depths up to 200 km that they correlate with fossil slab structures. Other recent studies took advantage of the improved station density coverage to retrieve regional velocity structure of the crust and uppermost mantle using seismic tomography (e.g. Hauksson, 2000; Prindle and Tanimoto, 2006), adjoint waveform tomography (Tape et al., 2009) or receiver function techniques (e.g. Zhu and Kanamori, 2000; Yan and Clayton, 2007; Lekic et al., 2011; Levander and Miller, 2012; Ford et al., 2014). Many of these regional velocity features are incorporated in the development of 3D velocity models by the Southern California Earthquake Center (SCEC), which are discussed later.

Multiple earthquakes, namely the 2014/03/10 Mw 6.8, 2005/06/15 Mw 7.2, and 2010/01/10 M6.5 events in Mendocino region and the 2014/08/25 Mw 6.0 Napa earthquake, present a unique opportunity to directly study the lateral variation in the lower crust–upper mantle structure beneath the California margin using regional waveforms. The earthquakes occurred in Northern California and the waveforms were recorded by the BK network operated by the Northern California Seismic Network (NCSN) and the CI network operated by the Southern California Seismic Network (SCSN) at regional distances (3–11°) (Fig. 2a inset). The recorded waveforms exhibit significant travel time differences (discussed in Section 2), suggesting possible lateral heterogeneity of the lithospheric structure beneath the California margin.

3D waveform-modeling is useful to investigate anomalous behaviors in the seismic wave field, but can be prohibitive when modeling at large continental scales due to high computational cost. One previous known effort in continental-scale modeling is by Ji et al. (2005) which is able to explain large scale Rayleigh-wave multipathing phenomenon across western North America, but lacks resolution for detailed study on ocean–continent transition. Specifically modeling the crustal-sensitive waves that sample the whole continental margin on a reduced regional scale allows us to refine current velocity models and constrain key features across the plate boundary.

In this study, we show that the travel times of the regional SH waveforms from these events cannot be well explained by existing 1D and 3D velocity models, which are poorly constrained in lower crust–upper mantle structure. We propose that a fast seismic layer beneath the California coast coupled with a thick, relative slow crust beneath eastern California is necessary to explain the discrepancies in travel times. The lateral variation of velocity in the lower crust–upper mantle region in our proposed model suggests a similar lateral variation in lithospheric strength which may play a strong role in modulating long term plate deformation and explain the strain rate asymmetry across the SAF.

Table 1
A description of the modified 1-D ‘Gil7’ model. The main modification is a simplification of the crustal layer where the number of layers is reduced from 7 to 3. The Moho depth in this model is 25 km. The parameters of the fast lid and the thicker, slower crust used in western and eastern parts, respectively, of this study's preferred model, are listed in parentheses.

Layer	Thickness (km)	V_s (km/s)	V_p (km/s)	Density (g/cc)
Upper crust	5	2.60	4.50	2.40
	12	3.40	6.21	2.68
Lower crust	8 (18)	3.98 (3.70)	6.89 (6.70)	3.00 (2.80)
(Lid)	(varies)	(4.80)	(8.30)	(3.20)
Upper mantle	–	4.40	7.80	3.00

2. Observations

The challenge in studying the ocean–continent plate boundary using regional waveforms in California is that it is difficult to model the different types of waveforms (P, SH and SV) simultaneously because of the limited aperture of the station distribution and the nodes in the radiation patterns for strike-slip events. In this study, we concentrate on the tangential component in displacement, because the stations are located close to the maxima of SH wave radiation pattern for the earthquakes we analyze.

We perform cross-correlation to see how the travel times of the observed SH waveforms compare with that computed from a 1-D velocity model (see Table 1) modified from the layered ‘Gil7’ velocity model (Dreger and Romanowicz, 1994). The 1-D synthetics are computed using frequency-wavenumber method by Zhu and Rivera (2002). The ‘Gil7’ velocity model is derived from broadband waveform modeling and routinely used in moment tensor inversions in Northern California. The ‘Gil7’ model is a relatively fast model, which has a shallow Moho boundary at 25 km and includes a fast, mafic lower crust with a P-wave velocity (V_p) of 6.89 km/s and shear wave velocity (V_s) of 3.98 km/s, as revealed from the San Francisco Bay area seismic imaging experiment (BASIX) in 1991 (Brocher et al., 1994). The time differences between the data and synthetics will show how much the 1-D velocity model deviates from the true velocity structure. In this study, we use published moment tensor solutions provided by the ANSS Comprehensive Earthquake Catalog (listed in Table 2). We concentrate our analysis in the period range of 30 to 50 s. The waveforms sample up to a depth of 100 km and are sensitive to both the lower crust and upper mantle structure (see Fig. S2 in SM for sensitivity kernel produced using tools from Herrmann, 2013).

For both Mendocino and Napa earthquakes, the observed long period SH waves show a systematic pattern of later arrival times (positive time delay) for sites in eastern California and early arrival times (negative time delay) for sites along the coast, demonstrating that the velocity structure varies laterally across California (Fig. 3). The range of time shifts for the 2014 Mendocino event is stronger than that seen for the 2014 Napa earthquake, suggesting that the waveforms from the Mendocino event are able to better sample this considerable structural variation, which extends from Mendocino region to the south of Napa region along the coast. Additionally, the pattern and strength of the time shifts seen for the 2014 Mendocino event are consistent with that found for other events of similar magnitudes in the Mendocino Triple Junction