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The crust and uppermost mantle structure of Southern Peru from ambient noise and earthquake surface wave analysis

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ABSTRACT

Southern Peru is located in the northern Central Andes, which is the highest plateau along an active subduction zone. In this region, the Nazca slab changes from normal to flat subduction, with the associated Holocene volcanism ceasing above the flat subduction regime. We use 6 s to 67 s period surface wave signals from ambient noise cross-correlations and earthquake data, to image the shear wave velocity (V_{SV}) structure to a depth of 140 km. A mid-crust low-velocity zone is revealed, and is interpreted as partially molten rocks that are part of the Andean low-velocity zone. It is oblique to the present trench, and possibly indicates the location of the volcanic arcs formed during the steepening of the Oligocene flat slab beneath the Altiplano plateau. The recently subducted slab beneath the forearc shows a decrease in velocity from the normal to flat subduction regime that might be related to hydration during the formation of the Nazca ridge, which in turn may contribute to the buoyancy of the flat slab. The mantle above the flat slab has a comparatively high velocity, which indicates the lack of melting and thus explains the cessation of the volcanism above. A velocity contrast from crust to uppermost mantle is imaged across the Cusco–Vilcanota Fault System, and is interpreted as the boundary between two lithospheric blocks.

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1. Introduction

Southern Peru is an interesting area to study subduction, orogeny and the related volcanism processes along an active continental margin. The dip of the subducted Nazca slab changes from 30° in the southeast to nearly horizontal at a depth of ~100 km in the northwest (Fig. 1). Closely linked with the subduction process, the Quaternary volcanic arc is well developed where the slab is steeper and is absent where the slab is nearly flat (Allmendinger et al., 1997). This area is also characterized by the over 4 km high orogeny of the Central Andes. The high topography is widest above the normal subduction regime, and narrows considerably to the northwest over the flat subduction regime. From the coast to inland, the main tectonic units include the offshore and onshore forearc region, the Western Cordillera, the Altiplano plateau, and an eastern belt of fold and thrust structures comprising the Eastern Cordillera and the Sub-Andean Ranges (Fig. 1) (Oncken et al., 2006). The major crustal thickening is suggested to have initiated around 30–40 Ma (asynchronous for each tectonic unit), and is continuing to present (Mamani et al., 2010; Oncken et al., 2006).

Recent studies in Southern Peru using receiver functions (Phillips and Clayton, 2014; Phillips et al., 2012) suggest that the crustal thickness changes from ~20 km near the coast to ~70 km below the Altiplano plateau. The crustal P-wave structure under the plateau has been investigated by an active seismic survey along a profile from Peru to Bolivia, and is characterized by two low-velocity layers at 9–12 km and 36–46 km depth ranges (Ocola and Meyer, 1972). The deeper layer at the mid-crust depth is also detected in the receiver function (Yuan et al., 2000) and ambient noise surface wave (Ward et al., 2013), as well as other geophysical observations (Schilling et al., 2006) in the Central Andes, and is interpreted as a large volume of molten rocks (Schilling et al., 2006; Yuan et al., 2000). The extensive crustal melting can be attributed to the steepening of an Oligocene flat slab beneath the Altiplano plateau and an early Miocene flat slab beneath the Puna plateau (Kay and Coira, 2009; Ramos and Folguera, 2009). The mantle-wedge convection and arc volcanism resumed when the flat slab began to steepen, and because of the increase in the dip of the slab, the arc migrated trench-ward from inland to the present location (Allmendinger et al., 1997; Mamani et al., 2010) leading to widespread magmatism and heat input into the crust, which caused the crustal melting. While the magmatic addition is not as important as tectonic shortening to the crustal thickening, it had a

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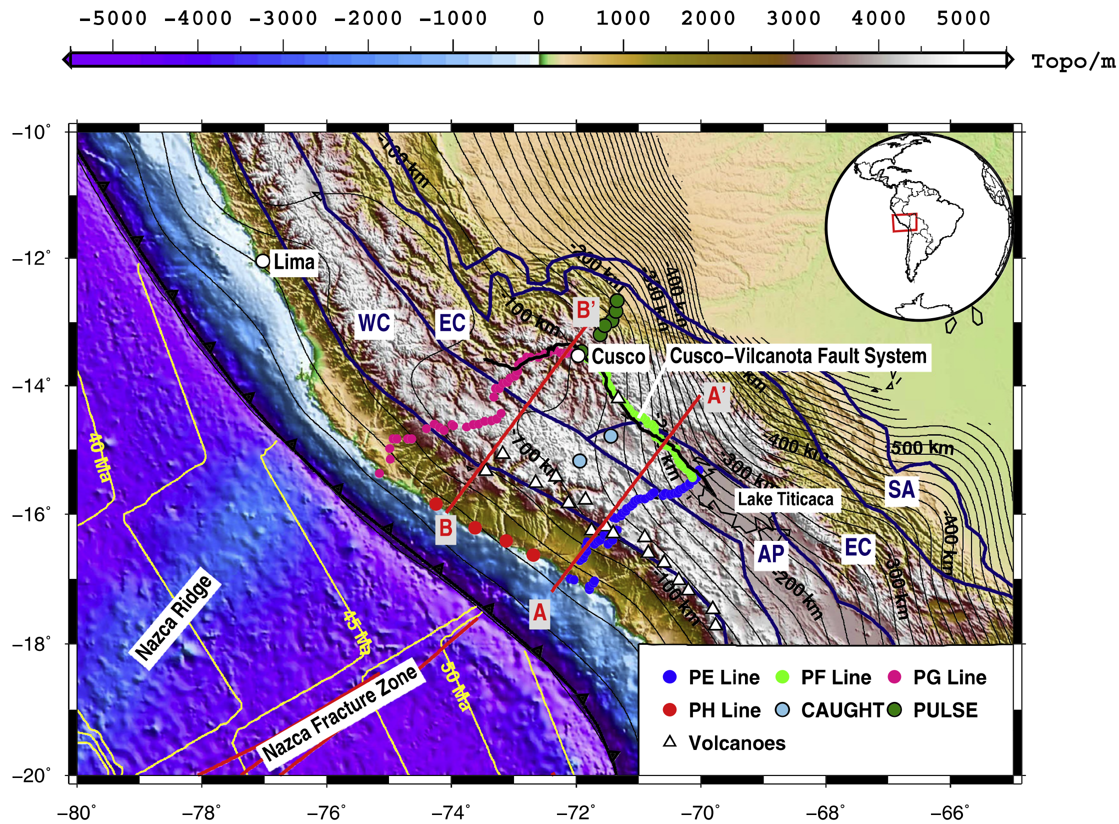

Fig. 1. Location of the seismic stations (dots) used in this study. The main units building the Central Andes are delineated with navy lines (modified from Oncken et al., 2006). WC: Western Cordillera; EC: Eastern Cordillera; AP: Altiplano Plateau; SA: Sub-Andean Ranges. The Holocene volcanoes are denoted with white triangles (data from http://www.volcano.si.edu/world). The thick black line is the Cusco–Vilcanota Fault System digitized from Carlier et al. (2005). Slab contours are from http://earthquake.usgs.gov/research/data/slab, plotted at 20 km intervals. The Nazca fracture zone data are from http://www.soest.hawaii.edu/PT/GSFML. Ocean floor age data are from http://www.earthbyte.org/Resources/Agegrid/2008/grids, plotted in 2.5 Ma intervals. Topography data are from http://glcf.umd.edu/data/srtm.

major effect on rheology and the mechanical behavior of the crust (Allmendinger et al., 1997).

The Peruvian flat subduction is not unique, as approximately 10 percent of present day subduction zones are considered to have flat slabs (Gutscher et al., 2000; Skinner and Clayton, 2013). Many of the present normal subduction regimes, such as the ones under Altiplano and Puna plateaux (Ramos and Folguera, 2009) mentioned above, are also considered to have experienced flat subduction in the past. The major driving forces of the flat subduction are still unknown, but some possible causes are summarized in Gutscher (2002), among which the subduction of thickened oceanic crust (e.g. the Nazca ridge and the Inca Plateau Gutscher et al., 1999) is suggested to be the dominant one. However, Skinner and Clayton (2013) argue through plate reconstructions that there is no clear correlation between the arrival of the thickened crust and the onset of slab flattening in South America. In addition, geodynamical modeling (Gerya et al., 2009) shows that the buoyancy of the thickened crust itself is not sufficient to raise the slab to the flat orientation, even including a less-dense depleted mantle associated with the formation of a thick crust (Abbott, 1991). The importance of the enhanced mantle wedge suction caused by the thick continental craton near the subduction zone is raised by several other studies (Manea et al., 2012; O'Driscoll et al., 2012). For example, O'Driscoll et al. (2012) suggested that the subduction towards the Amazonian Craton of South America, which is close to the trench, contributed to the flattening of the slab beneath the Altiplano plateau during the late Eocene and Oligocene, while the steepening of this Oligocene flat slab was associated with a change in the subduction direction, which resulted in a weakened wedge suction.

In this paper, we present the velocity structure in the crust and uppermost mantle from surface wave analysis. We show the extent of the mid-crust Andean low-velocity zone in the study region, the two lithosphere blocks across the Cusco–Vilcanota Fault System, and the velocity differences between the flat and normal subduction regimes. This study complements the receiver function studies of Phillips et al. (2012) and Phillips and Clayton (2014) that focuses on the velocity discontinuities (e.g. the Moho and slab depths) of this area.

2. Data and method

The data used in this study are primarily from a box-like array deployed progressively from June 2008 to February 2013 in Southern Peru (Fig. 1). The array is composed of ~150 broadband stations (PE, PF, PG, PH lines), each with ~2 yrs of deployment. We also use data from 8 broadband stations from the CAUGHT and PULSE experiments (Ward et al., 2013). We correct the data for the instrument response, integrate the velocity records to displacement, and use the vertical 1-sample/s channel to obtain the Rayleigh wave signals.

The phase velocity of Rayleigh wave is sensitive to the shear velocities over a range of depths, but is most sensitive to a depth range that is approximately one-third of its wavelength. By combining the phase velocities at various periods, we are able to invert for the shear wave velocity structure as a function of depth. For periods 6 s to 25 s, we use the surface wave signals from the ambient noise cross-correlations, and for 25 s to 67 s, we use the earthquake surface wave signals. We first make a phase velocity map of the area for each period and then perform a 1-D structure

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