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Seismic properties of the Nazca oceanic crust in southern Peruvian subduction system

YoungHee Kim [a,*], Robert W. Clayton [b]

[a] School of Earth and Environment Sciences, Seoul National University, Republic of Korea
[b] Seismological Laboratory, California Institute of Technology, United States

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ABSTRACT

The horizontal Nazca slab, extending over a distance of ∼800 km along the trench is one of enigmatic features in Peruvian subduction zone. Increased buoyancy of the oceanic lithosphere alone due to the subduction of Nazca Ridge is insufficient to fully explain such a lengthy segment. We use data from the recent seismic experiment in southern Peru to find that the subduction-related hydration plays a major role in controlling shear wave velocities within the upper part of the oceanic crust and overlying materials. We observe substantial velocity reductions of ∼20–40% near the top plate interface along- and perpendicular-to the trench from ∼40–120 km depths. In particular, significant shear wave velocity reductions and subsequently higher P-to-S velocity ratio (exceeding 2.0) at the flat slab region suggest that the seismically probed layer is fluid-rich and mechanically weak. The dominant source of fluid comes from metasediments and subducted crust (Nazca Ridge). Long-term supply of fluid from the southward migrating Nazca Ridge provides additional buoyancy of the subducting oceanic lithosphere and also lowers the viscosity of the overlying mantle wedge to drive and sustain the flat plate segment of ∼800 km along the trench. Also, by comparing calculated seismic velocities with experimentally derived mineral physics data, we additionally provide mechanical constraints on the possible changes in frictional behavior across the subduction zone plate interface. Observed low seismic velocities in the seismogenic zone suggest a presence of low strength materials that may be explained by overpressured pore fluids (i.e., accreted sediment included in the subduction channel).

1. Introduction

The effects of the aseismic ridge subduction on the subduction dynamics have been long debated. Slab-flattening process have been commonly attributed to the excess buoyancy provided by the subduction of an anomalously thick crust of young oceanic lithosphere, as seismically imaged for Alaska (Kim et al., 2014), or of aseismic ridges, as proposed for South America (Gutscher et al., 2000). Skinner and Clayton (2013) systematically evaluated proposed hypotheses for flat subduction in South America based on the spatial and temporal evidence, and found no simple or obvious explanation for such feature.

Along the South American margin, the Nazca Plate subducts beneath the South American Plate, causing upper-plate deformation, earthquakes, and volcanism (e.g. Cahill and Isacks, 1992; Bilek, 2010). Earthquakes in this region exhibit heterogeneous rupture characteristics, which are related to the subducting asperity on the Nazca Plate (Bilek, 2010). In particular, significant subduction zone complexity in southern Peru (from 14°S to 20°S) has been previously attributed to the moderate-size (approximately 200 km × 18 km) Nazca Ridge and the Nazca fracture zone. This region involves the transition in slab geometry from flat to normal from north to south (Cahill and Isacks, 1992; Hayes et al., 2012; Phillips et al., 2012; Phillips and Clayton, 2014), decrease of magmatic activity towards the flat slab subduction (Ramos and Folguera, 2009), and variability of earthquake rupture pattern and coupling state (Chlieh et al., 2011).

In this paper, we focus on the region of flat-slab subduction, where the Nazca Ridge subducts, normal-dip subduction zone, south of Nazca Ridge, and the region between the two (Figs. 1 and 2), to examine both perpendicular and along-strike variations in the plate interface properties. We use teleseismic earthquakes recorded from the Peru Subduction Experiment (PeruSE), and then relate obtained seismic properties, such as slab geometry and seismic velocities, to infer the subducted materials near the plate interface and the degree of hydration, and to understand present-day subduction dynamics beneath southern Peru.

* Corresponding author.
E-mail addresses: younghkim@snu.ac.kr (Y. Kim), clay@gps.caltech.edu (R.W. Clayton).

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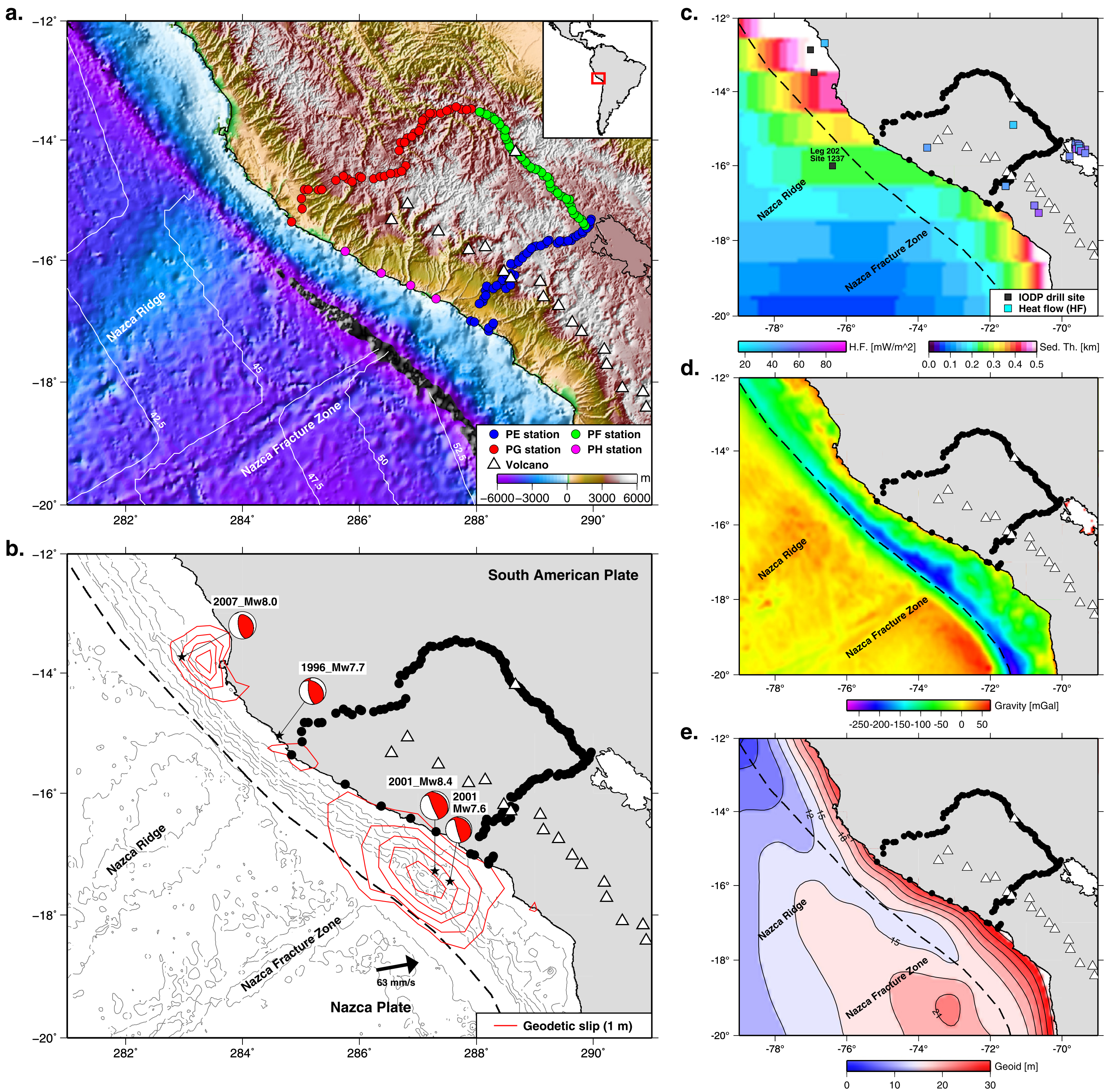

Fig. 1. Geophysical datasets probing the subducted Nazca Plate beneath southern Peru. Locations of broadband seismic stations, volcanoes, and bathymetric anomalies (Nazca Ridge and Nazca fracture zone) are shown as circles, triangles, and texts in all panels (a–e). a. Topographic–bathymetric map showing the region of the study. Each seismic profile of Peru Subduction Experiment is shown as a different colored circle. The age of incoming Nazca Plate is shown as a white text. b. Seismotectonic setting of southern Peru with rupture of large-magnitude ($Mw > 7.5$) earthquakes on the Peru megathrust. Red contours represent slip distributions of the 2007 $Mw = 7.0$ Pisco, 1996 $Mw = 7.7$ Nazca, and 2001 $Mw = 7.6$ & 8.4 Arequipa earthquakes, and they were determined from joint inversions of the InSAR and GPS data (Chlieh et al., 2011). The source mechanisms of the earthquakes are from the global CMT catalog (Ekström et al., 2012). c. Sediment thickness (Laske and Masters, 1997), and heat flow data (colored squares; Pollack et al., 1993). IODP drill hole sites are shown as gray squares. d. Gravity anomaly (Sandwell et al., 2013). e. Geoid (Förste et al., 2008). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

2. Bathymetric anomalies on the subducting Nazca plate

Although the correlation between the subduction of the bathymetric anomaly and the change in the subduction angle in southern Peru is not yet clear, its influence on the plate interface properties appears apparent. The variability of subducted materials (thickness of the trench sediment) and/or the roughness of the seafloor strongly influence the interplate coupling and transient slip along the subduction interface (Perfettini et al., 2010; Chlieh et al., 2011; Wang and Bilek, 2014). Furthermore, the processes of sediment compaction and dehydration, and/or other reactions within the fault zone materials can bring about changes in strength or fluid pressure along the plate boundary thrust zone. Scattered coda of teleseismic P waves, such as in receiver functions, often show a thin low-velocity layer corresponding to the top of the subducting plate. These have been best documented in Mexico (Kim et al., 2010, 2012a, 2013), Alaska (Kim et al., 2014), and Cascadia (Hansen et al., 2012), where a 2–4 km