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Seismicity and state of stress in the central and southern Peruvian flat slab

Abhash Kumar[a,*], Lara S. Wagner[b], Susan L. Beck[c], Maureen D. Long[d], George Zandt[c], Bissett Young[a,1], Hernando Tavera[e], Estella Minaya[f]

[a] Department of Geological Sciences, University of North Carolina at Chapel Hill, 104 South Rd., Mitchell Hall, CB #3315, Chapel Hill, NC 27599-3315, USA
[b] Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Road, NW, Washington, DC 20015-1305, USA
[c] Department of Geosciences, University of Arizona, 1040 E. 4th Street, Tucson, AZ 85721, USA
[d] Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, CT 06511, USA
[e] Instituto Geofisico del Peru, Calle Badajo No. 169, Urb. Mayorazgo IV Etapa, Lima, Peru
[f] El Observatorio San Calixto, Calle Indaburo 944, Casilla 12656, La Paz, Bolivia

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ABSTRACT

We have determined the Wadati–Benioff Zone seismicity and state of stress of the subducting Nazca slab beneath central and southern Peru using data from three recently deployed local seismic networks. Our relocated hypocenters are consistent with a flat slab geometry that is shallowest near the Nazca Ridge, and changes from steep to normal without tearing to the south. These locations also indicate numerous abrupt along-strike changes in seismicity, most notably an absence of seismicity along the projected location of subducting Nazca Ridge. This stands in stark contrast to the very high seismicity observed along the Juan Fernandez ridge beneath central Chile where, a similar flat slab geometry is observed. We interpret this as indicative of an absence of water in the mantle beneath the overthickened crust of the Nazca Ridge. This may provide important new constraints on the conditions required to produce intermediate depth seismicity. Our focal mechanisms and stress tensor inversions indicate dominantly down-dip extension, consistent with slab pull, with minor variations that are likely due to the variable slab geometry and stress from adjacent regions. We observe significantly greater variability in the P-axis orientations and maximum compressive stress directions. The along strike change in the orientation of maximum compressive stress is likely related to slab bending and unbending south of the Nazca Ridge.

1. Introduction

The term "flat slab subduction" is often used to refer to the subduction of an oceanic plate that enters the trench at a normal dip angle (∼30°), continues subduction up to 100 km depth, and then abruptly bends to travel horizontally (∼0° dip) for several hundred kilometers before resuming its descent (Hasegawa and Sacks, 1981; Cahill and Isacks, 1992). The depth of flattening and inboard extent of the horizontal segment varies between different regions of flat slab subduction, for reasons that are still under investigation (e.g. Manea and Gurnis, 2007; Gerya et al., 2009; Manea et al., 2011; Hu et al., 2016). Flat slab subduction is of particular interest because it has often been causally linked to unusual tectonic processes such as the cessation of arc volcanism, inboard thick-skinned deformation of the overriding plate and the evolution of high plateaus (e.g. Isacks and Barazangi, 1977; Jordan and Allmendinger, 1986). In particular, the Laramide uplift of the Rocky Mountains and subsequent ignimbrite flare-up in the western United States have been attributed to a period of flat subduction of the Farallon plate (80–55 Ma) (e.g. Dickinson and Snyder, 1978; Humphreys et al., 2003).

In this study, we investigate the southern portion of the Peruvian flat slab (Fig. 1). The western margin of Peru between 2° and 15°S is characterized by the flat subduction of the oceanic Nazca plate beneath the continental South American plate (e.g. Hasegawa and Sacks, 1981; Cahill and Isacks, 1992; Hayes et al., 2012; Dougherty and Clayton, 2014). The Peruvian flat slab is associated with the marked absence of any known Quaternary arc volcanism and with generally low surface heat flow measurements (Henry and Pollack, 1988). While the causes of flat slab subduction are still controversial (e.g. Gerya et al., 2009; Skinner and Clayton, 2013), one possible contributing factor beneath Peru is the subduction of the less dense oceanic lithosphere associated with

* Corresponding author.
E-mail address: abhash.kumar84@gmail.com (A. Kumar).
[1] Now at Donskoj and CO, Kingston, NY.

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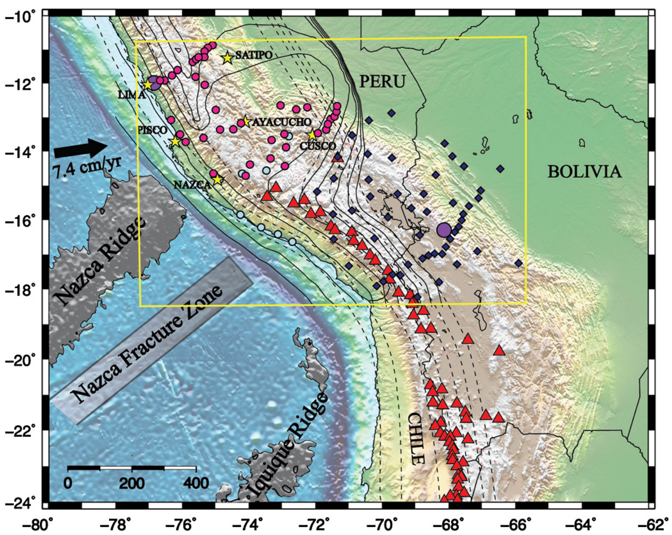

Fig. 1. Map showing the Peruvian flat slab region, our study area (yellow box), and the locations of seismic stations used in this study. Dark pink circles are PULSE stations. Dark blue diamonds are CAUGHT stations and light blue circles are PERUSE stations used in this study. Large purple circles represent GSN stations at Lima, Peru and LaPaz, Bolivia. Yellow stars are the location of important cities. Red triangles are Holocene volcanoes (INGEMMET, www.ingemmet.gob.pe). Solid lines are slab contours from Antonijevic et al. (2015). Dashed lines are slab contours from Cahill and Isacks (1992). The Nazca Ridge, Iquique Ridge and Nazca Fracture Zone are shaded gray offshore. The black arrow offshore represents the plate motion of the Nazca plate from HS3-NUVEL1A (Gripp and Gordon, 2002). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the Nazca Ridge (e.g. Hu et al., 2016). The crust of the Nazca Ridge is unusually thick (~17 km) and was formed at the Pacific Nazca spreading center along with its conjugate on the Pacific Plate, the Tuamoto Plateau, in the early Cenozoic (Hampel, 2002; Hampel et al., 2004). The track of the Nazca Ridge and the convergence direction are not parallel (Fig. 1), resulting in a southward migration of the ridge relative to the overriding continent. Since it first began subducting ~11.2 Ma at ~11°S (Hampel, 2002), the ridge has migrated ~480 km south relative to the South American margin (Hampel, 2002; Hampel et al., 2004). The timing of slab flattening is well constrained by radiometric ages of the cessation of arc volcanism, episodes of intense metallogenic activity (Rosenbaum et al., 2005) and basement involved thrust deformation (Shira uplift) on the overriding South American plate. The spatio-temporal pattern of these indicators seems to follow the southward migration of the Nazca Ridge (Rosenbaum et al., 2005; Bissig et al., 2008).

Previous studies have analyzed the Wadati–Benioff zone (WBZ) seismicity in Peru, primarily using data from stations at teleseismic distances or local data collected from small seismic networks (Hasegawa and Sacks, 1981; Cahill and Isacks, 1992; Hayes et al., 2012). Here we present estimates of earthquake locations and focal mechanisms for slab events between 10° and 18.5°S using data from three co-deployed local seismic networks. We also estimate the regional stress field tensor south of the Nazca Ridge in order to better understand the current state of stress of the subducting slab in this region of complex subduction geometry. We note a number of striking seismicity patterns that may indicate variations in slab hydration and dehydration processes along strike. Our regional stress field estimates show significant changes over short spatial scales, consistent with the rapidly changing slab geometry. For the most part, our results are consistent with previous work showing down-dip extension below 60 km depth (Marot et al., 2013; Rontogianni et al., 2011), with slight variations likely due to the regional tectonic setting and complex slab geometry.

2. Data

We use data collected from the temporary broadband stations of three independent seismic arrays (Fig. 1). The CAUGHT (Central Andean Uplifts and the Geodynamics of High Topography) experiment comprised 50 broadband seismometers deployed for 21 months between November 2010 and July 2012 between 13°S to 18°S across the northern Altiplano. Thirty stations were deployed in Bolivia and 20 stations in Peru with a higher density line across the cordillera that spanned both Peru and Bolivia. The "PULSE" (PerU Lithosphere and Slab Experiment) network (e.g., Antonijevic et al., 2015) was deployed from May 2011 to June 2013 and consisted of 40 broadband seismometers. The PULSE network was located above the southern part of the Peruvian flat slab roughly along three transects. The southern transect extended north and east from the city of Nazca to beyond Cusco. The middle and northern transects were located between Pisco and Ayacucho, and Lima and Satipo, respectively. The northern transect was situated above the paleo-location of the subducted Nazca Ridge between 10–8 Ma (Rosenbaum et al., 2005). The southern and middle transects straddle the projected current location of the subducted Nazca Ridge. We also use data from the PERUSE project deployed by the California Institute of Technology and UCLA between July 2008 and June 2012 (e.g., Phillips and Clayton, 2014). We use data for 8 stations from this deployment located along the coast in southern Peru and along the southern transect of the PULSE network.

3. Methods

3.1. Event locations and error analyses

We identify possible earthquakes recorded by our three arrays using the dbdetect tool that is part of the ANTELOPE software package (http://www.brtt.com). This method is based on a short-term average (STA) versus long-term average (LTA) trigger mechanism. An event is detected if the ratio of energy between STA and LTA windows exceeds a user-defined threshold. We use an energy threshold ratio of 5 and STA and LTA moving time windows of 1 second and 10 seconds respectively. Of the 3000 possible events identified, we selected 952 earthquakes after individual inspection of the seismic waveforms for each event.

We calculate absolute event hypocenter locations using the single event location algorithm HYP, incorporated into the SEISAN software package (Havskov and Ottemoller, 1999). HYP determines earthquake locations using an iterative linearized least squares inversion of travel time data (Aki and Lee, 1976). We use a modified version of the P-wave velocity model of Dorbath and Granet (1996) that takes into account the 65 km average crustal thickness in our study area as determined from recent analyses of teleseismic receiver functions (Phillips and Clayton, 2014; Bishop et al., 2014). S-wave velocities are determined using a Vp/Vs ratio of 1.75 (Dorbath and Granet, 1996).

In order to determine the sensitivity of our event locations to starting depth, we calculate the hypocenters of all 952 events with a starting depth of 5 km, 100 km, 200 km, and the initial hypocentral depth from dbdetect. Of the 952 events, 838 had final depths that differ by less than 10 km irrespective of the starting depths. From those 838 events, we then select events with depths greater than 50 km and azimuthal gaps <270°. For events south of 15°S, we eliminated those events with depth errors of >15 km. Given the sparsity of seismicity north of 15°S, we included some events with slightly larger depth errors whose latitudes, longitudes, and depths were stable over all tested starting depths. After these criteria were applied, we are left with 568 event locations.