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The deep Peru 2015 doublet earthquakes

S. Ruiz [a,*], H. Tavera [b], P. Poli [c], C. Herrera [d], C. Flores [a,e], E. Rivera [a,e], R. Madariaga [f]

[a] *Geophysics Department, Universidad de Chile, Chile*
[b] *Geophysical Institute of Peru, Lima, Peru*
[c] *Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA, USA*
[d] *School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada*
[e] *Geology Department, Universidad de Chile, Chile*
[f] *Laboratoire of Geologie, Ecole Normale Superieure, Paris, France*

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ABSTRACT

On 24 November 2015 two events of magnitude Mw 7.5 and Mw 7.6 occurred at 600 km depth under the Peru–Brazil boundary. These two events were separated in time by 300 s. Deep event doublets occur often under South America. The characteristics that control these events and the dynamic interaction between them are an unresolved problem. We used teleseismic and regional data, situated above the doublet, to perform source inversion in order to characterize their ruptures. The overall resemblance between these two events suggests that they share similar rupture process. They are not identical but occur on the same fault surface dipping westward. Using a P-wave stripping and stretching method we determine rupture speed of 2.25 km/s. From regional body wave inversion we find that stress drop is similar for both events, they differ by a factor of two. The similarity in geometry, rupture velocity, stress drop and radiated energy, suggests that these two events looked like simple elliptical ruptures that propagated like classical sub-shear brittle cracks.

1. Introduction

On 24 November 2015 two large earthquakes of magnitudes Mw 7.5 and 7.6 occurred at 22:45:38 (UTC) and 22:50:54 (UTC) under the Peru–Brazil boundary between 9°S and 11°S inside a band between 600 and 700 km depth. Fig. 1 shows the epicenters of the November 2015 doublet and that of other large magnitude deep events that have occurred under South America: 1994 Bolivia Mw 8.2 (Kikuchi and Kanamori, 1994; Kirby et al., 1995) and 1970 Colombia Mw 8.0 (Furumoto, 1977). The mechanism of generation of these deep earthquakes is still unclear (Frohlich, 2006; Houston, 2015). Under the pressure and temperature condition of hundreds of kilometers deep into the mantle, plastic flow should be favored rather than brittle failure. Yet deep events on subducting tectonic plates are observed as shear rupture on faults, just as crustal earthquakes. Seismological observations show that deep events are characterized by certain properties that are different from shallower events: Radiated seismic energies (Wiens, 2001), *b*-values and aftershock sequences (Wiens and Gilbert, 1996; Frohlich, 2006; Houston, 2015; Zhan, 2017), source durations and stress drops (Campus and Das, 2000; Frohlich, 2006; Poli and Prieto, 2014, 2016).

Deep event doublets frequently occur in South America where several Mw ∼7.0 events occurred clustered in time and space 1921–1922, 1961–1963, 1989–1990 and 2002–2003 (Okal and Bina, 1994; Ye et al., 2016). Using teleseismic data, Ye et al. (2016) proposed that the two events of 2015 had diverse rupture processes although they are closely located on the same fault structure. According to their study, the second event (E2) had a smaller rupture area and lower rupture velocity than the first event (E1). Zahradník et al. (2017) modeled regional waveforms for these events and observed close similarities in the total duration of both events and smaller rupture velocities than those proposed by Ye et al. (2016). Here, we determine the seismic source properties of these earthquakes using data obtained from regional networks, see Fig. 2, as well as teleseismic recordings. We also used the broad band regional data of the Peruvian and Brazilian networks to relocate the aftershocks of the doublet. We performed regional kinematic inversions for both events considering an elliptical source for both of them (Ruiz and Madariaga, 2013; Madariaga and Ruiz, 2016; Herrera et al., 2017). We obtain the rupture geometry, rupture velocity and the slip distribution of both events and we discuss the close similarity between them.

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[*] Corresponding author.
E-mail address: sruiz@dgf.uchile.cl (S. Ruiz).

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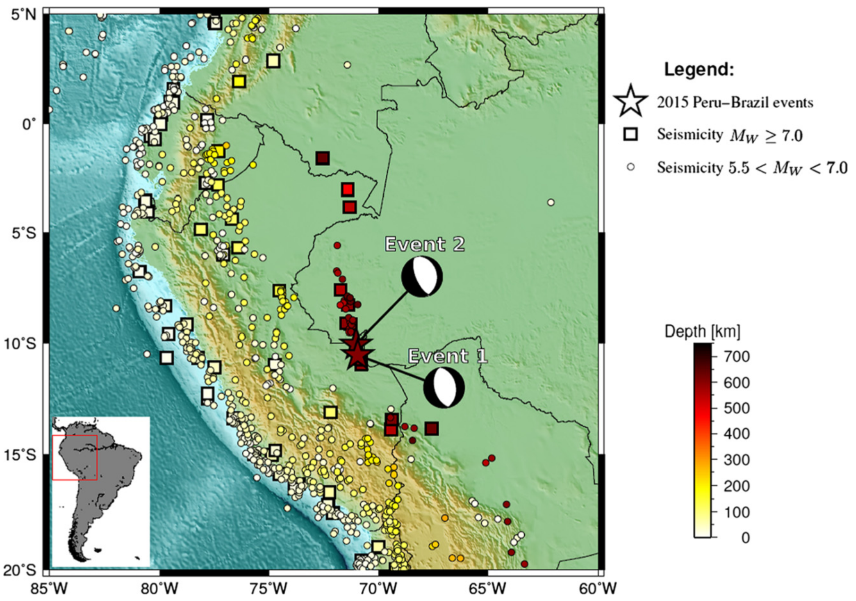

Fig. 1. Seismicity of South America since 1900 for events of magnitude larger than M 5.5 from the NEIC catalog. Squares denote events of magnitude larger than M 7.0. The stars denote the epicenters of the two events in the doublet of November 2015. The focal mechanism corresponds to the deep event doublet (USGS, National Earthquake Information Center, PDE).

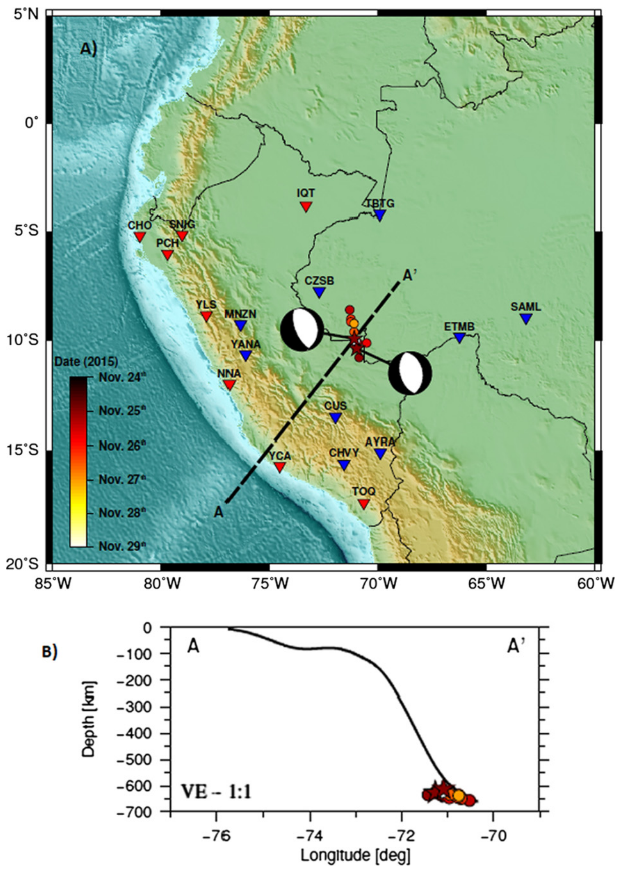

Fig. 2. Regional seismic data used to study the 2015 doublet in Peru. A) Inverted triangles denote the regional broad band instruments of the Peruvian and Brazilian seismic networks. The blue inverted triangles were used in the kinematic inversion and all of them were used to compute the localization of aftershocks. Dots are the aftershocks localized in this work. B) Vertical cross section along profile AA shown in panel A. Dots are the aftershocks of the Peru deep doublet, stars the hypocenter of the two main-shocks. The continuous line is the slab modeled by Hayes et al. (2012). The focal mechanisms are those of the two events in the 2015 doublet (USGS, National Earthquake Information Center, PDE). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Data, methodology and results

The location of the two deep Peruvian events is shown in Figs. 1 and 2 as well as the local stations used to do body wave inversion. Throughout the paper we used the fault plane solutions proposed by USGS. Event E1 had a main fault plane with strike = 165, dip = 50, rake = −94 and event E2 had a fault plane with strike = 157, dip = 64, rake = −98 (USGS focal mechanism). Ye et al. (2016) and Zahradník et al. (2017) proposed slightly different mechanisms determined with either W-phase or moment tensor methods. As we will show the most likely rupture plane is the West dipping fault plane with dip of 50° (event E1) or 64° (event E2).

2.1. Teleseismic data and methodology

We use broadband seismic data for all the stations available at the time of the earthquakes. After deconvolution of the instrumental response we obtained velocity waveforms. We then analyzed the P waves in a frequency range from 0.01 to 2 Hz, ensuring that the signal to noise ratio (SNR) for each trace was larger than 10. The SNR is evaluated by comparing the maximum amplitude in 10 s window after the P wave arrival, with the mean absolute noise level in a similar window before the P wave arrival. We align the traces as explained by Poli and Prieto (2014) and Poli et al. (2016) to build an average source time function, from which approximate rupture duration is measured. The aligned data are then re-sampled in space using takeoff and azimuth grid of 10°, to avoid dominant azimuths in the inversion. Only data from 0° to 8° and from 32° to 88° distance were retained. We thus ensure that both down-going and up-going P waves are observed as they are needed to resolve the depth of the rupture (Kiser et al., 2011). Each signal is windowed from 5 s before the P waves to twice the estimated rupture duration.

We use the method of Warren and Silver (2006) to evaluate the source geometry and rupture velocity. This approach has been successfully applied to resolve the fault plane of different earthquakes from subduction zones and deep continental zones (Prieto et al., 2017). For each couple of waveforms we measure the stretching factor and the associated correlation coefficient. We retain all data with correlation larger than 0.9 after stretching. For each value of