Aseismic and seismic slip on the Megathrust offshore southern Peru revealed by geodetic strain before and after the Mw8.0, 2007 Pisco earthquake.

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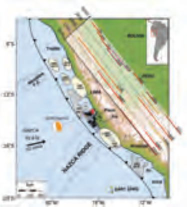
(1) Sismotectonic setting



The Mw8 Pisco earthquake ruptured the subduction interface along which the Nazca plate subducts beneath the south American plate at about 6 cm/yr. Similar interplate M > 8.0 earthquakes have occurred offshore South and Central Peru in 1604, 1687, 1746, and 1868 16. In 2007, the same segment as the one that broke in 1746 ruptured again.

Distribution of recent large interplate earthquakes (light yellow ellipses). Approximate rupture areas for 1974, 1996, and 2001 (grey polygons) from Langer and Spence (1995) and Pritchard et al. (2007). Ellipses for events without detailed models are scaled approximately. The graph shows the distribution in time since 1604 of ruptures as a function of their along trench extent (adapted from Dorbath et al., 1990). NEIC Epicenter and GCMT centroid of the 2007 Pisco earthquake are indicated by the red star and an orange circle, respectively. Small black dots indicate aftershocks during the 45 days period following the mainshock recorded by a local network operated by IGP (stations : open triangles) . From Sladen et al (2009)

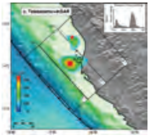
Introduction

The seismic hazard on any major fault depends primarily on the partitioning between seismic and aseismic slip. Identifying where and when aseismic creep is taking place and what fraction of long-term motion it accounts for are therefore critical questions. Slip is almost purely aseismic on megathrust at depth greater than about 40 km. At shallower depths, seismic slip is probably prevalent as both modes of slip occur leading to heterogeneous strain (e.g., Chlieh et al, 2008). Aseismic slip can occur as result of steady or transient creep in the interseismic and postseismic periods. Thus, megathrusts seems to comprise areas that mostly slip during earthquakes (governed by a rate-weakening friction law), and areas that mostly slip aseismically (governed by rate-strengthening friction law).
Here we try to image the patchwork of rate-strengthening and rate-weakening areas that paves the Megathrusr offshore southern Peru using geodetic observation of postseismic deformation following the Mw8.0 Pisco earthquake of 2007, the source model of that earthquake (Sladen et al, 2009), and geodetic measurements of interseismic strain acquired before that earthquake.

Discussion

Our modeling results show that the post- and co-seismic slip distributions complement each other (the small overlap might simply reflect the smoothing effect of the regularization). This observation is consistent with the view that the shallow portion of the megathrust is paved with areas that are rate-weakening within which earthquake can nucleate and propagate, and areas that are rate-strengthening within which slip is mostly aseismic. In that regard, we speculate that the two subevents during the Pisco earthquake could reflect the effect of the intervening rate-strengthening patch (labeled B). A most striking finding is that the prominent aseismic patch (labeled A) coincides with the northern side of the Nazca ridge where the 2007 rupture stopped. Interestingly, none of the M > 8 historical earthquakes which have occurred either north (1687, 1746) or south (1604, 1868) ofPisco in the past 500 years, seem to have ruptured across that particular patch of the megathrust (see (1)). Thus, we infer that this patch is a permanent barrier characterized by a rate-strengthening friction, plausibly related to the subduction of the Nazca ridge. The intrinsically creeping character of the Peru megathrust in the area where the Nazca ridge subducts beneath the forearc is also visible from the pattern of interseismic strain. Modeling of the interseismic geodetic data indeed shows a locally low interseismic coupling in this area, while the rupture areas of the 2007, Pisco and 1974 Lima earthquakes coincide with higher coupling . The morphology of the forearc, characterized by an interruption of the forearc basins and a narrower distance from the trench to the coastline also probably reflects the effect of the Nazca ridge.
With regard to the aseismic/seismic slip budget, the modeling of interseismic implies that 41-62% of the long-term interplate slip results from aseismic slip in the interseismic period (see (6)). The remaining fraction must result from transient seismic or aseismic slip. Assuming that the ratio between the moments released by afterslip and by seismic slip is about 30%, as typically found for large megathrust earthquakes, aseismic slip would contribute between 50% and 70% of the total slip. This might still be an underestimate since the possibility of spontaneous aseismic transients is ignored.
The interseismic coupling model suggests a moment deficit accumulation rate of 0.61 10^19 N.m/yr in the area that ruptured during the Pisco earthquake (latitude 13° S to 15° S, depth lower than 40 km). At this rate, we estimate it would take 251 yr to accumulate a deficit of moment equivalent to the 1.5 10^21 N.m moment released by coseismic and afterslip during the Pisco earthquake. This estimate is close to the 261 years between the 2007 Pisco earthquake and the previous large megathrust earthquake in this area which occurred in 1746

(2) The Mw8.0, 2007 Pisco Earthquake



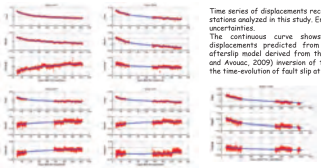
In 2007 the rupture initiated north of Pisco and propagated towards the south producing up to 8 m of slip parallel to the Nazca-South America plate convergence. The source model shows that the earthquake broke two distinct asperities 60 seconds apart.

Surface projection of co-seismic slip distribution derived from the joint inversion of telseismic waveforms and InSAR measurements of static ground defrmation. Slip contour lines every 1 m starting at 2m (only areas where slip is larger greater than 2 m are shown). Inset shows the estimated source time function. The red star locates the epicenter as located by USGS-NEIC. Bathymetry and topography are taken from the ETOPO2 and GTOPO30 databases, respectively. From Sladen et al (2009)

Abstract

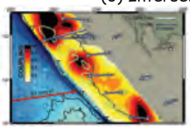
We show that the Pisco earthquake ruptured two asperities within a patch that had remained predominantly locked in the interseismic period and triggered aseismic frictional afterslip on adjacent patches. The time evolution of afterslip, which is about 90% seismic, is consistent with a rate-strengthening friction law.The most prominent afterslip patch reflects the influence of the Nazca ridge. Aseismic sliding is also responsible for a locally low interseismic coupling in this area which seems to have acted as a systematic barrier to seismic rupture propagation repeatedly. Altogether aseismic slip on the seismogenic portion of the Peru Megathrust between latitude 11o S and 16 o S is estimated to account for about 50-70 % of the slip budget. Aseismic slip on the seismogenic portion of the Peru megathrust in the study area (between latitude 11° S and 16° S) is estimated to account for a large fraction of the slip budget. The megathrust appears to be paved with rate-strengthening and rate-weakening patches and the resulting pattern has a profound influence on its long term seismic behavior as well as on individual earthquakes.

(4) Geodetic Time Series



Time series of displacements recorded at the 5 GPS stations analyzed in this study. Errors bars show 2-σ uncertainties.
The continuous curve shows the theoretical displacements predicted from the best fitting afterslip model derived from the PCAIM (Kositsky and Avouac, 2009) inversion of the time series for the time-evolution of fault slip at depth.

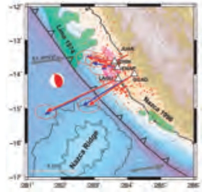
(6) Interseismic coupling



The modelling of interseismic strain measured from GPS campaigns shows that, on average over the study area, aseismic slip in the interseismic period accounts for about 60% of interplate slip at depths shallower than 40 km (the average interseismic coupling is 0.48). The Nazca ridge coincide with an area of locally low interseismic coupling.

Comparison of interseismic coupling with rupture areas of recent large earthquakes. Interseismic coupling, defined as (1 – Vi/Vpl) where Vi is the interseismic slip rate and Vpl is the long term slip rate, is derived from the modeling of geodetic data collected between January 1993 and March 2001 all referenced to stable South America. The data (white vectors) were corrected for 5 mm/yr of shortening across the Andes by least squares adjustment of the Euler pole describing the long term motion of the undeformed forearc with respect to South America. The small coupling along the trench may reflect the lack of resolution there, except in the north where sea bottom measurements are available.

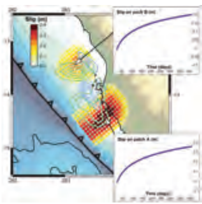
(3) Postseismic displacements



We installed a continuous GPS (cGPS) network of 5 GPS stations (Figure 1) which were in operation 20 days after the mainshock. The data analyzed here cover the time period until day 408 after the mainshock (see (4)). All horizontal displacements are trenchwards and reach up to 10cm over that period.

Co-seismic slip, aftershocks and postseismic displacements. Red vectors show horizontal postseismic displacements between days 20 and 408 after the mainshock and blue vectors show predictions from the best fitting afterslip model derived from the PCAIM inversion of the geodetic time series. The focal mechanism shows the GCMT solution. The 2 m slip contour lines of the 2007 earthquake are shown in cyan (Sladen et al, 2009). Red dots show aftershocks located from the IGP local seismic network. Green shading show the rupture area of the Mw 8.1 1974 Lima, as estimated from teleseismic waveforms and afershocks (Langer and Spence, 1995), and that of the Mw7.7 1996 Nazca earthquake as derived from the joint inversion of InSAR and teleseismic waveforms (Prichard et al, 2007).

(5) Afterslip Model



The post- and co-seismic slip distributions are observed to complement each other (the small overlap might simply reflect the smoothing effect of the regularization). This observation is consistent with the view that the shallow portion of the megathrust is paved with areas that are rate-weakening, within which earthquakes can nucleate and propagate, and areas that are rate-strengthening, within which slip is mostly aseismic. A most striking finding is that the prominent aseismic patch, labeled A. coincides with the northern side of the Nazca ridge where the 2007 rupture stopped.
We estimate that afterslip over the first 408 days released a geodetic moment of 3.33 10^20 N.m (Mw = 7.6), representing nearly 28% of the coseismic moment released. Given that the cumulative moment released by all aftershocks with Mw > 4 over the same period of time amounts to only 1.3 10^19 N.m, about 90% of the observed postseismic deformation was aseismic. The distribution of aftershocks is correlated with the distribution of afterslip, consistent with the notion that aftershocks are driven by afterslip (e.g., Perfettini and Avouac, 2004, Hsu et al, 2006).

Fault slip derived from the modeling of the geodetic time series from 20 to 408 days after the mainshock. The model shown here allows a variable rake. The weight put on smoothing and the choice of 3 principal components is justified from a Chi-squares test. The 2 m slip contour lines of the 2007 earthquake are shown in cyan. The green contour shows the density of aftershocks in the first 45 days following the mainshock. Inset show the slip at the center of patches A and B deduced from the inversion of the geodetic measurements (blue circles). Continuous lines show the theoretical displacements predicted from a rate-strengthening frictional sliding (Perfettini and Avouac, 2004), which assumes that friction increases linearly with the logarithm of the sliding velocity as observed in laboratory experiments (Marone et al, 1998).

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