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A comprehensive analysis of the Illapel 2015 Mw8.3 earthquake from GPS and InSAR data

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ABSTRACT

The September 16, 2015 Mw8.3 Illapel Earthquake occurred on a locked segment of the South American subduction in Chile. This segment ruptured during comparable size earthquakes in the past, in 1880 and 1943, suggesting a somehow regular pattern of characteristic Mw8+ earthquakes occurring every 60 to 80 yr. This recurrence is in agreement with the accumulation of elastic deformation in the upper plate due to the Nazca–South America subduction at a constant rate of 6.5 cm/yr, leading to a deficit of ∼4.5 m of slip to be released every 70 yr. Previous studies consistently imaged the distribution of co-seismic slip along the fault based on geodetic, seismological and far field tsunami data and all described a significant amount of shallow slip resulting in a large tsunami. In addition, some models highlighted an apparent mismatch between the modeled rake of slip and the direction of plate convergence, suggesting the buildup of large strike-slip deficit. Some of these important questions remain open. Is shallow slip really well resolved and substantiated? Is the apparent principal direction of slip during the earthquake really required by the geodetic data?

Here, using a comprehensive analysis of continuous GPS sites (including high rate and static displacements) and new survey data from acquired over more than 50 pre-existing sites, complemented with InSAR data, we show that the 2015 rupture overlaps very well the 1943 rupture, with the absence of significant slip south of 32°S and north of 30.2°S (peninsula Lingua de Vaca). Despite the wealth of geodetic data, the shallowest part of the subduction interface remains poorly resolved. We also show that the rake of the earthquake is fully compatible with the oblique plate convergence direction (rather than perpendicular to the trench), meaning that no subsequent trench-parallel motion is required by the data. We propose that the large Low Coupling Zone (LCZ) at the latitude of La Serena revealed by present day coupling distribution is stable over at least two seismic cycles. Inside the coupled area, peak coseismic slip is located precisely offshore the highest coastal topography and elevated terraces, adding weight to a potential correlation between the seismic cycle and long term permanent deformation. Finally, we show that early post-seismic after-slip occurs mostly down-dip of co-seismic asperity(ies), extending north and south of the 2015 rupture area.

1. Introduction

The September 16, Mw8.3 Illapel earthquake, occurred at 22:54:31 (UTC), on an active segment of the central Chilean subduction zone. Uncertainties and errors in magnitude estimates of past large earthquakes in the literature might conceal a sequence of Mw8+ earthquake. Although different magnitudes have been proposed for the 1943 earthquake (Mw7.9, Beck et al., 1998; 8.2, Engdahl and Villaseñor, 2002 and 8.3, Lomnitz, 2004), we consider the magnitude estimates in the most homogeneous catalog (Engdahl and Villaseñor, 2002) (Fig. 1). Therefore, using coherent re-estimations of past earthquake magnitudes, a cycle of Mw8+ earthquake every 60 to 70 yr seems to emerge with the last 3 occurring in 1880, 1943 and 2015. Superimposed on this cycle, a giant earthquake of magnitude 9 ruptured in 1730 a longer section of the subduction, including the Illapel segment (e.g. Udias et al., 2012), raising questions about a "super cycle", with larger (and

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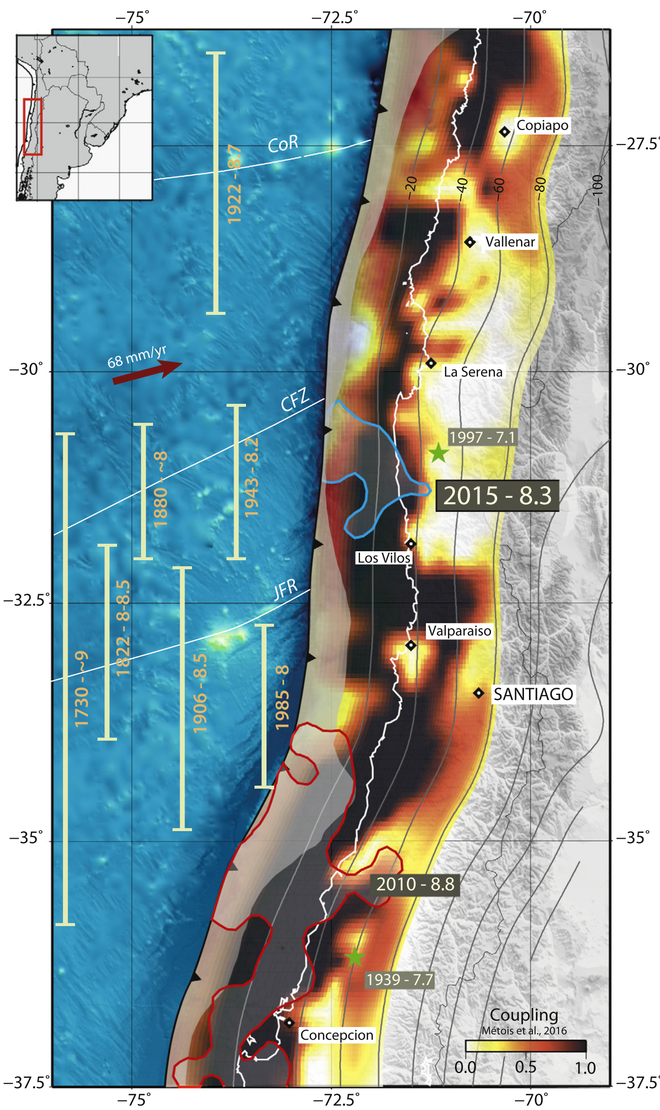

Fig. 1. Seismotectonic context of the Central Chile subduction interface. The Nazca/South-America convergence rate is represented by the red arrow. Green stars, which depict the large intraplate earthquake epicenters, and estimated historical rupture extents are based on Engdahl and Villaseñor (2002); Lomnitz (2004). Slip contour of the Maule earthquake from Klein et al. (2016); Slip contour of the Illapel earthquake is the preferred model presented in this study. Coupling model (red color scale) from Métois et al. (2016). The area of very low sensitivity is depicted by the grey area at the trench (based on sensitivity studies both for the interseismic model (Métois et al., 2016) and the coseismic model). Depth contours of the slab are extracted from the Slab1.0 model (Hayes et al., 2012). The topography and bathymetry are extracted from ETOPO5. *Inset:* localization of the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

unknown) recurrence time, similar to Sumatra (Sieh et al., 2008) and Ecuador (Nocquet et al., 2016). Although the 2015 event may have closed the Illapel gap (Tilmann et al., 2016), the status of a potential larger supercycle remains unknown. Slip during the 2015 Illapel event might have delayed the occurrence of an earthquake similar to that of 1730, by releasing some of the accumulated strain. However, it might just as well have promoted it by redistributing stresses along the megathrust.

In addition to the historical seismicity, the region of Illapel is also known for its strong seismic activity over the last 20 yr. Starting in 1997, the seismic activity shows a peculiar increase, with the occurrence of six shallow thrust events, located between 30.5°S and 31.5°S during the month of July 1997 (Gardi et al., 2006; Vigny et al., 2009), until the occurrence of the Punitaqui intraplate earthquake at 56 km depth, two months later (Lemoine et al., 2002). This Mw7.1 slab-push event has been related to a tear in the slab due to the strong accumulation of stress in the transition zone at the interface (Gardi et al., 2006). Since the Punitaqui earthquake, seventeen Mw > 6 events occurred on adjacent segments of the subduction together with regular seismic swarms. 18 yr later, the Illapel earthquake broke about 200 km of the subduction interface offshore Punitaqui.

Starting in 2004, a small scale GPS network of about 50 benchmarks has been deployed. Ten years of annual measurements revealed a highly coupled segment overlapping with the estimated rupture area of the 1943 earthquake and bordered to the north by the Low Coupled Zone (LCZ) of La Serena (Métois et al., 2012, 2014). This LCZ coincides with the northern limit of several large subduction earthquakes (i.e. 1880 and 1943). The southern boundary of this segment is unclear. Past Mw∼8 ruptures seem to have stopped near 32°S, where the Juan Fernandez ridge enters into the subduction (Yáñez et al., 2001), but no significant decrease of present day coupling can be identified there (although this was established before the 2010 Maule Earthquake) (Métois et al., 2016).

Most studies of the 2015 Illapel earthquake agree on two main characteristics. First, it appears as a characteristic earthquake, repeating those of 1880 and 1943 (e.g. Tilmann et al., 2016; Shrivastava et al., 2016; Feng et al., 2017). Second, the rupture nucleated deep on the interface, propagated updip and reached the shallow part of the interface, generating a significant tsunami (e.g. Ruiz et al., 2016; Melgar et al., 2016). Nevertheless, several issues remain.

First, daily GPS and InSAR data include coseismic displacements caused by the largest aftershock (which occurred only 25 min after the main shock) and aseismic slip that occurred during the first day. Therefore, deriving a purely coseismic deformation field for the main shock requires high rate cGPS data.

Second, the exact amount and location of shallow slip remains unclear. Geodetic data provide poor resolution over the shallowest part of the interface (the first 3 to 5 km from the trench), hence poorly constrain potential shallow slip. Therefore, if the seismic moment independently determined from seismology or tsunami records is larger than the moment inferred from geodesy alone, then slip must have occurred on the shallowest part of the interface (e.g. Hill et al., 2012). But one can also wonder whether the approximations used in the elastic properties of the various models could not be as well responsible for the difference in the moments. We will compare potencies of different models, independent from elastic shear moduli to investigate the need for significant shallow slip.

Third, previous studies in agreement with the USGS focal mechanism (http://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#moment-tensor; Duputel et al., 2012) assume a slip vector perpendicular to the trench. This led to an apparent strike slip deficit (e.g. Tilmann et al., 2016) due to the obliquity of the convergence between the Nazca and South America plates (e.g. Angermann et al., 1999; Vigny et al., 2009). In such case, the resulting strike-slip deficit should be balanced by trench parallel motion, either seismically (a strike-slip earthquake) or a-seismically (a trench parallel silent slip). However, no significant partitioning of the deformation has been documented along the Illapel segment.

We carefully investigate these points using GPS data, including continuous data acquired by a dozen of cGPS stations operated over more than 10 yr in near field and newly acquired survey data over 50 benchmarks in the Illapel area. We also use SAR data acquired by the Sentinel-1A satellite. Our dataset provides snapshots of the deformation over different timescales, from seconds (HR cGPS) to days (static cGPS, InSAR) and weeks (sGPS).