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Double pincer movement: Encircling rupture splitting during the 2015 Mw 8.3 Illapel earthquake

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ABSTRACT

The 2015 moment magnitude (Mw) 8.3 Illapel earthquake, that ruptured the central section of the Chilean subduction zone, is among the largest megathrust events in recent years. The coseismic rupture processes of the Illapel earthquake are imaged by the back-projection (BP) method in previous studies. But these models differ significantly in the extent of high-frequency radiations in the along-dip direction. Here, we conduct a refined High-resolution MUSIC BP imaging analysis of the Illapel earthquake based on teleseismic recordings in continental US. In contrast to conventional BP imaging, we add a slowness (ray parameter) error term calculated based on aftershock locations to effectively mitigate the spatial biases of BP. This correction accounts for the P-wave travel time errors at each receiver as a result of approximating the 3D Earth structure with 1D models. The calibrated BP images of aftershocks indicate that the root-mean-square location error was reduced from 24.17 km to 8.11 km. Our refined BP of the mainshock reveals geometrical rupture complexity with unprecedented details, involving stages of diverse rupture speeds and simultaneous up-dip and down-dip high-frequency bursts. The earthquake starts with a slow initiation phase propagating northward at a speed of 1 km/s in the first 13 s. Between 14 s to 34 s, the rupture diverges into two simultaneous fronts seemingly unzipping the rim of a circular patch of large slip at a speed of 3.5 km/s. The two fronts reemerge as a single front between 35 s and 45 s. The rupture splitting repeats in a second episode from 46 s to 60 s. The two episodes of encircling rupture involve intermittent high-frequency radiations both up-dip and down-dip, which reconcile the discrepancy of the extent of along-dip ruptures reported in previous BP studies. Key features of the rupture process correlate with the prominent pulses recorded by local strong-motion network. In one possible scenario, the rupture initially encounters and splits around a barrier of higher strength or an asperity of higher prestress but eventually breaks into the asperity/barrier and produces large slip in the center. Another scenario is the cascade-up growth model in which the nucleation process initiates inside a small weak patch and tends to grow into large-scale rupture surrounding the rim of a larger and stronger patch. Such degree of complexity is previously only reproduced in dynamic simulations but is directly observed with sufficient level of details for the first time. This case study demonstrates the capability of the BP method, enhanced by aftershock calibrations, to observe and probe the geometrical complexity of dynamic ruptures.

1. Introduction

The Chilean margin is under a compressive tectonic setting characterized by the rapid subduction of the Nazca Plate under the South American Plate during the last 26 Myr (Pardo-Casas and Molnar, 1987; Angermann et al., 1999). In central Chile, the Nazca plate under-thrusts the South American Plate obliquely at a convergence rate of ∼67 mm/yr (Angermann et al., 1999; Kendrick et al., 2003; Vigny et al., 2009). This segment of the Chilean margin has historically generated frequent and large megathrust earthquakes (Lomnitz, 2004; Udías et al., 2012).

On September 16th 2015, a moment magnitude (Mw) 8.3 subduction earthquake occurred at a depth of 23.3 km (Centro Sismológico Nacional), 233 km NNW of Santiago, near the city of Illapel. The quake lasted for over one minute (An et al., 2017; Okuwaki et al., 2016), and was followed by several aftershocks greater than M 6. The 2015 Illapel earthquake ruptured a large segment of Central Chile that covers the similar rupture zone of the 1943 Illapel–Salamanca earthquake (Lomnitz, 1970). The 1943 event is uncertain in its magnitude between M 7.8 (Beck et al., 1998) and M 8.3 (Lomnitz, 1970) and may have ruptured only the

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deeper parts of the 2015 event (Tilmann et al., 2016). Immediately north of the 2015 event, a much larger M 8.5 earthquake struck the Atacama region of Chile in 1922. To the south, the 2015 Illapel earthquake is adjacent to the source area of two other large events of the last century: the 1906 M 8.2 Valparaiso earthquake and the 1971 M 7.5 Illapel earthquake (Beck et al., 1998; Campos et al., 2002).

The 2015 Illapel earthquake caused strong shaking and flooding hazards in the proximate coastal region of Chile, resulting in 13 deaths and 6 missing. One million people were evacuated from affected areas and 9,000 people were left homeless. The first tsunami wave arrived on the Chilean coast within 15 minutes after the earthquake. A wave of 4.5 m (15 ft) high was observed along the coast of Coquimbo, flooding the nearby cities (Tilmann et al., 2016). The focal mechanism of the earthquake was almost purely thrust (strike: 353°, dip: 19°, rake: 83°, USGS W-phase solution, https://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#moment-tensor) and consistent with rupture on the plate interface. Numerous efforts on observations of the Illapel earthquake, based on seismic waveform modeling, space-geodesy and tsunami inversions (Heidarzadeh et al., 2016; Li et al., 2016; Melgar et al., 2016; Okuwaki et al., 2016; Tilmann et al., 2016; Ye et al., 2016; An and Meng, 2017; An et al., 2017), revealed that the rupture spanned an area of over 150 km wide north of the epicenter, possibly extending from near the trench to under the Chilean coastline, coinciding with regions of high seismic coupling (Métois et al., 2013; Tilmann et al., 2016). The event was also followed by an intensive aftershock sequence located along strike and in a cluster near the trench from −30°N to −31°N. The stress-driven postseismic slip was found to wrap around the mainshock rupture area according to the repeating earthquakes and geodetic observations (Huang et al., 2017; Barnhart et al., 2016).

The high-frequency aspects of the coseismic rupture processes are captured by various back-projection (BP) analyses. These BP images are overall consistent in the northward rupture expansion but differ in the rupture extent along dip. Ye et al. (2016) imaged two regions of concentrated high-frequency energy, one near and the other down-dip from the hypocenter. Ruiz et al. (2016) recovered similar patterns of bilateral rupture in the first 50 s, which later merged and propagated up-dip. The Hybrid back-projection (Okuwaki et al., 2016) imaged unilateral northward propagation with both up-dip and down-dip rupture episodes. Tilmann et al. (2016), on the other hand, revealed only one branch of the rupture down-dip from the hypocenter, possibly breaking beyond the seismogenic depth. Two other BP studies, Yin et al. (2016) and Melgar et al. (2016), focusing on the frequency-dependent rupture behaviors, suggested low-frequency up-dip and high-frequency down-dip rupture expansion. Here, we apply the MUSIC BP approach improved by slowness calibrations which provides superior resolution and precision than conventional linear beamforming (Meng et al., 2011, 2016). The MUSIC approach first evaluates the covariance matrix of waveforms in each sliding time window and sampling frequency. The steering vector composed of the travel-time shifts at each station are computed for each candidate source node. The direction of arrival corresponding to the most likely source location is then determined by the maximum amplitude of the frequency-average MUSIC pseudospectrum, defined as the inverse of the projection of the steering vector onto the noise subspace (Schmidt, 1986). The MUSIC method is particularly capable of separating closely-spaced simultaneous sources (Meng et al., 2012a). Our observations suggest that the discrepancies of previous BP images can be reconciled by simultaneous up-dip and down-dip emissions from encircling sources, which we interpret as splitting of rupture fronts running around the rim of a large asperity/barrier. This encircling pattern is analogous to the double-pincer movement in military tactics. Our results open a direct window into the dynamic rupture of a complex megathrust earthquake.

The rest of this article is organized as follows. In section 2, we briefly describe the slowness-enhanced MUSIC BP approach, and test its performance on the aftershocks of the Illapel earthquake. In section 3, we present the coseismic source process of the mainshock revealed by the slowness-enhanced MUSIC BP. In section 4, we validate the key features of the BP results with independent analysis of the local strong motion recordings. In section 5, we test synthetic rupture scenarios to understand how well the encircling ruptures are resolved by BP. Finally, in section 6, we discuss the mechanical interpretations of the encircling rupture, as well as the contributions and limitations of the slowness calibration to earthquake source imaging.

2. High-resolution back-projection enhanced by slowness calibrations

The back-projection (BP) method provides the high-frequency view of the 2015 Mw 8.3 Illapel earthquake. The BP technique takes advantage of the global dense arrays of broadband seismometers and images the wavefield of the earthquake to determine its rupture properties. These properties include several spatiotemporal characteristics, such as rupture length, direction, speed, and segmentation (see review by Kiser and Ishii, 2017). In contrast to classic source inversions based on waveform fitting, the BP approach does not rely on the Green's function and is based on solely the phases of coherent seismograms. The BP method is therefore less affected by uncertainties on seismic velocity structure and fault geometry, and is not restricted by parameterization of the rupture kinematics. This simplicity allows the technique to be conducted as soon as the data are available and to be free of ambiguity of the source images due to the parameter selections (e.g. IRIS DMC back-projection, Trabant et al., 2012). Here we adopted the Multitaper-MUSIC array processing technique, which resolves more closely spaced sources and is less sensitive to aliasing, yielding a sharper image of the rupture process than the standard beamforming approach (Meng et al., 2011). This capability of high-resolution imaging enables the observations of simultaneous sources and hence the splitting of the encircling rupture fronts. We also applied a "reference window" strategy, which eliminates so-called "swimming" artifacts, a systematic apparent drift of the high-frequency (HF) energy towards the station arrays (Meng et al., 2012b). Our BP analysis is performed on coherent P-wave seismograms recorded by all available broad stations across continental US, composed of 421 seismometers with epicentral distances between 60° and 90° (Fig. 1c). The data are available from the IRIS data center (www.iris.edu). We filtered the seismograms in the passband between 2 s and 0.5 s, the highest range with adequate waveform coherency (mutual correlation coefficients larger than 0.85 in the first 10 s of the P wave).

In standard BP, the only prior information required is the hypocenter location and a teleseismic travel-time table based on 1D reference velocity model (e.g. IASP91, PREM and AK135). The process of determining the later sub-sources with respect to the hypocenter is similar to that of the "master event" location technique (Ito, 1985). To account for the travel time variations due to 3D Earth structures, BP applies a timing correction inferred from the "hypocenter alignment" (Ishii et al., 2005, 2007). The first arrival of the Illapel earthquake is assumed to come from the hypocenter location (71.741°W, 31.637°S) issued by Centro Sismólogico Nacional (CSN). A set of travel time errors due to 3D structures is obtained by cross-correlating the initial 10 s of the P-waves. The subsequent ruptures are tracked based on their differential travel times relative to the hypocenter. A layered IASP91 (Kennet, 1991) velocity model is adopted to compute the travel