The Mw 8.3 Illapel earthquake (Chile): Preseismic and postseismic activity associated with hydrated slab structures

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ABSTRACT

The accumulated stress in subduction zones is discharged with earthquake and aseismic activity; the latter is hosted in rheological complex regions, characterized by high pore fluid pressure, and is often accompanied by repeated earthquakes and earthquake swarms. The spatiotemporal analysis of seismic activity can reveal the presence of aseismic transients associated with large earthquakes. Here we study 20 years of seismicity prior to and after the Mw 8.3 earthquake that occurred in A.D. 2015 in central Chile. We identified several earthquake swarms before the main shock and repeating aftershocks at the border of the main slip area. Spatial clustering of the seismic activity shares similar orientation with the main fracture zones observed on the outer rise of the subducting Nazca plate. Our findings suggest that the fracture zones enclosing the rupture are playing a major role in accommodating the pre- and post-main shock stress evolution. We further recognize how fracture regions have acted as barriers to the propagation of large earthquakes in the region.

INTRODUCTION

On 16 September 2015, a Mw 8.3 earthquake struck the north-central Chile subduction zone near the city of Illapel. This event broke a 150 × 100 km area (Melgar et al., 2016; Tilmann et al., 2018). The northern rupture limit of the Illapel earthquake also coincides with the Challenger Fracture Zone and La Serena low interseismic coupling zone (Ruiz et al., 2016; Métois et al., 2016). In a similar manner, earthquakes in 1943 and 1880 could have stopped in the same zones (Beck et al., 1998). The northern rupture limit of the Illapel event coincides with the Challenger Fracture Zone and La Serena low interseismic coupling zone (Métois et al., 2016); the northern termination of the 1730 megaeearthquake (Mw ~ 9.0) (Ruiz et al., 2016) and the southern extent of the 1922 Atacama megaeearthquake also coincide with these features. The southern limit of the 2015 Illapel earthquake is close to the Juan Fernández ridge and the low interseismic coupling zone offshore Los Vilos at 31.8°S (Métois et al., 2016). Series of historical earthquakes (i.e., 1822, 1906, and 1971; Ruiz et al., 2016) show a northern extent of rupture at this latitude. Persistent seismicity has been observed in the past 20 yr around the Illapel region, with several swarm activities near the fracture zones, together with seismicity migration, aseismic slip (Gardi et al., 2006), and the occurrence of intraslab events such as the Mw 7.1 Pumataqui earthquake in 1997 (Lemoine et al., 2001; Pardo et al., 2002; Holtkamp et al., 2011) (Fig. 1; Figs. DR1 and DR2 in the GSA Data Repository1).

The regions around the main slip area of the Illapel earthquake also host large afterslip (Barnhart et al., 2016). Little sedimentary fill of the trench and the high convergence rate of 6.8 cm/yr (Vigny et al., 2009) favor the process of tectonic erosion (Clift and Vannucchi, 2004) in the Illapel region. The roughness of the slab, resulting from tectonic evolution of the oceanic plate before its subduction, generates high fracturing in the interplate boundary and favors the collapse of the continental wedge due to the process of basal tectonic erosion (Contreras-Reyes et al., 2015). Therefore, the long-term rheological conditions at the interplate boundary are related to heterogeneities, both in the oceanic and continental crust. Numerous papers have highlighted the relation between subducted features and the earthquake sources; one example of this is the location of asperities around subducted seamounts (Cloos, 1992; Bilek et al., 2003). However, the process of seamount subduction can also prevent slips under favorable conditions of fluid migration and fracturing (Mochizuki et al., 2008; Wang and Bilek, 2014). Moreover, a correlation of the subducted aseismic ridges and fracture zones with the distribution of earthquakes is observed along the subduction margins (Kelleher and McCann, 1976; Contreras-Reyes and Carrizo, 2011; Nishikawa and Ide, 2015). However, observation of high pore-fluid pressure is also correlated with low interseismic locking regions (Moreno et al., 2014). These hydrated regions are also the locus of aseismic phenomena as slow slips and earthquake swarms (Rogers and Dragert, 2003; Saffer and Wallace, 2015, and references therein).

We analyzed geological and seismological data, which suggest a complex distribution of frictional properties on the megathrust in the Illapel area. Our study also suggests the presence of aseismic slip in the hydrated regions, taking place for at least 20 yr before the event. The same regions are hosting large postseismic slip.

TECTONIC SETTING

The northern limit of the Illapel coseismic slip patch correlates with the subducted trace of the Challenger Fracture Zone at ~30°S (Fig. 1A). This large structure corresponds to a northward slab age discontinuity of ~5 m.y. (Müller et al., 2008), but it is not associated with high roughness in the seafloor, suggesting little or no disruptive effect on the margin. The total magnetic intensity anomaly reveals a width of 40 km for this structure and the free-air gravity anomaly shows local subsidence of the continental wedge aligned with its trace (Fig. DR3), which we interpreted as an effect of high fluid content on the interplate boundary along the Challenger Fracture Zone that reduces the effective basal friction coefficient, generating a local bathymetry low with the corresponding decrease of slope angle (Maksymowicz, 2015).

Observing the swath bathymetric data of the studied area (Contreras-Reyes et al., 2015), we identified and traced large structures formed by the Nazca plate bending (black lines in Fig. 1A) that show a rotation from a northeast strike south of ~31°S to a near north-south direction to the north. The oblique-strike structures are located around the Juan Fernández ridge, suggesting that its collision with the subduction margin (joined with its buoyancy) locally rotates the stress field. According to the bathymetry the influence of the Juan Fernández ridge on the oceanic fracturing is extended to 100 km around the ridge trace. A conjugate set of outer-rise structures is observed with northwest direction (some of these structures are shown with red lines in Fig. 1A) with a strike similar to that observed for the magnetic fabric of the slab (magenta lines in Fig. 1A). We interpret this second structural set as fractures generated at the spreading center that are possibly reactivated near the trench (similar to Ranero et al., 2005). Ranero et al. (2005) showed evidence...
that some of these structures can be reactivated as intermediate-depth intraslab seismicity, highlighting a long-term permanence of the outer-rise faulting during the subduction process. The role of the slab faults in the interplate boundary is poorly understood, although the nature of these faults as important fluid transport zones has been observed seaward from the trench by numerous geophysical studies, such as refraction seismic experiments (Ranero et al., 2003; Han et al., 2016), electromagnetic surveys (Naif et al., 2015), and wide-angle seismic tomography that show a decrease of Vp and Vs (P and S wave velocities) inside the oceanic crust and mantle, which are interpreted as an effect of the hydration process favored by the fault bending (Contreras-Reyes et al., 2008; Moscoso and Greve Meyer, 2015; Shillington et al., 2015). It is important to note that the extension of the outer-rise fault lengths at the sea bottom is typically >50 km, indicating their crustal-scale influence and that they probably reach the upper mantle below an ~7-km-thick oceanic crust (Zelt et al., 2003).

SEISMICITY ANALYSIS

For a detailed study of the seismicity in the Illapel region, we compiled a composite catalog. We use the U.S. Geological Survey National Earthquake Information Center catalog from 1990 to 2000, and for data since 2000, the Chilean National Seismological Center (CSN) catalog. Our composecatalog has a time-variable completeness around magnitude 4.0. The observed seismicity shows a pattern complementary to the slip distribution of the Illapel Mw 8.3 earthquake (Fig. 2A; Fig. DR1). Most of the events are located near the north, south, and east edges of the 2015 Illapel asperity. A similar pattern is recognized in the aftershock distribution (Tilmann et al., 2016; Figs. DR1 and DR2) and postseismic slip (Barnhart et al., 2016).

Several swarms can be observed in the time-dependent seismicity plot (Fig. 2B; Figs. DR1 and DR2). We consider a swarm as a cluster of events in time, space, and magnitude (Holtkamp et al., 2011). The most remarkable swarm started in July 1997 and ended in February 1998 (Gardi et al., 2006, Holtkamp et al., 2011). The swarm started in zone 1, then a stress transfer from the aseismic slip at depths >50 km triggered the swarm of zone 2 and the Punitaqui 1997 Mw 7.1 intraslab earthquake (Gardi et al., 2006). Zone 3 is characterized by a sudden change of seismicity rates after the Punitaqui swarm in 1997 (Fig. 2B). Zones 1 and 2 underwent seismicity acceleration from February to June 2003 (Fig. 2B). Seismicity starts in zone 1, with interplate events at depth <30 km, and extends downdip (depth >30 km) in zone 2. Since 2005, we only observed swarms in zone 3, including a small swarm that happened some weeks before the main shock in Illapel (Figs. DR1K and DR2K).

We also found 86 repeating earthquakes (Fig. 2A; see the Data Repository), 3 of which occurred before the main shock (Fig. 2C). The magnitude of the repeating events spanned Mw 4–Mw 4.9 and they were localized in the same place of the observed swarms (zones 1, 2, and 3) where large afterslip is occurring (Barnhart et al., 2016).

The spatial distribution of the repeaters and normal seismicity follow a preferential north-south distribution on zone 1 (Fig. 2) and a WSW–ENE alignment in zone 3 (Fig. 2). This feature correlates with the strike of bending slab fractures seaward to the trench (Fig. 1A).

DISCUSSION

The ensemble of our observations is shown in Figure 3. The geological interpretation of the magnetic intensity anomaly, the free-air gravity anomaly, and the bathymetric data revealed important fractured zones in the Nazca plate. The signature of the fractures is likely to extend to the seismogenic zone contact. The orientation of slab faults correlates with the preferential orientation of earthquake swarms and repeaters. We can thus define two or three main fractured zones in the seismogenic contact that are most relevant. These fracture zones control the seismicity of zones 1, 2, and 3 (Fig. 3). Despite the lack of three-dimensional velocity models in the zone that show low values of Vp and Vs, we propose that zones 1, 2, and 3 have high pore-fluid pressure favoring the presence of persistent swarm-type seismicity (Fig. 2). The correlation of the fracture zones with the observed low interseismic coupling value (Ruiz et al., 2016; Métois et al., 2016) supports our hypothesis and suggests the important role of water in controlling the frictional behavior of the plate interface, as proposed in Moreno et al. (2014). Why some of the subducted slab fractures favored the seismic activity, rather than others, cannot be explained without a complete knowledge of the stress and strain fields on the interplate boundary. However, it is a common behavior of the seismogenic zones that only few structures of the complete set of faults are seismically active at the same time, depending on the stress field and the rheology of the faults.
The fluid-rich low coupling regions act as barriers to propagation during large megathrust events (Figs. 1B and 3) and host high seismicity rates in the interseismic and postseismic periods (Sammonds et al., 1992; Schlaphorst et al., 2016). The swarm-like seismicity and repeating earthquakes are characteristic of fluid-rich and geologically complex regions (Fagereng and Sibson, 2010) and are associated with slow slip events (Crescintini et al., 1999; Rogers and Dragert, 2003; Saffer and Wallace, 2015, and references therein) and postseismic deformation (Nadeau and Johnson, 1998; Perfettini et al., 2010). We thus have enough evidence to recognize the presence of aseismic slip at the border of the Illapel asperity at least since 1997, together with a large afterslip (Barnhart et al., 2016).

The overall seismic behavior of the plate interface in the Illapel region seems to obey the rate and state formalism shown by numerical simulation (Kaneko et al., 2010), with a high seismicity rate near the low coupling region and a moderate seismic rate inside the locked zones. From our analysis, we can conclude the important role of hydrated geological features in controlling the megathrust coupling and in modulating the stress. Our study illustrates the importance of integrated geological and seismological data analysis to inform predictive models for long-term megathrust dynamics.

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**REFERENCES CITED**


Several other references are also included in the text, discussing topics such as the geometry of the Chilean margin, the role of pore fluids in seismic processes, and the dynamic interactions between subduction zones and tectonic processes.

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