Suspected Deep Interaction and Triggering Between Giant Earthquakes in the Chilean Subduction Zone

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Key Points:
- Seismic analysis shows how an earthquake triggered a tear in the slab 1,200 km away which led to another major earthquake 18 months later
- The 2015 *M*8.3 Illapel (Chile) earthquake was preceded by the deformation of the slab below the future rupture zone
- Large earthquakes interact in the Chilean subduction

Supporting Information:
- Supporting Information S1

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Suspected Deep Interaction and Triggering Between Giant Earthquakes in the Chilean Subduction Zone

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Abstract Between 2010 and 2015 three giant earthquakes occurred in the Chilean subduction where the oceanic Nazca plate plunges under South America. These were the largest events there since the gigantic *M*9.5 1960 earthquake so their close occurrences raise the question of a possible link between them. We show here that two-and-a-half days after the *M*8.2 Iquique earthquake, seismic activity started to increase downdip below (depth~100 km) the future Illapel epicenter. This increase, which began with the largest intermediate-depth earthquake in the Chilean subduction after Iquique, lasted until the *M*8.3 Illapel earthquake, 18 months later. The mechanisms involved suggest that the Iquique earthquake started a tear in the slab directly downdip from the future epicenter. This study relies on seismicity which occurs in the cold core of the slab and which is the only direct information we have on processes occurring at these depths. The results support that giant earthquakes interact at the scale of a subducting plate and suggest that this interaction occurs through the deep slab.

Plain Language Summary Our study shows that giant earthquakes interact and can trigger one another at the scale of a subducting plate. Studying the evolution of seismic activity in the deep (~100 km) slab, which is the only tool we presently have to investigate physical processes taking place at these depths, we show that, accompanying a giant earthquake, the slab deforms to large depth and far distances, something unthought of before. This paper is able to trace the path which links two recent major earthquakes in the Chilean subduction, the *M*8.2 2014 Iquique and the *M*8.3 2015 Illapel earthquake. We show that the first event produced a tear in the deep slab 1,200 km away, directly downdip from the second event epicenter. We show how this tear expanded with time for 18 months and finally spread to the seismogenic zone and the future epicentral area 2 months before the second megathrust. These results support that most large subduction earthquakes are not spontaneous ruptures but are preceded by the slow deformation/slip of the plates below the seismogenic zone, which is a very encouraging result for the future.

1. Introduction

While subducting plates slip slowly and continuously below about 50 km, slip above occurs mostly intermittently during subduction earthquakes. Below about 70 km, seismic events of another type, termed intermediate-depth earthquakes, occur. They result from the internal deformation of the downgoing plate. Recent observations that several large subduction earthquakes were preceded by increase of background seismic activity deep in the slab while foreshocks were occurring in the epicentral area (Bouchon et al., 2016) suggest that the slab can deform over a broad spatial range in a short time and that what happens below the lithospheric plate contact affects the shallow seismogenic zone where subduction earthquakes occur. The existence of a long-term correlation between shallow and deep activities in the North Chile subduction, recently reported (Jara et al., 2017), supports this view.

To investigate whether deep seismic activity in the slab can provide clues of a link between the three giant Chile earthquakes of 2010–2015 (Metois et al., 2016; Figure 1), we study the evolution of intermediate-depth seismicity in the vicinity of the Illapel earthquake, the last one of these three events (Ruiz et al., 2016).

2. Evolutions of Deep and Shallow Activities

We use the catalog made by the Centro Seismologico Nacional of Chile (www.sismologia.cl). We begin by exploring a broad volume of the slab around the Illapel earthquake before progressively focusing on the

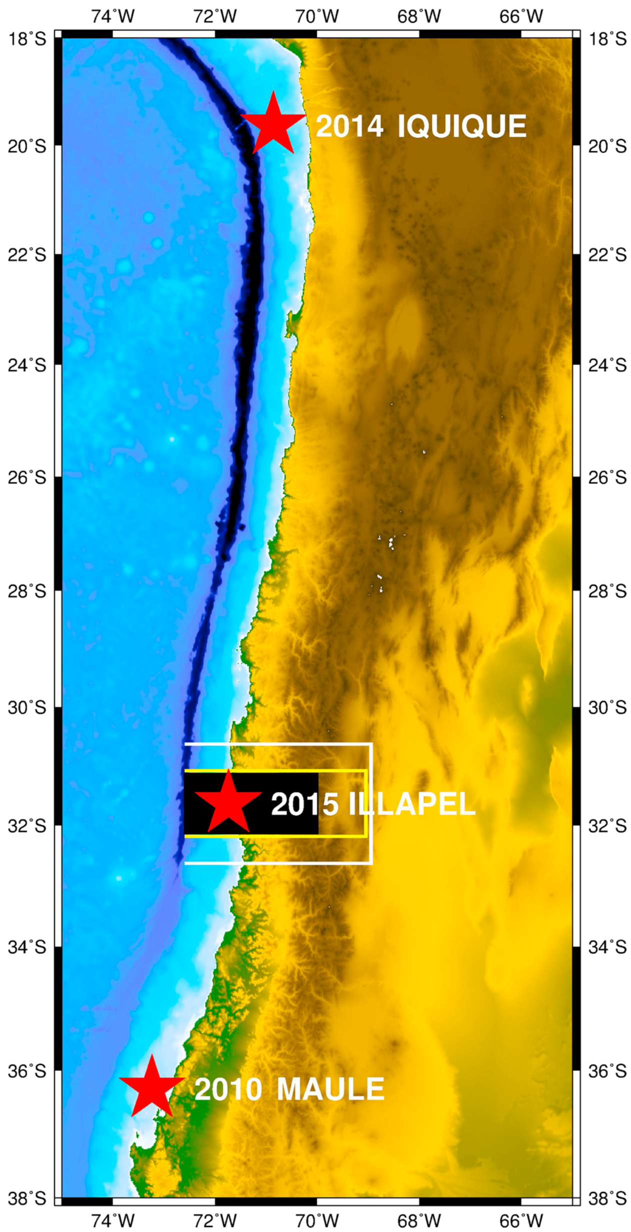

Figure 1. Epicentral locations of the 2010–2015 $M > 8$ Chile megathrust earthquakes (red stars). The trench makes the dark blue in the bathymetry. The boxes show the geographical extent of the zones where deep seismicity is investigated: white (Figures 2a and 2b), yellow (Figure 2c), and black (Figure 2d).

part of the slab lying directly downdip from the epicenter. The broad zone considered extends over 2° of latitude (~220 km) centered on the epicenter and is limited inland to 69°W, about 250 km east of the epicenter. Beyond this longitude, already within Argentina, the seismic network coverage degrades. We consider all the events deeper than 70 km with magnitude larger than 4, which is the magnitude of completeness of the catalog for deep events in the region (Figure S1 in the supporting information). What we observe in this broad zone (Figure 2a) is a slight activity increase after the Iquique earthquake. To investigate where this increase originates, we first eliminate the very deep events by restricting our exploration to the depth range between 70 and 120 km (Figure 2b). The change of rate of seismic activity between the pre- and post-Iquique periods becomes clear, indicating that it originates from this depth range. We then focus on the slab volume downdip from the Illapel epicenter. To do this, we reduce the latitude extent of the zone from 2° to 1° (Figure 2c).The rate change between the pre- and post-Iquique periods is now very strong. A further reduction of the eastern limit of the zone to 70°W (approximately the Chile/Argentina border, Figure 2d) shows that the zone of the slab where the activity increase is the strongest lies directly downdip (along the slab) from the future hypocenter.

Extending the time period investigated to include the occurrence time of the 2010 *M*8.8 Maule earthquake (Figure S2) shows an increase of deep activity in the months following the megathrust. This activation begins with relatively small shocks (*M*~4) in the weeks following the earthquake and is followed a few months later by two $M > 5$ earthquakes (Figure S3). Although the link between this activation and the Maule earthquake may be questioned because of the delay, it is notable that the largest intermediate-depth earthquakes in the zone in the 10 years preceding the Illapel earthquake occur in the year following Maule and in the year following Iquique (Figure S3). After 2010 the deep activity dies down until the Iquique earthquake (Figure S2).

The evolution of the shallow seismic activity in the future epicentral area is presented in Figure 3a. The zone investigated is a circle of 0.5° (~55 km) radius centered on the epicenter and includes all $M > 4$ events shallower than 50 km. The activity is displayed as the monthly rate of events. Except for one immediate aftershock of Maule, this shallow seismicity does not seem significantly affected by the two megathrusts. Part of this activity has been attributed to the presence of important fluid-filled fractures in the Nazca plate (Poli et al., 2017). The two largest bursts of shallow events since 2009 occur in January 2012 and in July to August 2015, shortly before the September 16 2015 Illapel earthquake. What is special about this latter activity is that it follows by a few days an increase of activity at depth (Figure 3a). It is the first time since 2009 that both deep and shallow activities are correlated in time. The number of events in the slab ($0 < \text{depth} < 120$ km) is then the highest in the more than 6 years investigated (Figure 3b). A zoom on the evolution of seismicity over the 18 months between the Iquique and Illapel earthquakes (Figure 3c) confirms that this acceleration of activity, which shortly precedes Illapel, begins at depth. This activation spreads in a few weeks to the shallow part of the slab.

3. Interpretation of the Observations

A map of the geometry of the slab in the region (Anderson et al., 2007) provides valuable information (Figure 4a). The post-Iquique increase in deep intraslab activity takes place in the narrow zone where the

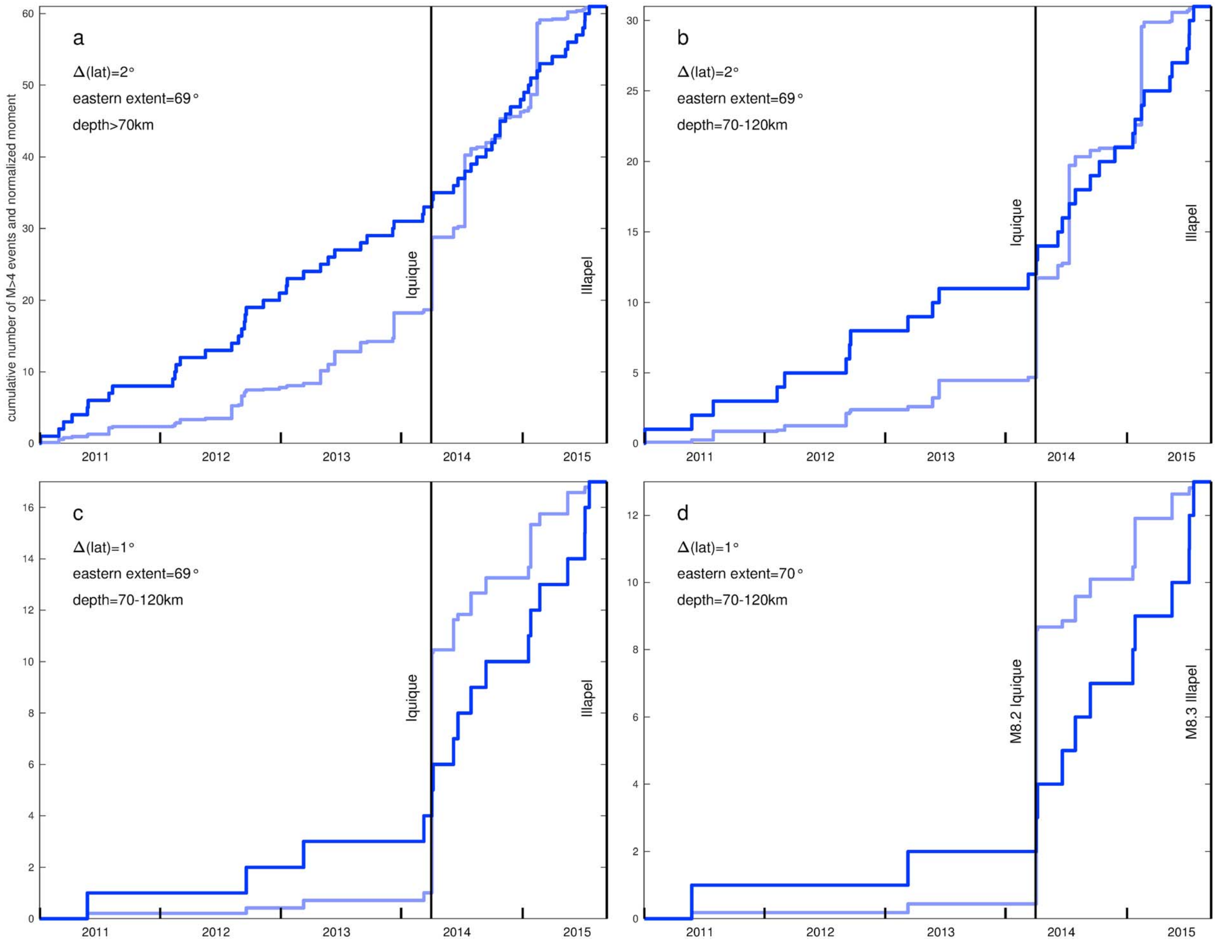

Figure 2. Evolution of the deep seismicity before the Illapel earthquake. The dark blue curves show the cumulative number of $M > 4$ events since 2011 and the light blue curves the corresponding normalized seismic moment. (a–d) Progressive focusing of the zone investigated on the slab volume directly downdip from the Illapel hypocenter. The latitude and longitude extents of the zones explored and the depth range are indicated. The vertical lines show the occurrences of the megathrusts.

Chilean slab flattens. There the presence of the Juan Fernandez ridge in the subducting plate deforms the slab. Flattening occurs because the ridge buoyancy is resisting the plunge (Anderson et al., 2007; Pardo et al., 2002; Pilger, 1981; von Huene et al., 1997). Elsewhere between the Iquique and Maule locations, the Nazca plate subducts at a nearly constant ~27° dip (Barazangi & Isacks, 1976; Cahill & Isacks, 1992; Pardo et al., 2002). Thus, the activation begins two-and-a-half days after the Iquique earthquake precisely at the junction between the regularly dipping slab to the north and the flattening slab to the south. The strike-slip mechanism of the earthquake (www.globalcmt.org), unusual for intermediate-depth events, indicates a tear in the slab (Figure 4a). The depth of the earthquake (106 km) places it ~20 km below the slab interface, in the depth range where the flexure of the oceanic plate is maximum (Figure 4b). The continuation of the deep activity in the zone for 18 months at a much higher level than before Iquique indicates that tearing continued during this period. The observations show that this activity occurred over a broad volume of the slab extending from 70 to 120 km in depth and ~180 km in width (Figures 4a and 4b). Interestingly, many large earthquakes in South America occur where large topographic features of the Nazca plate enter the subduction (Contreras-Reyes & Carrizo, 2011; Perfettini et al., 2010).

The depth range where the intraslab activity is observed (70–120 km) lies just below the lithospheric plates contact. There the slab slowly and continuously descends into the asthenospheric mantle. The thermal conditions at the slab/asthenosphere interface render this descent aseismic because rocks there are hot enough to plastically deform. The internal part of the slab, however, is still cold enough to sustain brittle fractures.

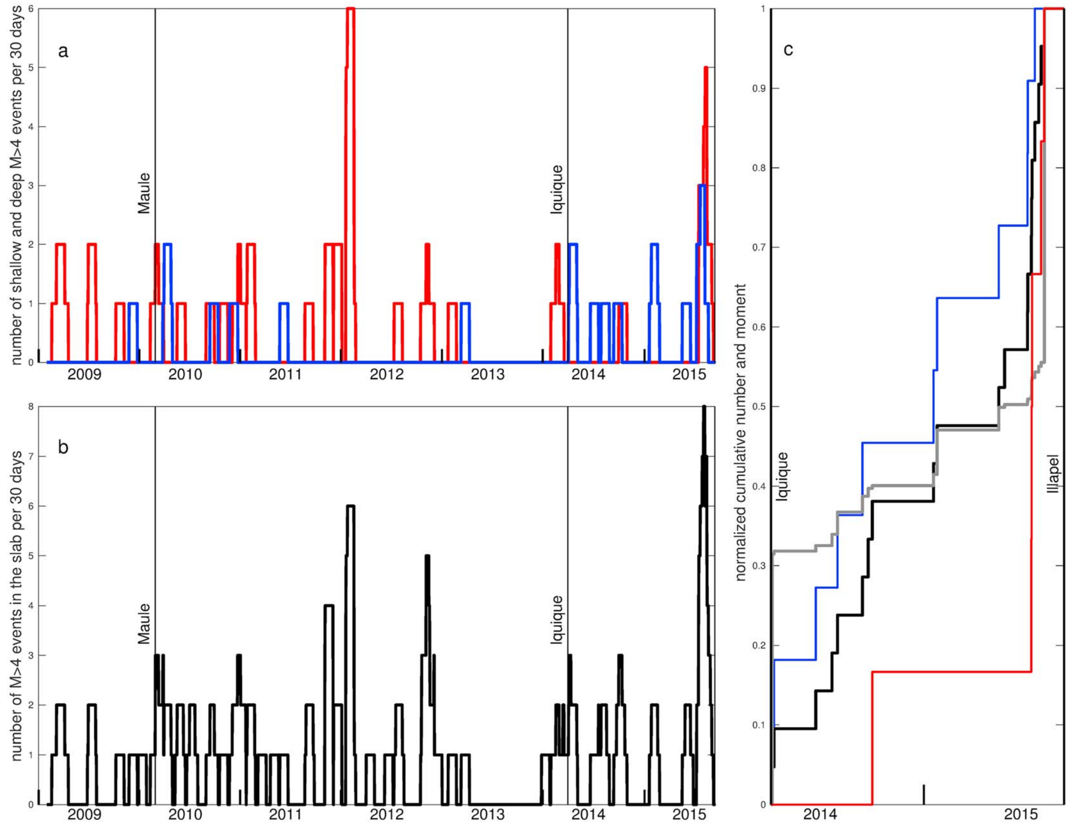

Figure 3. Evolution of seismicity ($M > 4$) in the slab before the Illapel earthquake. (a) Compared evolutions of the number of events per month in the epicentral area (red) and downdip below in the slab (blue) before Illapel. The deep zone explored is the black box in Figure 1. A sliding window 30 days long is used for the representation. The vertical lines show the occurrences of the megathrusts. (b) Evolution of the number of events in the slab ($0 < \text{depth} < 120$ km) per month. (c) Cumulative number of events near the epicenter (red) and downdip below (blue) between the times of the Iquique and Illapel earthquakes. The black line is the cumulative number of events in this slab section; the gray line is the corresponding seismic moment.

These ruptures are thought to result from hydrofracturing induced by metamorphic dehydration of slab minerals (Green & Houston, 1995; Raleigh & Paterson, 1965). The depth where the activity takes place also corresponds to the zone of transition of mantle viscous stresses exerted on the slab from oversupporting it above ~100–150 km to undersupporting it below (Royden & Husson, 2006). The magnitude of the events observed here is moderate in comparison to the large (~*M7*) intermediate-depth earthquakes which occur from time to time in the subduction. This suggests that the numerous small ruptures of the slab observed are only the seismic signature of a mostly aseismic process. What is seen is the progressive tearing of the slab, but what causes it evades measurements and can only be speculated. The fact that it evolves slowly, spreads over a broad zone, and lasts for months is reminiscent of the characteristics of SSEs, slow slip events which occur in some subductions near the base of the seismogenic zone (Beroza & Ide, 2011; Peng & Gomberg, 2010). This suggests as possible interpretation a local increase in the downgoing slip velocity of the slab triggered by the Iquique earthquake. As the upper part of the slab is locked, this would produce internal tension that would foster intraslab fracturing. This mechanism already explains the predominance of extensional events at intermediate depths (Astiz & Kanamori, 1986; Dmowska et al., 1988; Malgrange et al., 1981). Regardless of the interpretation, the observations support that a process, which begins at ~100 km depth, will lead to a major rupture of the seismogenic zone, directly above, 18 months later. The change of static stress produced by Iquipe at the Illapel location is of the order of $\Delta\sigma^*(L/r)^3$, where $\Delta\sigma$ and L are respectively the stress drop and the size of the Iquique rupture and r is the distance between the two earthquakes. Taking values of ~30 bars for the stress drop and ~200 km for the rupture size yields a change of stress of the order of 15 kPa (0.15 bar) at the Illapel location, a small value unlikely

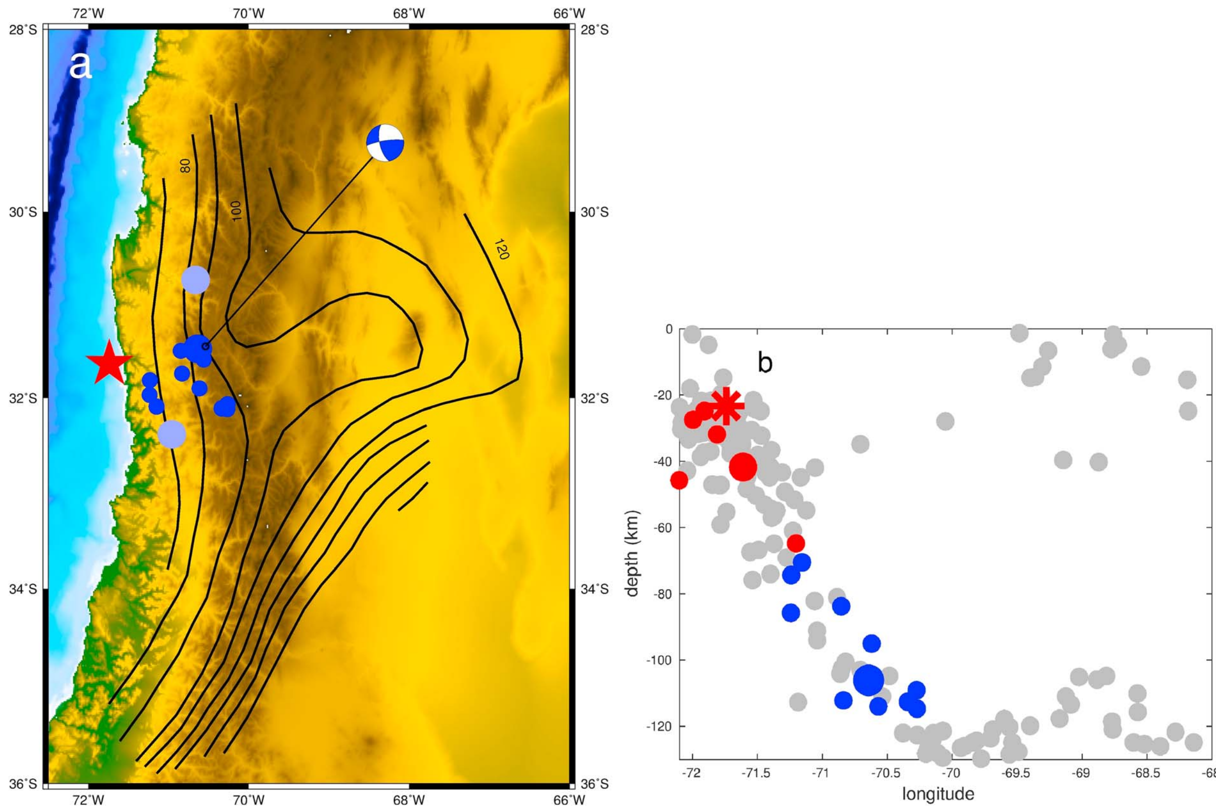

Figure 4. Location of seismic activity ($M > 4$) in the period between the Iquique and Illapel earthquakes. (a) Deep ($70 < \text{depth} < 120$ km) events (dark blue) in the zone downdip from the hypocenter (black box in Figure 1). The largest event is the *M*5.4 earthquake which initiated activity two-and-a-half day after Iquique, shown with its mechanism. The light blue dots are the two other deep $M > 5$ earthquakes in the broader zone considered (white box in Figure 1). The black curves are contour lines of the slab interface (Anderson et al., 2007) drawn at 10 km interval. The red star shows the hypocenter. (b) Vertical cross section perpendicular to the trench. The blue dots and the red star are the same as in (a). The red dots are events shallower than 70 km in the same geographic zone during the acceleration of activity of July to August 2015. The large dots are $M > 5$ events. The gray dots are the other events in the zone since 2005.

to trigger rupture. Similarly, the peak dynamic stress is of the order of $\Delta\sigma_d$* (*L*/*r*), where $\Delta\sigma_d$ represents the average dynamic stress drop on the Iquique rupture. Taking a value of $\Delta\sigma_d$ 50% higher than $\Delta\sigma$ as is typically observed (Bouchon, 1997) yields a peak dynamic stress of the order of 0.75 MPa (7.5 bar). The existence of a long evolving process, as observed here, triggered by waves from a large distant earthquake, and leading to another major earthquake several months later, has been proposed to explain some observations (Brodsky, 2009). Whether the present triggering was induced by seismic waves (Gomberg & Johnson, 2005; Hill et al., 1993) or broad-scale rigid slab deformation, the triggered event was the largest intermediate-depth earthquake to occur in the Chilean subduction in the month following the Iquique earthquake (Figure S4a). Apart from the Iquique region itself, it is also in this zone, directly downdip from the future Illapel rupture, that the highest concentration of deep earthquakes occurred in the period between the two megathrusts (Figure S4b). In the 2 months preceding rupture, the largest seismic moment release at seismogenic depth (<50 km) occurred in the future epicentral zone (Figure S5).

These results confirm that some large subduction earthquakes are preceded by increases in deep seismic activity, indicating that the slab is slowly deforming well below the seismogenic zone (Bouchon et al., 2016). One further information available is what happens deep in the slab after rupture. This is shown in Figure S6 for the broad zone of the slab previously considered in Figure 2a. After rupture of the seismogenic zone, the deep activity decreases and is back to about its pre-Iquique level. This indicates a relaxation of the stress at depth, which is consistent with the unlocking and freeing of the upper part of the slab. The rapidity with which relaxation occurs supports the existence of a scenario similar to what has been proposed to explain the time evolution of GPS measurements after Maule (Klein et al., 2016). In their study the authors cite two possible scenarios: either the presence of a low viscosity channel at the slab/mantle interface extending down to 135 km or the occurrence of afterslip down to the same depth. The presence of a low viscosity channel along the slab/mantle interface, often advocated (Hebert et al., 2009; Heki & Mitsui, 2013; Hilairet et al., 2007; Kawakatsu & Watada, 2007), would also help understand the rapid upward spread of deformation observed along the slab in July to August 2015, shortly before the Illapel earthquake.

4. Conclusions

The reported observations support that giant earthquakes can interact at relatively far distances, a subject of long animated debate (Brodsky, 2009; Lay, 2015). The existence of such interactions at the scale of a subduction impacts the concepts of seismic cycle, characteristic earthquake, or recurrence time on which seismic risk assessment largely relies. It also helps understand the diversity of large historical earthquake ruptures (Bilek, 2010; Konca et al., 2008; Lomnitz, 1970) in a subduction, as local conditions are not the only factor which sets the timing and size of ruptures.

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