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Observation of a Synchronicity between Shallow and Deep Seismic Activities during the Foreshock Crisis Preceding the Iquique Megathrust Earthquake

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Abstract We analyze at a broad spatial scale the slab seismicity during one of the longest and best recorded foreshock sequences of a subduction earthquake to date: the M8.1 2014 Iquique earthquake in Chile. We observe the synchronisation of this sequence with seismic events occurring in the deep slab (depth ~100 km). We show that the probability that this synchronisation is obtained by chance is infinitesimal (<10^{-5}), indicating that it is the result of a physical process taking place in the subduction. A mechanically logical explanation for this synchronicity seems to be the presence of fluid connections between the intermediate-depth range of the slab and the shallow seismogenic zone where foreshocks occur. These connections could be in the form of transient fluid channels in which bursts of pressure pulses would propagate, or localized high permeability paths along the plate interface in which pore-pressure waves would travel. It suggests that, like for the 2011 Tohoku earthquake, the deep slab was involved in the nucleation process of the Iquique earthquake. These observations may seem surprising but they are in line with the short-lived pulse-like channelized water escape from the dehydration zone predicted by recent studies in slab mineralogy and geochemistry.

Non-technical summary In 2014 a large earthquake (M8.1) occurred in the North Chile subduction. This earthquake was preceded by an intense foreshock crisis which lasted for nine months. We analyze here this foreshock activity and we observe that it is synchronised with seismic activity occurring deep (~100 km) in the slab, far down-dip from the foreshock locations and below the future rupture zone of the earthquake. As this deep seismic activity is thought to be associated with the dehydration of slab minerals and the release of water, it suggests that rapid water ascent from the dehydration zone may have triggered the foreshocks. Other possible mechanisms for this synchronicity of foreshocks with activity deep in the slab are discussed.

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1 Introduction

Although it is still a controversial subject, an increasing number of observations support that broad spatial interactions occur in slabs. The rapidity and the scale of some of the interactions reported (Bouchon, 2016, 2022; Panet et al., 2018, 2022; Bedford, 2020; Bouih et al., 2022; Karabulut et al., 2022; Rousset et al., 2023) challenge our present understanding of slab dynamics and raise questions about the mechanism of communication across long (100km or more) distances. We analyze here, at a broad spatial scale, the long and well-recorded foreshock sequence which preceded the M8.1 2014 Iquique earthquake in the North Chile subduction. Signs of short-term and long-term correlations between shallow and deep seismic activities there have been previously reported (Bouchon, 2016; Jara et al., 2017). We present here more detailed observations expanded to the whole foreshock crisis which lasted for nine months. The earthquake broke the Nazca/South-American plate interface in a region which had been identified as a major seismic gap (Madariaga, 1998). Although its foreshock sequence has attracted considerable attention Ruiz (2014); Schurr (2014); Kato and Nakagawa (2014); Kato et al. (2016); Lay et al. (2014); Bedford et al. (2015); Meng et al. (2015); Duputel (2015), these investigations concerned activity in the the seismogenic zone, which in subducting plates is limited to ~50 km depth. Below, the plate boundary slips almost continuously due to ductile deformation at elevated temperature. Megathrust earthquakes break the seismogenic zone but are not thought to extend much deeper. Below ~60 km, another type of seismic event, however, occurs in the descending plate. These events, termed intermediate-depth earthquakes, take place not along the interface but inside the cold core of the slab. They are believed to be linked to the metamorphic dehydration of slab minerals.

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2 Synchronicity of Foreshocks with Activity Down-Dip in Slab

The pre-Iquique activity begins to be noticeable ~9 months before the mainshock (Kato et al., 2016; Socquet, 2017; Jara et al., 2017). The first phase of foreshock activity occurs in July-August 2013. It begins north of the epicenter and spreads southwards up to ~80 km from it in following weeks (Fig. 1). A quiescence period follows for a few months (September-December 2013, Aden-Antoniow et al., 2020). A second phase of foreshocks starts ~120 km south from the epicenter in January 2014, three months before the earthquake, and in the following weeks a broad slab segment is activated (Fig. 1). This activity intensifies on March 16, two weeks before the earthquake, when a M6.7 shock occurs. The evolution of this activity has been interpreted as migrating slow slip which is supported by GPS and tilt observations (Socquet, 2017; Boudin, 2021). The spatial extent of the foreshock zone, about 180 km, is intriguing as well as the rapidity with which seismicity spreads over a plate interface known to have been locked for decades (Madariaga, 1998; Chlieh, 2011; Metois et al., 2016).

We first study the relatively large (M > 4) events occurring in the subduction before the earthquake. We use for this the national catalog made by the Centro Seismologico Nacional of Chile (CSN, www.sismologia.cl, www.isc.ac.uk), whose completeness magnitude is around M4 (Jara et al., 2017). Whenever available (generally around and above magnitude 5), we use for these events the moment magnitudes published by the Global Centroid Moment Tensor (GCMT) Project (www.globalcmt.org, Ekström et al., 2012), which is the reference for large earthquakes worldwide.

In Fig. 2 we present the timing and magnitude of the shallow (depth<40 km) and deep (80 km<depth<125 km) earthquakes within increasing radial distance range (160 km, 170 km, and 200 km) from the future epicenter. The large depth separation differentiates shallow events (i.e. foreshocks) associated with the slip of the slab and intermediate-depth events associated with its internal deformation. The lower depth limit (125 km) has little effect as few events are deeper during the periods considered. Beyond this limit, events are far from stations and catalog resolution degrades. The first epicentral distance range considered is 160 km (Fig. 2a). At lower radii from the mainshock epicenter, the deep slab is not yet sampled because of the low dip of the slab. Within this distance range, the deep slab volume sampled lies directly down-dip from the epicentral zone. Fig. 2a shows that deep activity there is confined to the two foreshock crises and that one deep event shortly precedes (1 day) the intensification of the foreshock crisis which will lead to the earthquake two weeks later. Fig. 2b extends the exploration range to 170 km and focuses on the period preceding and including the first crisis. At this range where a larger volume of deep slab is sampled, a correlation emerges between deep and shallow activities. Fig. 2c extends the exploration range to 200 km and focuses on the period around the second crisis and on the largest shallow (M>4) and deep (M>4.5) events, the higher magnitude cut-off used for deep events reflecting the higher level of deep background activity present in this subduction. At this distance range a time correlation between the two activities emerges clearly. The wider exploration needed for a correlation to emerge during the second crisis seems consistent with the broader spatial extent of this crisis (Fig. 1).

In statistics the two time series displayed in Fig. 2, are termed temporal point processes. To estimate the probability that one temporal point process (A) is dependent on the other one (B), a distribution of interevent times is constructed by fixing the events from series (B) and measuring the time from each event in (A) to the closest event in (B). This method is described in (Galbraith et al., 2020). Probability is calculated by fixing the times of the deep events, drawing randomly the times of the shallow events, and comparing their mean interevent time with the one observed. In doing so we do not make any hypothesis on any of the properties of the two time series. We simply look if the interevent time observed is due to random chance or if it is an intrinsic property of the data. The application of the method to seismic sequences is straightforward and described in Bouchon (2022). In Fig. 2b (first crisis) the chance probability that shallow events (i.e. foreshocks) are as closely synchronized with the occurrence of deep events is $< 10^{-5}$ (more than 100,000 random draws of the 9 M>4 shallow events are required to reach an interevent time with the 7 deep events present as small as the one observed). A similarly small chance probability $< 10^{-5}$ that shallow events occurring during the second crisis (Fig. 2c) would be as closely synchronized with deep events located within 200 km of epicentral distance is obtained. The combined probability that shallow events would be as closely synchronized with deep events below during the two foreshock crises is thus infinitesimal. The smallness of the values may seem surprising but it likely reflects the burst-like characteristic of the seismicity: As shown in Fig. 3, a burst is not simply made up of one shallow and one deep event, but usually of a multiplicity of them interweaved together within a short time, a characteristic difficult to be reproduced by a random process.

Using the catalog of Sippl et al. (2018a) for North Chile, which decreases the magnitude of completeness to ~2.7, we can explore shallow and deep activities at lower magnitude. Because of the high level of deep background activity below magnitude 4 in the subduction and the long duration and broad spatial extent of the crisis, we focus on the period when the first foreshock activity is the most intense and on the subduction segment where this activity takes place (Fig. 3). To interpret this figure, one has to realize that deep activity is continuously present in this zone, regardless of the occurrence or not of foreshocks. Consequently, if some interaction occurs between deep and shallow activities it probably does not involve all the deep population. Furthermore each family of events has necessarily dynamics of its own and smaller events may be aftershocks of the larger ones. A notable feature of Fig. 3 is that shallow activity is usually accompanied by deep activity. Calculating, as in Fig. 2, the chance probability

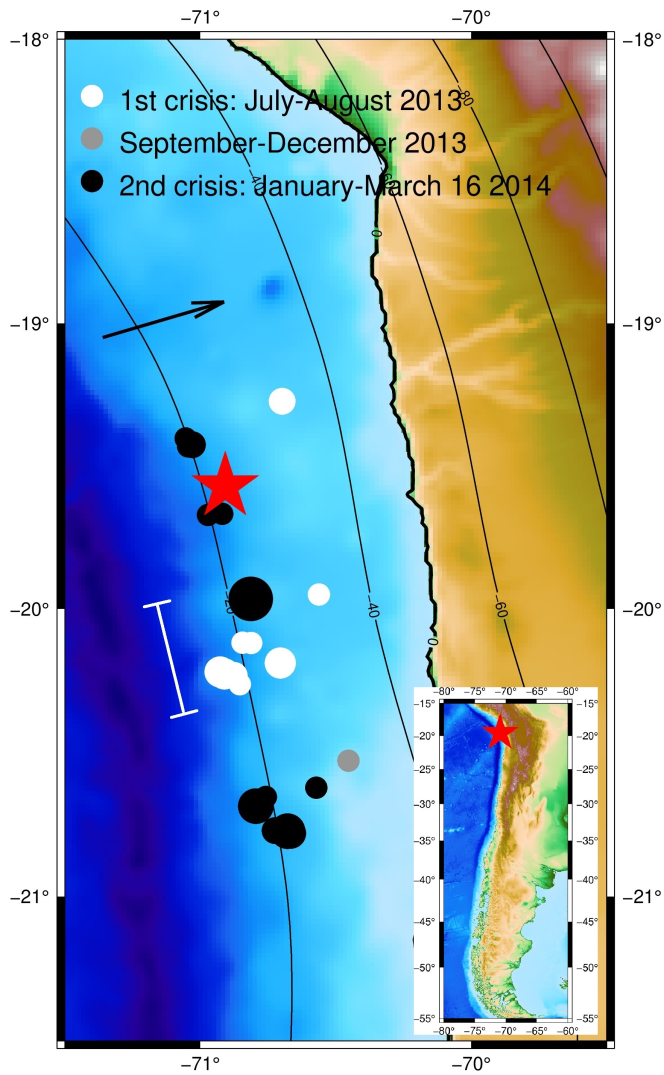

Figure 1 Location of the large (M>4) foreshocks showing their broad north-south spatial extent along the strike of the slab. All events with depth <40 km in the CSN catalog in the year preceding the earthquake up to the large M6.7 foreshock are shown. Most activity occurs in two crises. Circle size increases with magnitude. Star is the epicenter. Arrow indicates plate convergence direction (Vigny et al., 2009). Contour lines show slab interface depth (Hayes et al., 2012). Dark blue color marks the trench. White line shows the subduction segment considered in Fig. 3.

that the interevent time between the shallow (26 events) and the deep (22 events) occurrences is as small as the one observed yields a value $< 10^{-5}$.

An intriguing feature of Figs.2 and 3 is the burst-like occurrence of the events: The largest deep and shallow events occur in packets of short duration and, as can be seen in Fig. 3 (e.g. at -282, -266, -252 days etc), multiple deep and shallow events are often interweaved together within a burst. This complexity prevents the reading of a simplistic chronology between deep and shallow events.

3 Seismic Links indicative of Water Channels?

Fig. 4 shows where the M>4 shallow and deep events which make up the eight largest bursts (Fig. 2b-c) occur. It shows that during each burst, the deep events tend to occur nearly down-dip from the shallow events. This suggests a move along slab dip of the source of slip/deformation during each burst. The rapidity of this along dip move would be comparable to the migrating speed of tremors (Shelly et al., 2007; Ide, 2010; Ghosh, 2010; Gomberg, 2010; Peng and Gomberg, 2010; Beroza and Ide, 2011). The jumps of activity observed along subduction strike from one burst to the next are also tremor characteristics (Kao et al., 2007; Shelly et al., 2007; Ghosh, 2010).

Fig. 4 also displays the slab seismicity down to small magnitude during the entire 9-month long foreshock crisis. This seismicity map is made with the Sippl et al. (2018a) catalog. As we are interested in imaging possible seismic connections, it emphasizes clustered seismicity relative to isolated events. The spatial distribution of seismic events at depths of ~20-80 km, between the shallow and deep earthquake zones, is apparently aligned in lineaments parallel and oblique to the subduction interface dip direction. It supports the presence of seismic links connecting the shallow M>4 events to the deep slab. It also shows the tendency of these links to converge spatially towards the foreshock clusters and the epicenter. The paths these links define are

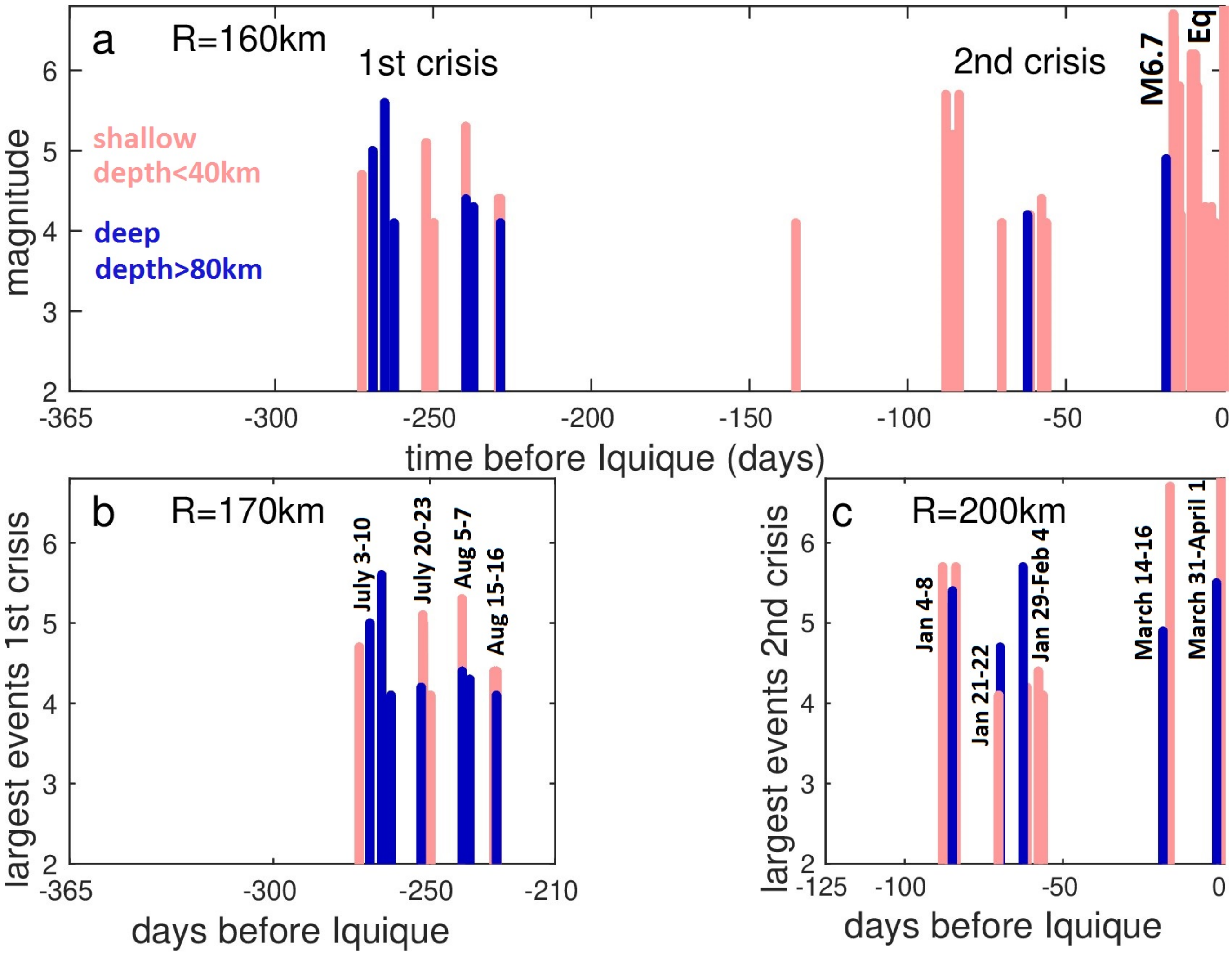

Figure 2 (a) Timings of all M>4 shallow and deep events located within 160 km from the epicenter in the year leading to the earthquake from the CSN catalog. The last event is the mainshock. (b) Increasing the epicentral distance to 170 km and focusing on the period before and during the first crisis. (c) Increasing the epicentral distance to 200 km and focusing on the largest shallow and deep events of the second crisis. Shallow events after the M6.7 foreshock are not shown because they are dominated by its own aftershocks. Periods of activity are indicated.

complex, sometimes multiple, but their long range continuity is notable.

Another illustration of seismic links between deep and shallow slab activities is presented in Fig. 5. This figure is made with the catalog of Aden-Antoniow et al. (2020) which uses a similar set of stations in North Chile as the Sippl et al. (2018a) catalog and has a comparable magnitude of completeness. It displays the seismicity pattern in August 2013 - the period when the first foreshock crisis is particularly intense. It shows the presence during this period of two seismic links connecting the future epicenter and the strongest foreshock cluster (M>5) to the locations of the largest intermediate-depth earthquakes (M>5) of this crisis.

4 Discussion

The presence of large volumes of water in subduction zones has long been documented (Raleigh and Paterson, 1965; Peacock, 1990; Green and Houston, 1995; Kirby et al., 1996; Hacker et al., 2003; Kawakatsu and Watada, 2007; Rondenay et al., 2008; Kawano et al., 2011; van Keken et al., 2011; John, 2012; Abers et al., 2013; Angiboust et al., 2014; Guillot et al., 2015; Plümper et al., 2017; Sippl et al., 2018b; Shapiro et al., 2018; Contreras-Reyes, 2021). The link between high-pressured fluids and seismic activity has itself long been recognized (Sibson, 1992; Miller et al., 1996).

The deep events in each burst occur in the depth range of 70 to 120 km where antigorite serpentine breaks down releasing the largest amount of water. Once released, water escape from the deep slab is thought to occur through transient channels (Miller et al., 2003; John, 2012; Angiboust et al., 2014; Plümper et al., 2017; Taetz et al., 2018).

The present observations are consistent with a mechanism involving the translation of pressure pulses in fluid-filled channels. The burst-like nature of the seismic activity would indicate that pressure propagation and fluid flow are very intermittent. This transient characteristic seems mechanically logical, with channels opening during overpressure passage and closing

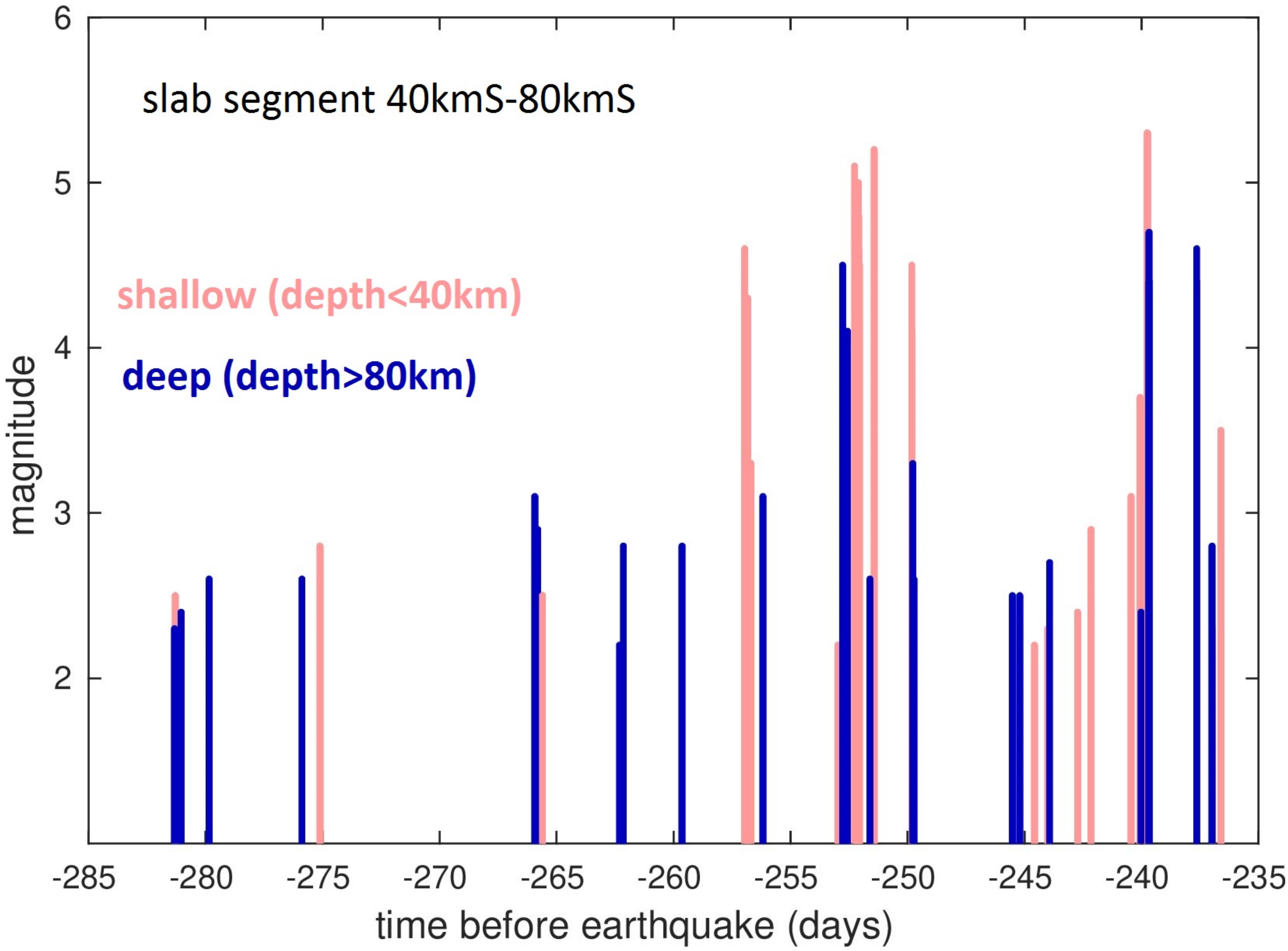

Figure 3 Timings of shallow and deep events in the subduction segment where the most intense activity of the first foreshock crisis takes place. This segment (white line in Fig. 1) extends from 40 km south to 80 km south of the epicenter and its limits are aligned with the plate convergence direction. All the shallow (depth<40 km) and deep (80 km<depth<125 km) events from Sippl et al. (2018a) catalog occurring on this segment during the period considered are presented. The segment and period investigated correspond to the occurrence of the second and third bursts in Fig. 2b. Slight differences in magnitude relative to Fig. 2 are catalog differences. What is notable is that shallow activity is closely synchronized with some deep activity.

as soon as fluid pressure locally in the channel drops below local confining pressure. The along-dip organization of the bursts denotes an along-dip orientation of the channels, which probably reflects the strong downslip corrugation of the Nazca slab interface (Soto, 2019). Such corrugations have been recently proposed to act as fluid conducts (Edwards, 2018). The occurrence of the events in packets of short duration, including both shallow and deep events, often interweaved together, suggests that they are associated with the updip and downdip propagation of pressure pulses. While surges of overpressured fluids in the seismogenic zone are probably producing the foreshocks, they are accompanied by decompression pulses propagating downdip.

Another clear characteristic of the seismic activity is its long remarkable extension along the strike of the subduction (Figs. 1, 4). This long extension of the activity does not evolve in a continuous fashion but occurs in jumps. For instance, after ~4 months of quiescence, the second crisis begins suddenly in early January ~150 km away from where the first crisis had started and 50 km beyond the zone where foreshocks had previously occurred. The activity was strong there for a few days, then completely disappeared and by the end of January, foreshock activity had jumped back to a zone close to where it initiated.

The major characteristics that are observed, the rapidity of the up-dip/down-dip interactions, the jumps of the activities along subduction strike, the broad width of the subduction zone involved are not characteristics unseen before. These same characteristics have long been reported for tremors (e.g. Shelly et al., 2007; Kao et al., 2007; Ide, 2010; Ghosh, 2010; Gomberg, 2010; Peng and Gomberg, 2010; Beroza and Ide, 2011). What is novel, here and before the Tohoku earthquake, are the very long range and the depth reach of these phenomena as well as the relatively large magnitude of the seismic events produced.

One may question the existence of physical fluid channels at the depths considered. Their presence in the dehydration zone itself, however, is observed in exhumed rocks originating from this zone and is now well

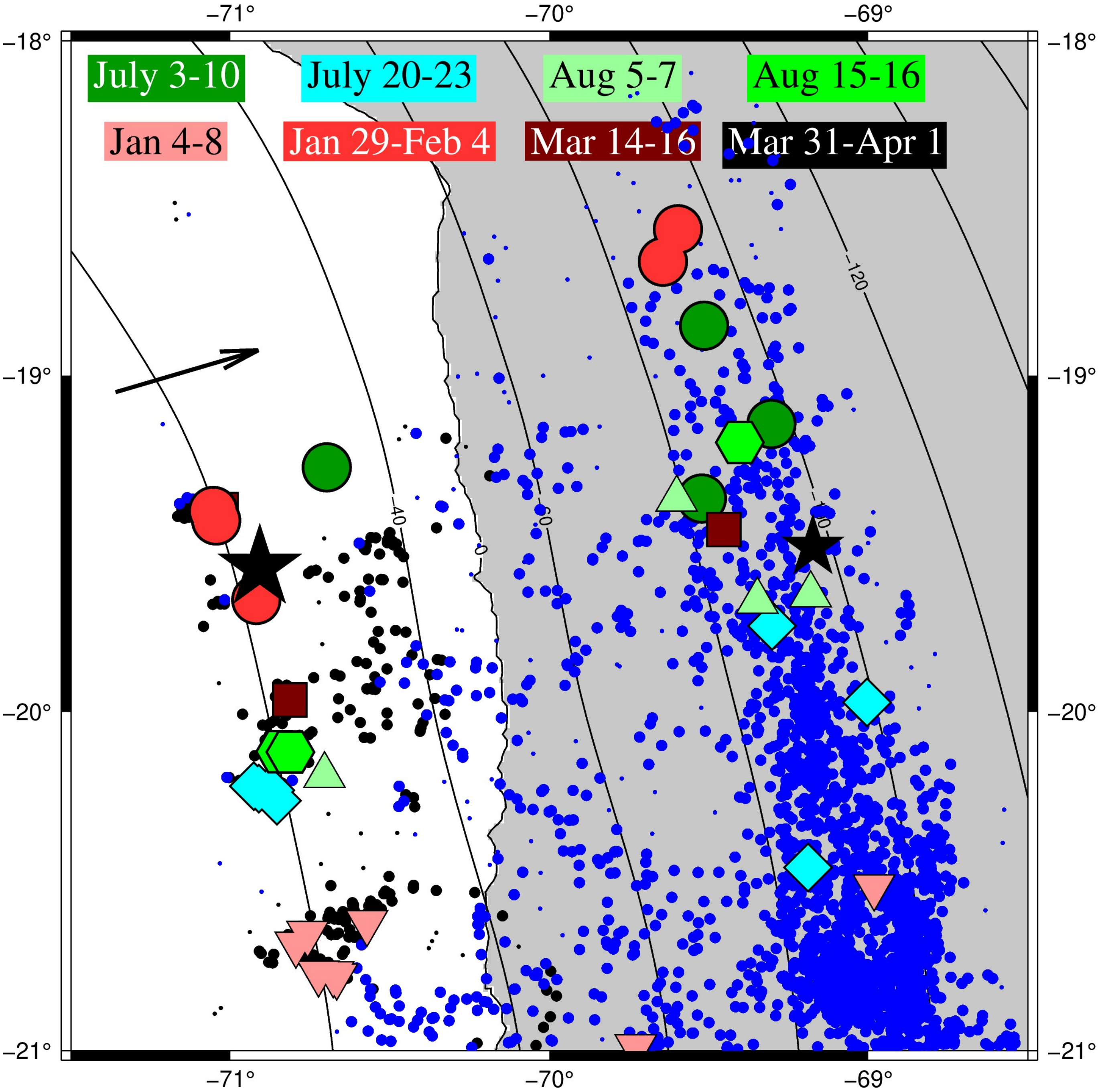

Figure 4 Location of M>4 shallow and deep events (large colored symbols) occurring during the eight largest foreshock bursts. Each color/symbol represents one burst (dates for each burst indicated at top of map). Last burst ends with the Iquique earthquake (large star). Shallow events are below sea, deep events below land. Shallow and deep events in each burst occur nearly along slab dip from each other. Superposed on the map is all the seismic activity during the entire crisis (July 2013 – March 2014) obtained from Sippl et al. (2018a) catalog (black dots: depth <40 km, blue dots: depth>40 km). The most spatially-clustered events (events with at least 3 neighbors within 10 km distance) are the larger dots.

documented (John, 2012; Angiboust et al., 2014; Plümper et al., 2017; Taetz et al., 2018) but direct observation on how these fluids migrate afterwards is lacking. Fig. 4 shows the presence of near continuous seismic paths connecting the foreshock zones to the locations of the largest intermediate depth events. The significance of these paths may at first be doubted on the ground that they are complex and multiple, but their convergence towards the foreshock and epicenter locations is clear and at least intriguing. The significance of the snapshot image of Fig. 5 might be also doubted because its statistical significance is difficult to assess, but it shows two clear seismic paths between the shallow and deep activities during one of the most active months of the foreshock crisis. The propagation of pore-pressure waves or porosity waves along or near the plate interface may be an alternative to the strong spatial localization of fluid flow of a channel model. Cruz-Atienza et al. (2018) have shown theoretically that tremor migration and speed can be explained by the propagation along the plate interface of non-linear pore-pressure waves under conditions that the interface is treated as a damage shear

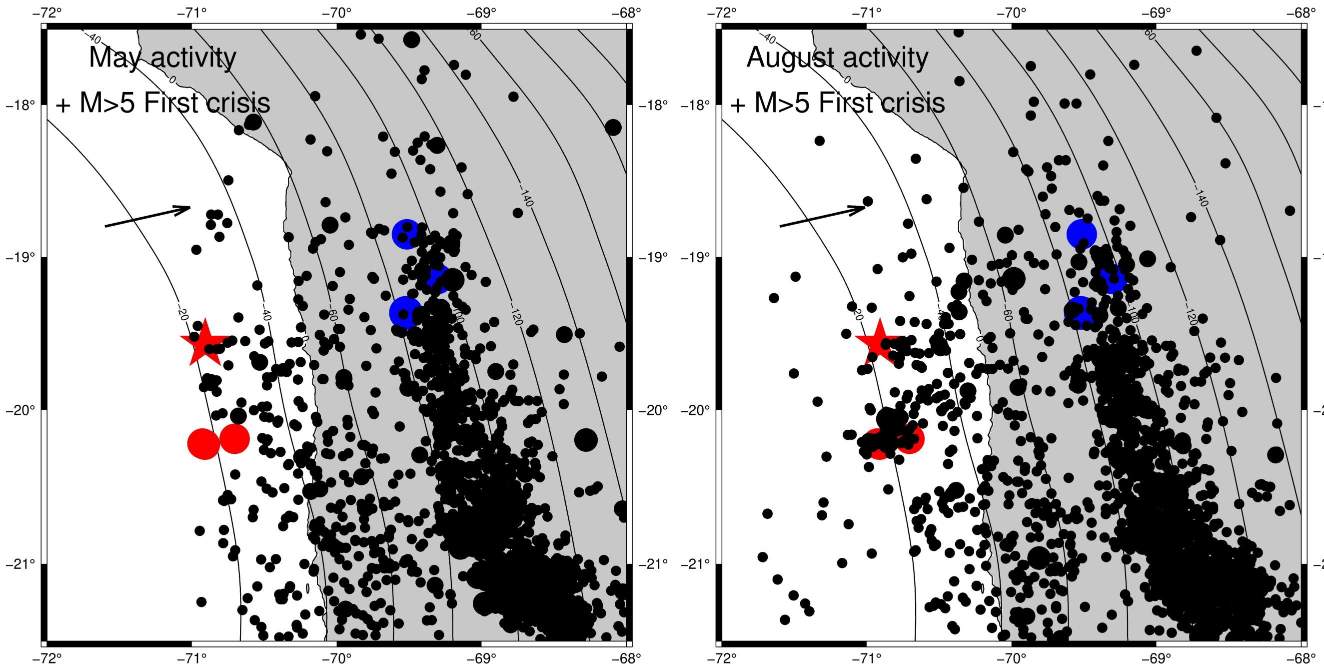

Figure 5 Seismic activity (black dots) in May (left) and August (right) 2013 from Aden-Antoniow et al. (2020) catalog. Only the events occurring near the slab interface and below are shown. Size of the dots increases with magnitude. Superposed on the maps are the locations of the largest (M>5) foreshocks (red dots) and intermediate-depth earthquakes (blue dots) during the first foreshock crisis (July-August 2013). Seismic paths, not present or recognizable in May, before the crisis begins, link in August the most intense intermediate-depth earthquake zone of this crisis (three blue dots) to the strongest foreshock cluster (two red dots) and to the future epicenter (red star).

zone with strong permeability anisotropy. The seismic paths observed here could then be following the zones of highest permeability/highest shear deformation at or near the plate interface.

If one accepts that fluid/pressure circulation is the motor of the slab seismic activity observed during the foreshock crisis, one intriguing question is why, in such a short time (a few months), overpressured pulses/fluids would ascend from different distant places spanning such a long segment of the subduction. One possible mechanism would be the existence of connections between the deep rock reservoirs where water from dehydration is thought to be stored, so that pressure changes in one would affect others. Another possible mechanism could be a rapid deformation or slip of the slab, too small or too deep to be detected geodetically, but of broad spatial extent, which could disturb the slab interface and the fluid present at depth. This probably would imply that the whole slab interface is nearing threshold stress so that effective stress limit is reached nearly simultaneously along strike for ~200 km. One may also wonder if the foreshock crisis could be driven by the up-dip pressures from slow slip events occurring at depth.

The present study is limited to the 9 months-long duration of the Iquique foreshock period, but it may be of interest that one of the largest intermediate-depth earthquake in instrumental time in Chile, the 2005 M7.8 Tarapaca earthquake, occurred 9 years before, precisely down-dip below the area which was to rupture during the Iquique earthquake (Jara, 2018; Ruiz and Madariaga, 2018). Although seismic instrumentation in North Chile at the time was too sparse to conduct the same study as the one done here, it is notable that this earthquake produced a long-term decrease in GPS eastward velocities in the region, interpreted as a decrease in plate coupling (Jara et al., 2017). This situation appears surprisingly comparable to the occurrence of the 2003 M7.1 intermediate-depth earthquake down-dip below the Tohoku epicentral zone 8 years earlier. Although the mechanisms by which slab dehydration, and its accompanying water release, induce intermediate-depth earthquakes are still debated (e.g. van Keken et al., 2012; Abers et al., 2013; Prieto, 2013; Poli and Prieto, 2014; Ferrand, 2017; Gasc et al., 2017; Cabrera et al., 2021), the association of the two seems now well established.

The interpretation of our observations seems supported by recent studies in subduction zone mineralogy and geochemistry which predict the short-lived pulse-like channelized water escape from the dehydration zone (John, 2012; Angiboust et al., 2014; Plümper et al., 2017; Taetz et al., 2018).

5 Conclusion

The present observations show the synchronisation of the foreshock activity which preceded the Iquique megathrust earthquake in Chile with seismic activity occurring below the foreshock locations in the intermediate-depth range of the slab. They also show the presence of near-continuous seismic links connecting the two activities. These characteristics are similar to the ones observed before the Tohoku earthquake, supporting that the same physical processes led to the two megathrust ruptures. The most logical interpretation of these observations in today's knowledge seems to be the rapid ascent of water from the slab dehydration zone.

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Data and code availability

The data used in this study are open and available at: Sippl et al. (2018b), Aden-Antoniow et al. (2020), www.sismologia.cl, www.isc.ac.uk and www.globalcmt.org.

Competing interests

The authors declare that they have no competing interests.

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