Historical and Recent Large Megathrust Earthquakes in Chile

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Review Article

Historical and recent large megathrust earthquakes in Chile

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ABSTRACT

Recent earthquakes in Chile, 2014, Mw 8.2 Iquique, 2015, Mw 8.3 Illapel and 2016, Mw 7.6 Chiloé have put in evidence some problems with the straightforward application of ideas about seismic gaps, earthquake periodicity and the general forecast of large megathrust earthquakes. In northern Chile, before the 2014 Iquique earthquake 4 large earthquakes were reported in written chronicles, 1877, 1786, 1615 and 1543; in North-Central Chile, before the 2015 Illapel event, 3 large earthquakes 1943, 1880, 1730 were reported; and the 2016 Chiloé earthquake occurred in the southern zone of the 1960 Valdivia megathrust rupture, where other large earthquakes occurred in 1575, 1737 and 1837. The periodicity of these events has been proposed as a good long-term forecasting. However, the seismological aspects of historical Chilean earthquakes were inferred mainly from old chronicles written before subduction in Chile was discovered. Here we use the original description of earthquakes to re-analyze the historical archives. Our interpretation shows that a-priori ideas, like seismic gaps and characteristic earthquakes, influenced the estimation of magnitude, location and rupture area of the older Chilean events. On the other hand, the advance in the characterization of the rheological aspects that controlled the contact between Nazca and South-American plate and the study of tsunami effects provide better estimations of the location of historical earthquakes along the seismogenic plate interface. Our re-interpretation of historical earthquakes shows a large diversity of earthquakes types; there is a major difference between giant earthquakes that break the entire plate interface and those of Mw ~ 8.0 that only break a portion of it.

1. Introduction

Recently four large earthquakes occurred in Chile: the Mw 8.8 2010 Maule in Central Chile; Mw 8.2, 2014 Iquique earthquake in Northern Chile, the Mw 8.3, 2015 Illapel earthquake in Central Chile and the Mw 7.6, 2016 Chiloé event in South Central Chile (Delouis et al., 2010; Lay et al., 2010; Moreno et al., 2012; Vigny et al., 2011; Ruiz et al., 2012; Lay et al., 2014; Hayes et al., 2014; Ruiz, S. et al., 2014; Schurr et al., 2014; Lay et al., 2016; Melgar et al., 2016; Ruiz et al., 2016; Tilmann et al., 2016; Melgar et al., 2017; Ruiz et al., 2017a), Figs. 1, 2 and 3. The first three events took place in zones identified as seismic gaps in the 1970s and 1980s (Kelleher, 1972; Nishenko, 1985). Although the seismic gap hypothesis has not been successful in predicting the time or the size of most of these events, it influenced seismic hazard analysis during several decades. The Mw 8.8 2010 Maule earthquake nucleated in the central region of the historic 1835 Concepción event, closely matching the highly coupled zone previously characterized as a mature seismic gap (Ruegg et al., 2009), but the largest slip (~16 m) was located in the northern portion of a ~500 km long rupture zone, the same area where a previous Mw 7.7 occurred in 1928 (Lay et al., 2010; Vigny et al., 2011; Moreno et al., 2012; Ruiz et al., 2012). The occurrence of the giant Mw 9.0 Tohoku earthquake of 2011 changed the assumption that events of magnitude < 8 occurred periodically in that region (Geller, 2011). The Mw 7.8 Pedernales earthquake of 2016 in Ecuador occurred in an area where probably not enough seismic slip deficit had accumulated since the last large earthquakes in 1906, 1942 and 1958 (Nocquet et al., 2017). These examples show that seismicity changes with time and that it is difficult to interpret historical earthquakes. Ruiz et al. (2017a) argue that in unpopulated regions such as Central-South Chile, large events like the 2016 Chiloé earthquake may have not been recorded in the seismic history, making it difficult to estimate seismic hazard documented in incomplete historical seismic catalogs.

The 2014 Iquique earthquake was preceded by large earthquakes in 1543, 1615, 1786 and 1877 in Northern Chile (Comte and Pardo, 1991). The 2015 Illapel earthquake occurred in a well-studied area where large events occurred in 1730, 1880 and 1943 (Beck et al., 1998). This quasi periodic sequence is reminiscent of the Parfield region in Central California where the most recent event occurred in 2004 (Bakun et al., 2005). These recurrences seem to confirm seismic gap ideas and may promote earthquake forecast based only on the time

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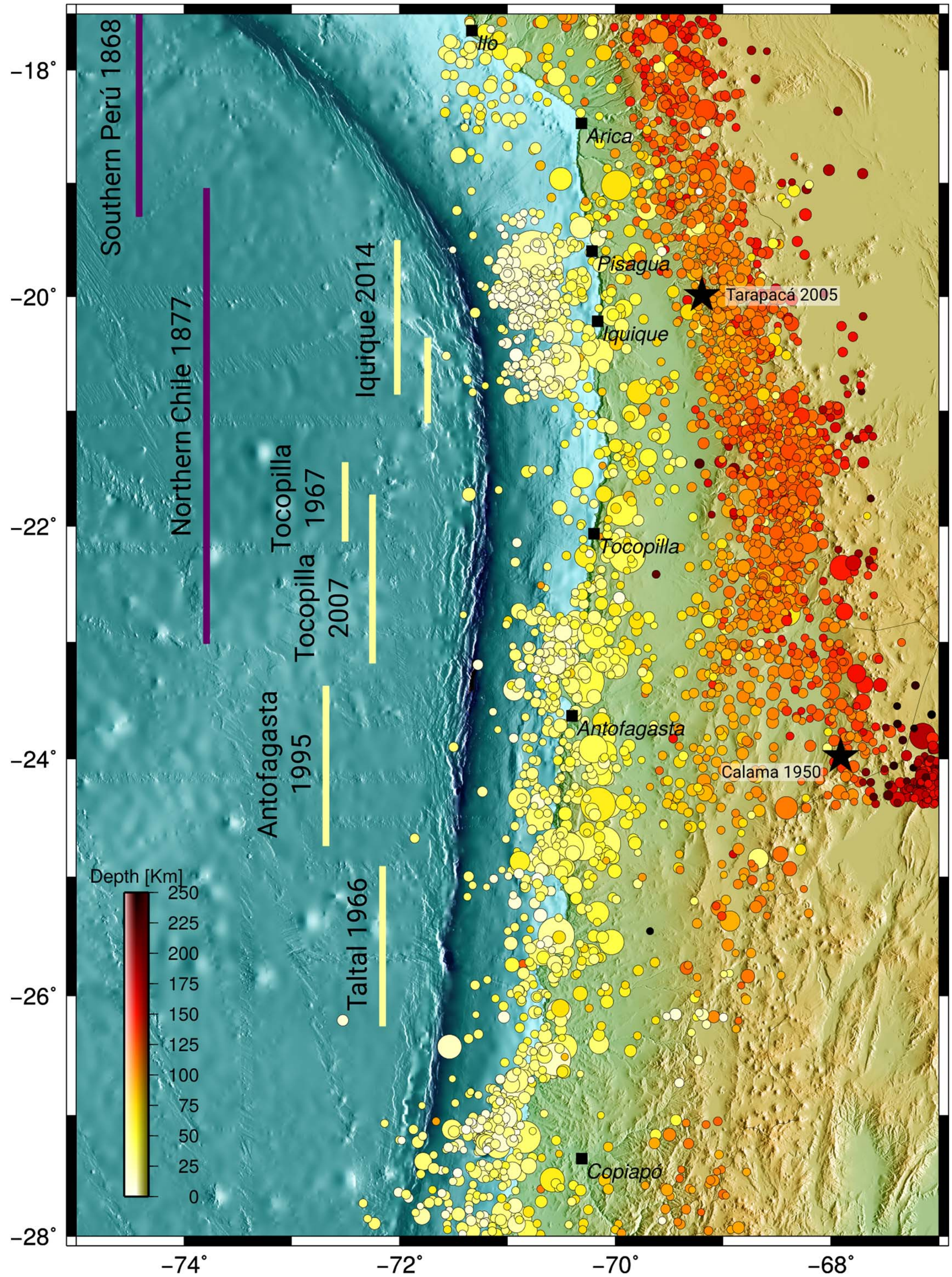

Fig. 1. Northern and North-Central Chile seismicity. Dots are epicenters of events larger than M 4.5 from the NEIC catalog from 1900 to 2017. The color bar is related with the depth of the hypocenters. The purple lines are the estimated rupture extent of giant earthquakes and the yellow color lines are the rupture lengths of smaller events that ruptured a partial zone of the interplate contact. The black stars indicate the epicenters of major intraplate intermediate depth events.

intervals of large events. A closer examination of the Chilean historical earthquake catalogs (Montessus de Ballore, 1911; Greve, 1964; Lomnitz, 1970, 2004) shows many problems related to the interpretation of magnitudes and the selection of the historical events in the catalog. The most probable reason is that the plate tectonics and seismic moment concepts did not exist when the catalogs were first made.

The rheological characterization of the plate interface between the Nazca and South-American plates, as well as the size of the tsunamis triggered by historical events allow us to the locate old events at different depths on the plate interface. Here, we propose that the classical segmentation along strike of Chilean earthquakes needs to be re-formulated taking into account the depth on the plate interface and the slip distribution associated to each of these event. We follow the proposition of Lay et al. (2012) and assigned a rupture type domain for mostly of large events. In this manuscript, we discuss the most important historical earthquakes; we review some of the

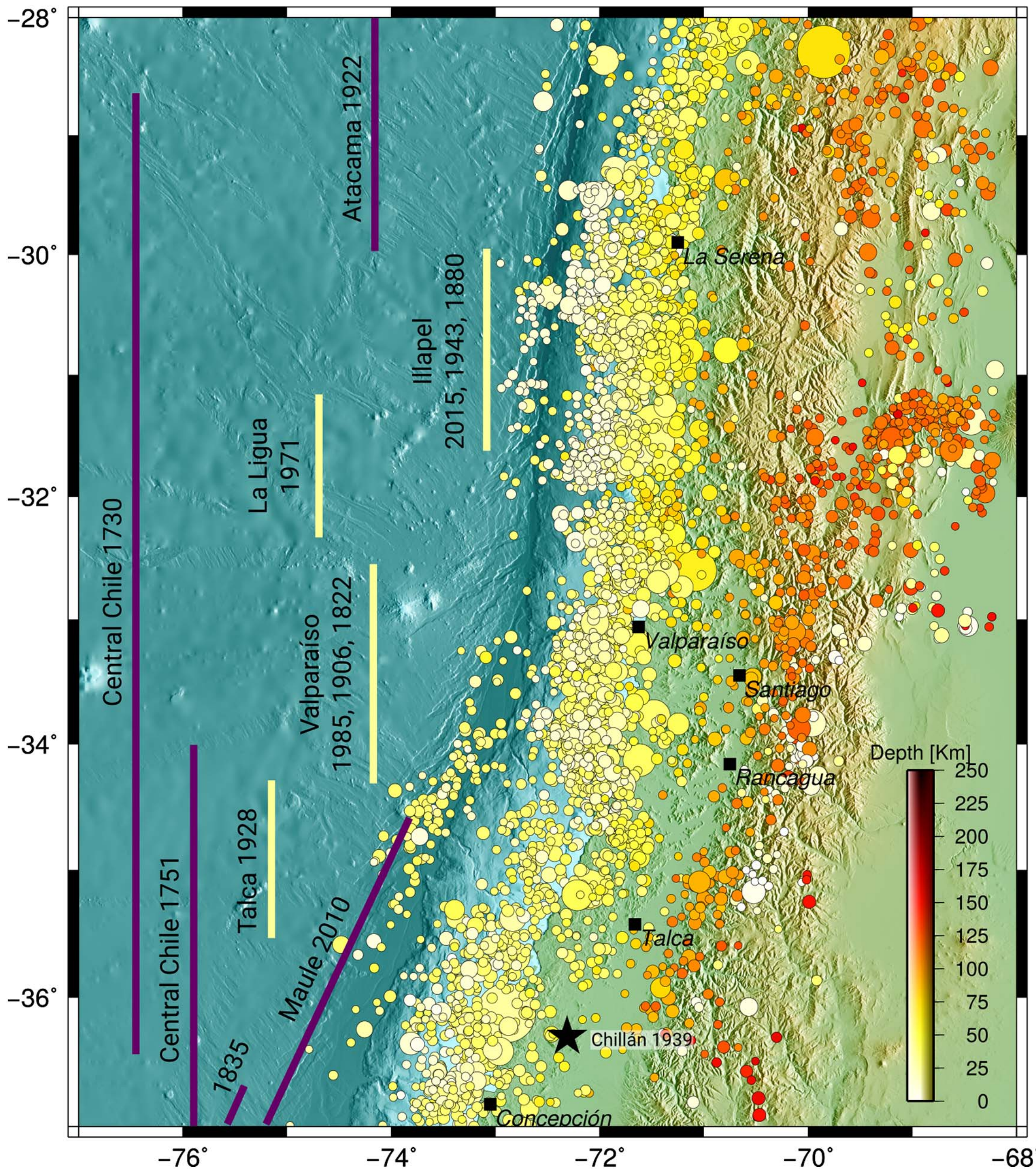

Fig. 2. North Central and Central Chile seismicity. Dots are epicenters of events larger than M 4.5 from the NEIC catalog from 1900 to 2017. The color bar is related with the depth of the hypocenters. The purple lines are the estimated rupture extent of giant megathrust earthquakes and the yellow color lines are the rupture lengths of smaller events that ruptured a partial zone of the interplate contact. The black stars indicate the epicenters of main intraplate intermediate depth events.

paleoseimological evidence, tsunami excitation and written chronicles. Then we show that subduction earthquakes present a large diversity that it is not incorporated in the traditional interpretation of Chilean seismicity. Finally we review recent megathrust earthquakes: the 2010 Mw 8.8 Maule event; the 2014 Mw 8.2 Iquique; the 2015 Mw 8.3 Illapel and the 2016 Mw 7.6 Chiloé events.

2. Historical earthquake information

2.1. Before written Chilean history. Paleo-seismology

The oral accounts about ancient earthquakes by the Chilean original population (before XV century) were not conserved, with the exception of Mapuche culture that represented earthquakes as the fight of two gods Treng-Treng and Cai-Cai vilu. Cai-Cai vilu was a snake that lived in the ocean generating large tsunamis and Treng-Treng protected the Mapuches by raising the hills and, this legend encouraged the Mapuche people to climb to the top of the hills with foods when an earthquake occurred (de Rosales, 1877; Lenz, 1912).

Recent paleoseismological studies have confirmed that tsunamigenic earthquakes were common in the Mapuche territory (South-Central Chile) and Central Chile (Cisternas et al., 2005; Dura et al., 2015; Kempf et al., 2017). The Mw 9.5 1960 Valdivia giant megathrust earthquake (Kanamori and Cipar, 1974; Cifuentes, 1989) occurred in South-Central Chile, it extended for almost 1000 km along the plate interface (Plafker and Savage, 1970; Barrientos and Ward, 1990; Moreno et al., 2009) (see Fig. 3) and produced a protracted postseismic viscoelastic relaxation observed in the regional deformation field after the event (Khazaradze et al., 2002; Hu et al., 2004; Ruiz et al., 2017a, 2017b). Paleoseismological studies made in the area (Cisternas et al., 2005; Ely et al., 2014; Cisternas et al., 2017a and references there in) identified other large tsunamigenic earthquakes similar to the 1960

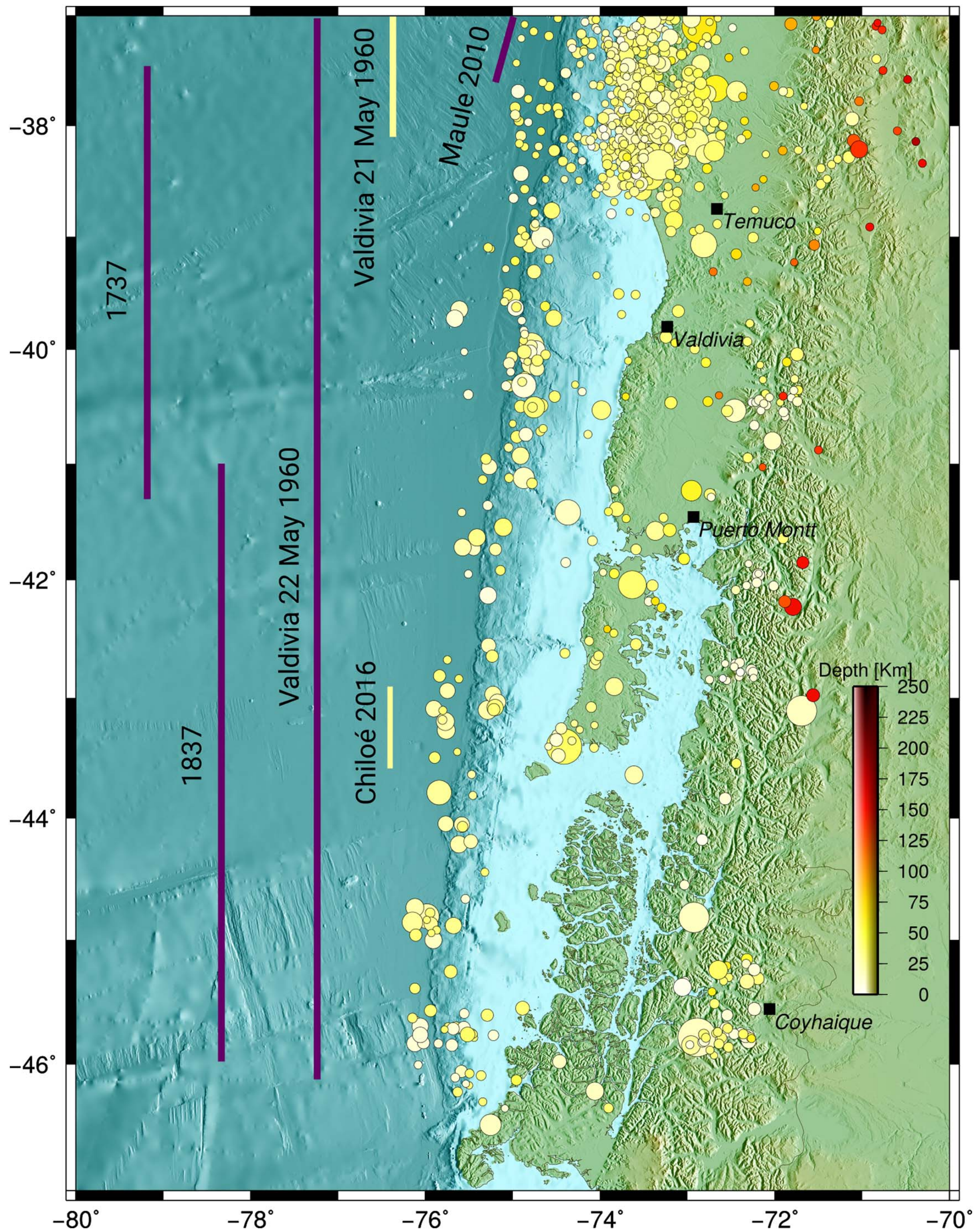

Fig. 3. South-Central Chile seismicity. Dots are epicenters of events larger than M 4.5 from the NEIC catalog from 1900 to 2017. The color bar is related with the depth of the hypocenters. The purple line is the estimated rupture extent the giant 1960 and 1737 and 1837 Valdivia earthquakes, and the yellow color lines are the rupture lengths of smaller events that ruptured a partial zone of the interplate contact.

event every 300 to 400 years, and some smaller magnitude events with shorter recurrence time similar to 1737 and 1837 earthquakes (Cisternas et al., 2017b). In Central Chile, the last tsunamigenic earthquake was in 1730, this event had an extension of > 600 km (Udías et al., 2012; Urbina et al., 2016; Carvajal et al., 2017a) (see Fig. 2). Other large tsunamigenic earthquakes have been identified in the Central Chilean coast with recurrence between 200 and 600 years (Dura et al., 2015). Finally in Northern Chile the largest tsunamigenic earthquake occurred in 1877 (see Fig. 1), previous tsunamigenic earthquake occurred between 1408 and 1499 (Vargas et al., 2005), this last event could be associated to a tsunami reported on the Japanese coast on 7 September 1420 (Tsuji, 2013).

2.2. The written earthquake descriptions of the XVI to XIX century

The historical earthquakes (XVI, XVII, XVIII centuries) were mainly reported by the settlers in correspondences with the kingdom of Spain, most of the documents concerning to the Spanish colonial administration are in the “Archivo de las Indias” in Sevilla, Spain (Udías et al., 2012; Cisternas et al., 2012). Some earthquake chronicles were written by Chilean historians, the best known of them being Amunátegui (1882), Barros Arana (1834) and Vicuña Mackenna (1869) and, since the XIX century, earthquakes were also reported by journalists of the early Chilean newspapers. Some scientists passing through Chile during the XIX and XX centuries published detailed characteristics of some specific earthquakes observed by them, e.g. Martha Graham (1824) described the 1822 earthquake in Central Chile; Fitzroy (1839) and Darwin (1851) described the 1835 earthquake which occurred in Central Chile; Gilliss (1870) described shallow events that occurred in Santiago close to the Andes Mountains, and Willis (1929) described the 1922 giant earthquake in the Atacama region. Some big Chilean earthquakes were also described in the classical book about earthquakes by Davison (1936). These historic chronicles reported damage to houses, villages, tsunami effects, apparent liquefaction and coastal uplift and subsidence. Some of the first observations of earthquake-related uplift were reported for the 1822 and 1835 earthquakes by Graham (1824) and Darwin (1851). Darwin and Fitz Roy described the coastal uplift and subsidence caused by the Concepción earthquake of 1835. Graham (1824) also described liquefaction phenomena in the coastal sands, important rise of the coastal zone during the 1822 Central Chile earthquake, and less important tsunami run-ups. The information reported by Graham, now suggests that the 1822 earthquake was an interplate event deep on the plate interface. A similar depth position along the plate interface rupture during the recent Mw 7.7, 2007 Tocopilla (Peyrat et al., 2010), Mw 7.2, 2011 Constitución aftershock of Maule 2010 (Ruiz et al., 2013) or the Mw 8.2, 1906 Valparaíso earthquake (Okal, 2005; Carvajal et al., 2017b).

The uplift and subsidence observed near coastal sites reported in the chronicles were not fully accepted during the first half of the 20th century, because there was no model of the seismic cycle. Some relevant information about vertical motions was not included in the Montessus de Ballore's books who compiled the historical earthquakes record in Chile, and was the basis of most Chilean earthquake catalogs (Greve, 1964; Lomnitz, 1970, 2004).

2.3. The Chilean Seismological Observatory, now National Seismological Center of the Universidad de Chile

At the beginning of the XXth century Valparaíso was an important port where ships from all world arrived until the Canal de Panama opened in 1914. The city of Valparaíso was severely damaged by the 1906 earthquake, especially the Almendral neighborhood, which was the main commercial and residential sector (Astroza, 2007). The destruction of important buildings encouraged the Chilean president Pedro Montt to create a Seismological Observatory in 1908 whose first director Montessus de Ballore generated periodic seismological reports (Montessus de Ballore, 1909; Cisternas, 2009; Valderrama, 2015). Montessus de Ballore deployed seismological instruments and created a network of observers along Chile that reported their perception of the ground motion (Montessus de Ballore, 1909). He made the main compilation of historical Chilean earthquakes since 1520 to 1911 in the sixteen volume book “Historia Sísmica de los Andes Meridionales abajo del paralelo XIV” (Montessus de Ballore, 1911–1916). In this work, he compiled mainly the colonial administration letters, historian texts and newspaper information. This book is the mainstay of successive compilations that summarize his work and was later complemented with data of more recent earthquakes e.g. Greve (1964); Lomnitz (1970, 2004) and Urrutia de Hazbún and Lanza Lazcano (1993).

After Montessus de Ballore's work, Federico Greve director of the Instituto de Sismologia of the Universidad de Chile (former Seismological Observatory), wrote a new compilation that summarized and completed the Montessus de Ballore (1911–1916) books including large events occurred until 1957. Greve (1964) added to the Montessus de Ballore catalog an interpretation of the structural damage using a “Chilean Seismic Intensity” scale comprising six grades, this scale was adapted to Chilean structure behavior from the Rossi and Forel intensity scale (Greve, 1949). The last three degree (IV, V, VI) are associated to damage:

IV Grade: Causes general panic; the bells ring; some loose objects and poorly built walls fall; cracks are produced in some buildings.

V Grade: Some chimneys, walls and other parts of the building are partially or totally destroyed; some houses fall.

VI Grade: General disaster; most houses fall and cracks are observed in the ground.

Lomnitz (1970, 2004), based on Montessus de Ballore (1911–1916) and Greve (1964), described the most destructive Chilean events from the seismological perspective of the 1970s, then he proposed a generic seismic magnitude for each event. After Lomnitz' first works of 1970, Barrientos (1980), Kausel (1986), Ramirez (1988), Dorbath et al. (1990) and Kausel and Ramírez (1992) worked extensively to associate seismic intensities and tsunami run up observations with the magnitude of the larger historical Chilean events. They followed the idea that the damage zone is related with the rupture area or magnitude (Gutemberg and Richter, 1956) and associated the length of the rupture with the length of isoseismal VIII. Generic magnitudes were estimated using empirical relations like:

$$\mathrm{M} = 1.62 \log L + 4.44 \qquad (1)$$

where L is the length of the isoseismal VIII (Dorbath et al., 1990).

Some specific earthquakes or zones were studied in detail, e.g. Kausel (1986) and Comte and Pardo (1991) proposed magnitudes for several Northern Chile earthquakes based on empirical relations (Barrientos, 1980; Dorbath et al., 1990 and Kausel and Ramírez, 1992). From a more quantitative approach, Abe (1979) evaluated the magnitude of tsunamigenic earthquakes in Chile since the end of the XIX century using the first tide gauges deployed in the Pacific Ocean.

3. The historical and present earthquake interpretation

In this section, we briefly describe the historical earthquakes chronicles. We divide our work in four zones: Northern Chile, North-Central Chile, Central Chile and Central-South Chile.

3.1. Northern Chile earthquakes

Northern Chile is an arid region, with few cities and sparsely populated. The zone is affected mainly by interplate events located in the contact between Nazca and South-American plates, but also by intraplate intermediate depth earthquakes and crustal events, Figs. 1 and 4. The intraplate intermediate depth region has a high rate of seismicity (Leyton et al., 2009, 2010) and in the last decades two events of Mw ~8.0 have occurred at depths around 100 km: Calama 1950 (Kausel and Campos, 1992) and Tarapacá 2005 (Peyrat et al., 2006; Delouis and Legrand, 2007; Kuge et al., 2010). Other intraplate intermediate depth events of magnitude Mw ~7.0 have been recorded in recent years with varying damage level e.g. Arica 1987 Mw 7.2; Michilla 2007 Mw 6.7 earthquake (Ruiz and Madariaga, 2011) and Jujuy Mw 6.7 earthquake (Herrera et al., 2017) (see Fig. 4). The 2005, Mw 7.8, Tarapacá intermediate depth earthquake, destroyed almost all adobe houses in the epicentral zone (Astroza et al., 2005). The completeness magnitude of CSN catalog in northern Chile is M_L ~3.5. At this cut off magnitude few crustal events are observed. The Mw 6.3 Aroma 2001 earthquake is one of the few crustal event reported (Farías et al., 2005; Legrand et al., 2007). It was also a destructive earthquake where the adobe houses collapsed in the Chusmiza town. Since 1877 several interplate thrust events of magnitude larger than Mw 7.4 have occurred in Northern Chile, e.g. Tocopilla 1967 and 2007 (Malgrange and Madariaga, 1983; Peyrat et al., 2010); Antofagasta, 1995 (Ruegg et al., 1996) and Iquique 2014 (Ruiz, S. et al., 2014; Schurr et al., 2014; Hayes et al., 2014). These events triggered small tsunamis and generated moderate structural damage (Astroza et al., 2008; Becerra et al., 2016). In spite of the high variability of earthquakes that occurred in the last century; we

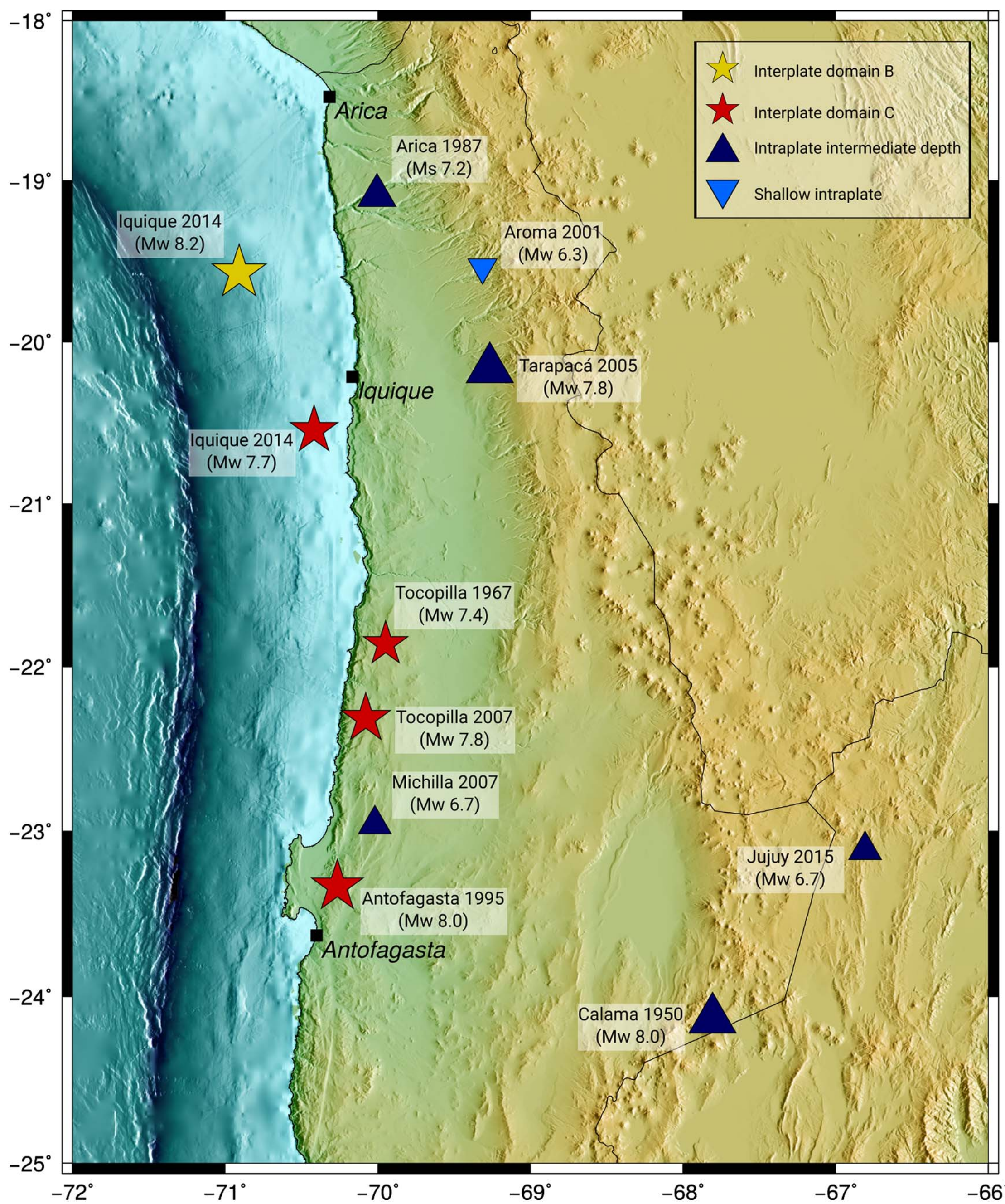

Fig. 4. Hypocenters of main earthquakes since 1900 in Northern Chile.

consider that 4 of them are the most important for the historical analysis of Northern Chile: 1543, 1615, 1768 and 1877 events. Recent paleoseismological study has identified a major slump in marine deposit, which can be associated to a major earthquake that occurred between 1409 and 1499 AD (Vargas et al., 2005); this event, as we mentioned earlier, may be associated to a tsunami on the Japanese coast on 7 September 1420 as reported by Tsuji (2013).

3.1.1. 1543 earthquake. An event that occurred in Northern Chile

There is only a brief description in Montessus de Ballore (1911–1916), who indicated that an event occurred in the Region of Tarapacá. Greve (1964), using the information reported by Montessus de Ballore (1911–1916), attributed an intensity V to it, and a possible epicenter situated between latitudes 19°S to 20°S. Finally, Comte and Pardo (1991) proposed a magnitude larger than 7.7.

3.1.2. 1615 earthquake. A destructive event for the cities of Arica and Tacna

The most complete information about this earthquake are two letters sent to the Viceroys of Peru describing the damage produced in Arica and Tacna (Montessus de Ballore, 1911–1916). Greve (1964) proposed a maximum Chilean intensity V, Lomnitz (1970) a magnitude of 7.5 and Comte and Pardo (1991) a magnitude of 7.9. Some years before, in 1604, a large earthquake occurred north of Arica, which destroyed several Peruvian cities, but also destroyed and flooded Arica prompting it to be moved to a different site (Fernandez, 2007).

3.1.3. 1768 earthquake. The event that destroyed two churchs

There is not much information about this earthquake; however Montessus de Ballore (1911–1916) associated the destruction of the Pica church (20.48°S, 69.33°W) and the damage reported in Matilla (20.53°S, 69.38°W) to a potential seismic event that occurred before

1768. Comte and Pardo (1991) proposed a magnitude larger than 7.7 for this event.

3.1.4. 1877 earthquake. A giant tsunamigenic earthquake

This was a giant earthquake, which occurred 11 years after the 1868 megathrust earthquake of Southern Perú. The Iquique 1877 megathrust earthquake triggered a large tsunami along the Chilean coast and across the Pacific Ocean. Most of the information was extensively compiled and described by Montessus de Ballore (1911–1916). Greve (1964) assigned the maximum value (VI) in the Chilean seismic intensity. Lomnitz (1970) proposed a magnitude between 8 and 8.5. Abe (1979) using tide gauge information proposed a tsunami magnitude of 9.0. Kausel (1986) proposed an isoseismal map, and he used the size of the iso-seism VIII to define the seismic rupture length, proposing a magnitude Mw 8.9. Comte and Pardo (1991) proposed a magnitude of 8.7. There were observations of coastal subsidence in Pisagua and Iquique (Vidal Gormaz, 1877; Montessus de Ballore, 1911–1916). Vidal Gormaz (1877) referred to a difference in position of the anchor of a ship in front of Pisagua, which could be interpreted as a subsidence observation.

3.1.5. 2014 Iquique earthquake in the middle of Northern Chile seismic gap

Despite the forecast made by Kelleher (1972), Nishenko (1985) and many others, an event similar to 1877 has not occurred in Northern Chile in the last 140 years, Fig. 4. On 1 April 2014 the Mw 8.2 Iquique earthquake occurred (Ruiz, S. et al., 2014; Hayes et al., 2014; Schurr et al., 2014; Lay et al., 2014). Why did the entire seismic gap not fail? What are the main new features observed in recent earthquakes in Northern Chile?

3.1.5.1. The interpretation of historical earthquakes. Of the four major events: 1543, 1615, 1768 and 1877, only 1877 was a giant earthquake. For 1615 a local tsunami is reported in Arica (Fernandez, 2007), but for 1543 and 1768 there is no information to identify them as interplate events. In particular 1768, if we interpret as a possible intraplate intermediate depth event, then the recurrence time based on assuming that these 4 events of Northern Chile were all interplate events is at least questionable.

3.1.5.2. Events magnitude Mw ≥ 7.0. After the 1877 giant event several important earthquakes have occurred, which sometimes are not considered. Events of magnitude larger than Mw 6.0 that occurred in the megathrust zone since 1900 are listed in the centennial catalog (Engdahl and Villaseñor, 2002). The large interplate events that occurred in Northern Chile were 1967 and 2007 Tocopilla and 1995 Antofagasta events of magnitude Mw 7.4, 7.8 and 8.0, respectively (Malgrange and Madariaga, 1983; Ruegg et al., 1996; Peyrat et al., 2010), Fig. 4. During the last century high rate seismicity is reported, but it is difficult to compare this seismicity with the previous historical catalog, since only large damaging events are cited in the chronicles.

3.1.5.3. Dynamic inter-relation between earthquakes. The loading and unloading process of interplate events is a dynamic process that it is controlled by a complex constitutive law, depending of the friction, temperature, slip weakening, etc. The Mw 7.8, 2005 Tarapacá earthquake, was an intraplate intermediate depth event (Peyrat et al., 2006; Delouis and Legrand, 2007). Its epicenter was located at the same latitude as Iquique, where the UAPE GPS stations is installed since ~2000. Ruiz, S. et al. (2014) showed that the velocity vector trend changed at UAPE after the 2005 Tarapacá earthquake proposing that this event might have triggered a very slow slip event that accelerated some weeks before the Iquique main-shock. Bie et al. (2017) and Jara et al. (2017) also proposed a relation between Tarapacá 2005 earthquake and 2014 Iquique sequence. Finally Bouchon et al. (2016) reported an increase of intraplate intermediate depth events before the Iquique earthquake as in several other large magnitude subduction earthquakes.

3.1.5.4. Possible Slow slip event. The 2014 Iquique earthquake may have been preceded by a slow slip event that could be observed in the GPS coastal stations at least 8 months before the main event (Ruiz, S. et al., 2014; Kato et al., 2016; Socquet et al., 2017). The slow slip event stressed an inactive reverse crustal fault located in the upper plate triggering a foreshock of magnitude Mw 6.7 on 16 March 2014 and also triggered the main Mw 8.2 earthquake. Some authors proposed alternative interpretations such as: the shallow event triggered the Mw 8.2 earthquake (González et al., 2015), or that precursory slip was only due to cumulative co-seismic moment released by plate interface foreshocks (Schurr et al., 2014; Bedford et al., 2015). Unfortunately, both silent and coseismic slip produce similar effects on the coastal GPS antennas, so that the interpretation must be based on very careful analysis.

3.1.5.5. Deep position. The recent events that have occurred in Northern Chile have different depth extent along the megathrust. Following the notation proposed by Lay et al. (2012). Tocopilla 2007 and probably Tocopilla 1967 occurred on the deep plate interface, Domain C. Iquique 2014 took place in the middle of the plate interface (Domain B) and the main Mw 7.7 aftershock of 3 April 2014 occurred deeper than Iquique 2014 (Domain C). On the other hand, foreshocks and aftershocks of Iquique with magnitude larger than Mw 4.5 occurred near of the trench (Domain A) (León-Ríos et al., 2016; Cesca et al., 2016). Thus we observe events across the entire plate interface. A possible tectonic differentiation along dip has been associated with the geometry of the Nazca plate (Contreras-Reyes et al., 2012) or differences in the tectonic fore-arc which have been detected mainly by anomalous gravity and seismic profiles (Álvarez et al., 2015; León-Ríos et al., 2016), for example near the trench the eroded and fractured wedge and basement rock of the south American plate (Contreras-Reyes et al., 2012; Geersen et al., 2015) probably control the seismic rupture, we will consider this topic in the Discussion.

4. North-Central Chile earthquakes

This segment, stretching from 23°S to 30°S, encompasses the Antofagasta and Atacama regions of Chile which are mostly desert with a very low population. Information about earthquakes before the 19th century is limited and concentrated around the cities of Copiapo-Caldera and La Serena (Fig. 5). The northern limit of the region is the city of Antofagasta founded in the middle of the 19th century. For this reason the information about past events is scarce and therefore incomplete. For practical purposes we will split the region into two separate segments: the Antofagasta segment from 23 to 26°S and the Atacama segment below 26°S. In the first segment there was practically no historical information before the 19th century. In contract with all the rest of Chile no giant earthquake of Mw close to 9 is known to have occurred in this region. Until the Mw 8.0 Antofagasta earthquake of 1985 (Ruegg et al., 1996, Delouis et al., 1997, Pritchard et al., 2002 and Chlieh et al., 2004) the only other large event to have hit this segment was the 28 December 1996 Taltal earthquakes of magnitude Mw 7.7 studied by Deschamps et al. (1980). Smaller Mw 7 events occurred in the 19th and 20th century but their magnitudes are subject to large errors. Thus, the Antofagasta segment of the subduction zone is considered by many as an atypical segment in which only moderately large events have occurred in the past, see Fig. 5. An important question is whether a large megathrust event may ever occur here in the future.

4.1. The Atacama earthquakes of 1922 and 1819

The second segment of North-Central Chile was broken on 11 November 1922 by an event of magnitude 8.5. This earthquake is one of the two giant earthquakes that occurred in Chile in the 20th century. In spite of a complete field survey by Willis (1929) the rupture zone and magnitude of the event remained very poorly known until the late 90s.

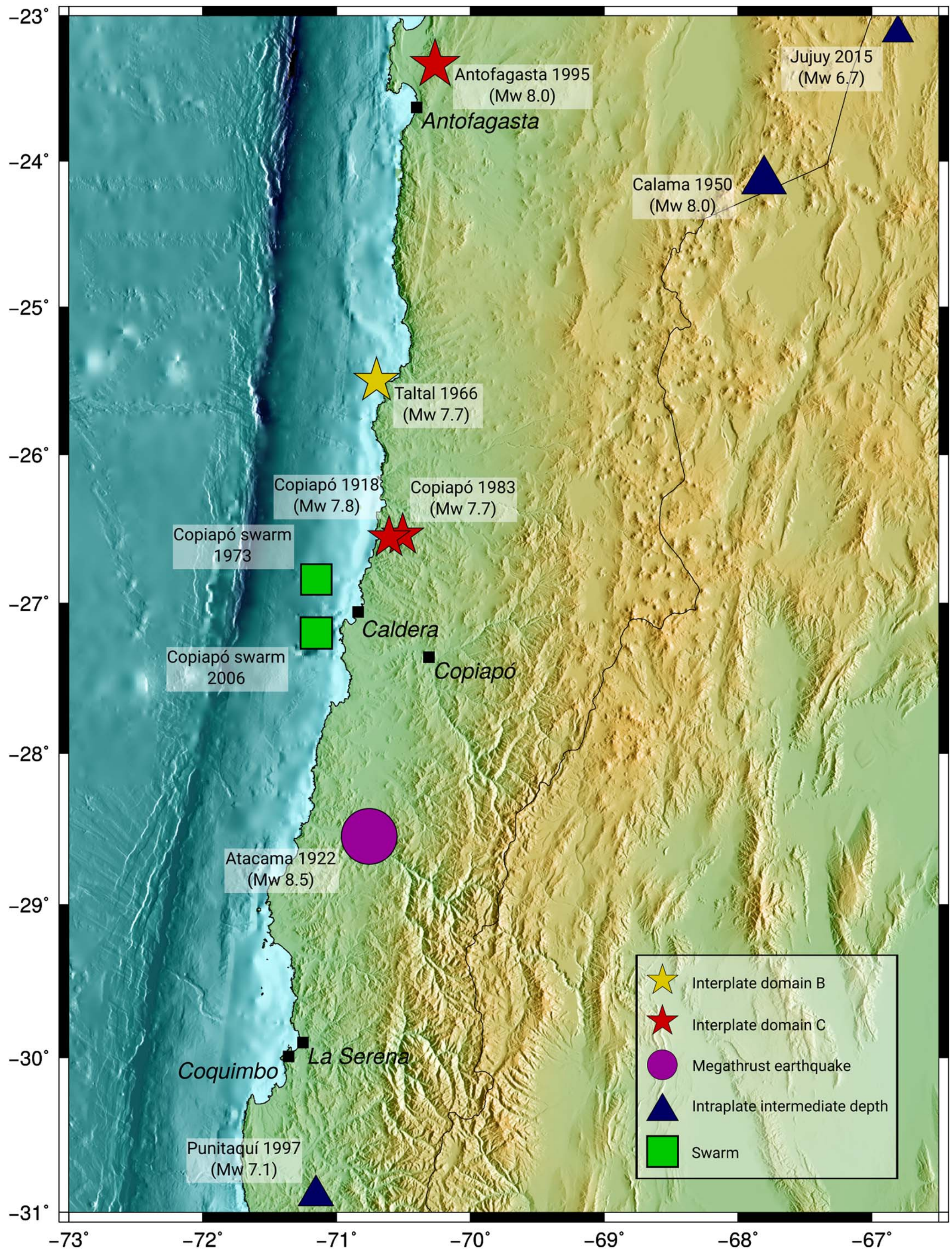

Fig. 5. Hypocenters of main earthquakes since 1900 in North-Central Chile.

Still today this event has a magnitude varying from 8.0 to 8.5 in worldwide catalogs, Gutenberg and Richter proposed a location at 70 km depth and attributed it a magnitude of 8.3. More work on it is certainly required, but fortunately Abe (1979) and Beck et al. (1998) computed the size of the event from tsunami and seismic data, respectively. Abe (1979) attributed a tsunami magnitude of 8.7 and an Mw = 8.5. This tsunami data was confirmed by the work by Soloviev and Go (1976) who collected a large number of tsunamic observations along Chile and the Pacific Ocean. The tsunami produced by the 1922 Atacama earthquake reached the Japanese Islands where Tsuji (2013) reported tsunami heights of up to a meter at Oofunato off the Miyagi prefecture of Northern Japan. Beck et al. (1998) restudied this event using body waves recorded at the De Bilt station in Holland (DBN). Although this station is at a distance of 99° from the hypocenter, beyond the core shadow, they could determine a duration 75 s for the rupture which is expected for a Chilean earthquake of magnitude Mw > 8.5. Because the signal at DBN is diffracted they could not compute Mw, nor the depth of the event. The main conclusion for this event is that it was without doubt a giant event that ruptured the entire plate interface for a length of at least 300 km and generated a great tsunami that produced extensive damage to the Chilean coast, especially to the coast line from Caldera to Coquimbo where it reached 7 m on average. The damage near Coquimbo was documented by many photographs from the local press in La Serena (El Día journal, unknown date).

Many magnitude 7 or similar earthquakes have been reported in the literature documenting seismic events in Atacama. Of these, two capture our attention. A major event occurred on 11 April 1819 that according to Abe (1979) had a tsunami magnitude type 2 but for which he could not compute a modern magnitude. This event is very interesting because it was preceded by several large earthquakes in its epicentral zone on 3 and 4 April. These events were discussed by Greve (1964). Lomnitz (2004) assigned a magnitude of 8.5 to the largest one; this seems to be based on reports of local tsunami and extensive damage to the city of Copiapo, and we feel that the magnitude was probably smaller. The two major foreshocks of the 1819 event are also interesting because the 1 April 2014 event of Mw 8.2 in Iquique had a long series of foreshocks that peaked with an Mw 6.7 earthquake on March 16, two weeks before the main event. Several other Mw 7.0 events near Copiapo are reported in the literature including the events of 5 October 1959 and 18 December 1918. All of them are discussed by Greve (1964) and Lomnitz (2004). The occurrence of the 1918 events is also discussed by Beck et al. (1998). The most recent large magnitude event occurred on 4 October 1983, Pacheco and Sykes (1992) proposed a magnitude Mw 7.7 and the centennial catalog located at $-26.541°$ and $-70.504°$, Comte et al. (2002) reported it and assigned it a source length of about 150 km that may be exaggerated. We suggest that this event was a deep plate interface event (Domain C), Fig. 5 and Table 2, similar to the Tocopilla earthquake of 2007.

4.2. The Antofagasta earthquake of 1995

This event ruptured on 31 July 1995 from roughly the Mejillones peninsula North of the city of Antofagasta for > 150 km along the coast. This earthquake was the first to be observed using static GPS vectors and InSAR interferometry methods (Pritchard et al., 2002 and Chlieh et al., 2004) producing a detailed distribution of slip that confirmed initial results from classical body wave modeling by Ruegg et al. (1996) and Delouis et al. (1997). The July 1995 earthquake was preceded by several earthquakes in the Antofagasta region. These include the Mw 7.6 event of 5 March 1987 in the southern end of the 1995 rupture, under the Cerro Paranal observatory. The 1995 event was also preceded by a local increase of seismicity near the epicentral area at the Mejillones Peninsula; this activity started with an Mw 6.2 event on 12 October 1994. These observations indicate an earthquake of Mw 8.0 that ruptured the deeper part of the plate interface, the area of the rupture coincides also with the aftershock distribution reported by Delouis et al. (1997). There is however an observation reported by Ihmlé and Madariaga (1996) that may favor rupture that reached closer to the trench. These authors observed large water reverberations after the P wave arrival. These reverberations are excited by P waves trapped in the oceanic water layer above the rupture zone. Recent observations of reverberations indicate that these are excited only by earthquakes whose ruptures reach close to the trench. On the other hand the tsunami excited by the earthquake was only 1.5 m near the source, favoring a deeper source.

4.3. The Taltal earthquake of 28 December 1966

The Taltal region is situated just south of the rupture zone of the Antofagasta earthquake of 1995. This region has a longer seismic history than Antofagasta as reported by Montessus de Ballore (1911–1916) and Greve (1964). A search in the Centennial catalog of Engdahl and Villaseñor (2002) retrieves at least two events with Ms close to 7: these are the events of 8 June 1909 and 13 July 1936 reported in Greve's catalog. Another large event in the area in 1887 was described by Montessus de Ballore (1911–1916). Finally, the 28 December 1966 was an event of magnitude Mw 7.7 characterized by a short total duration of the source process of 13 s, the aftershocks and slip distribution found by Deschamps et al. (1980) confirm that the 1966 event was a thrust earthquake situated on the deeper part of the plate interface.

Thus we conclude that the Antofagasta segment is the only region in continental Chile where no giant earthquake is known to have occurred in historical times. In earlier studies by Kelleher (1972) it was assumed that the 1877 Tarapaca earthquake in Northern Chile may have ruptured all the way to the Taltal area. This assumption is probably incorrect as carefully demonstrated by Kausel (1986) who studied the 1877 event with modern techniques and concluded that it did not break south of the Mejillones Peninsula, north of Antofagasta. Thus, it seems that the Antofagasta segment never had a giant earthquake. A possible way to estimate the likelihood of a large megathrust event occurring in this area is to look at geodetic coupling of the plate interface. According to Metois et al. (2016) the coupling in Southern Antofagasta is near the maximum but, unfortunately, as shown in Fig. 3 of Metois et al. (2016) the data in the region of Antofagasta had an obvious gap. Thus, the problem remains about what happens with slip near the trench in this region. Is it slipping silently or episodically? Resolving this problem is difficult because geodetic methods, for the moment at least, do not have enough resolution near the trench.

4.4. Copiapo swarms

In recent times, the Atacama region has been quiet of large magnitude events (Mw > 8.0), but at least a couple of swarms with maximum magnitude 6 have been observed in 1973 and 2006 (Comte et al., 2002; Holtkamp et al., 2011). The latter authors identified a smaller swarm in 1979. The relation of these swarms to the general seismogenic processes in the area needs to be elucidated because swarms occur very often at several places along the plate interface in Chile. Holtkamp et al. (2011) made a detailed study of the 2006 swarms and the associated ground deformation determined with InSAR interferometry. Their conclusion is that the ground deformation produced by the swarm did not require additional slow slip at the plate interface. Since the availability of the new CSN seismic network in Chile several other swarms have been detected in Chile in several sites along the plate interface. The most conspicuous occurred intermittently since mid 2013 on the middle of the plate interface between Pisagua and Iquique, eventually leading to the Iquique earthquake of 2014 (Ruiz, S. et al., 2014). A similar swarm occurred in front of Valparaíso in April 2017 that led to a medium size earthquake of Mw 6.9 on 24 April 2017 (Ruiz et al., 2017b). The occurrence of swarms in Chile and their relation to the seismicity of the plate interface remains an interesting subject, especially distinguishing between swarms and precursory foreshocks.

5. Central Chile earthquakes

Central Chile is a very active region, old giant earthquakes triggered large tsunamis with recurrence of 200 to 600 years (Dura et al., 2015), Fig. 2. In the last 4 centuries two large earthquake of magnitude M ~9.0 occurred in 1730 and 1751 (Udías et al., 2012) and recently in the southern zone occurred the Mw 8.8 Maule 2010 earthquake (Vigny et al., 2011; Moreno et al., 2012). Before and after 1730 a series of smaller magnitude events (Mw ~8.0) occurred (Comte et al., 1986; Ruiz et al., 2011). As in northern Chile three types of events have been frequent in the last century in Central Chile: interplate on the plate interface, intraplate intermediate depth and shallow events Figs. 2 and 6. The largest intraplate intermediate depth earthquake was Chillán 1939 Mw 7.8, the most destructive earthquake in Chile (Beck et al., 1998; Astroza et al., 2002), other large earthquakes that generated moderate damage in Santiago occurred in 1927 Mw 7.2 and 1945 Mw 7.1 (Barrientos et al., 1997). The largest crustal events have mainly occurred in the mountain range: Las Melosas 1958 Mw 6.3 (Sepulveda et al., 2008; Alvarado et al., 2009) and Curicó 2004, Mw 6.4. However, one of the largest Maule 2010 aftershocks occurred in the coastal zone, the Pichilemú earthquakes of magnitude Mw 7.0 and Mw 6.9 (Farías

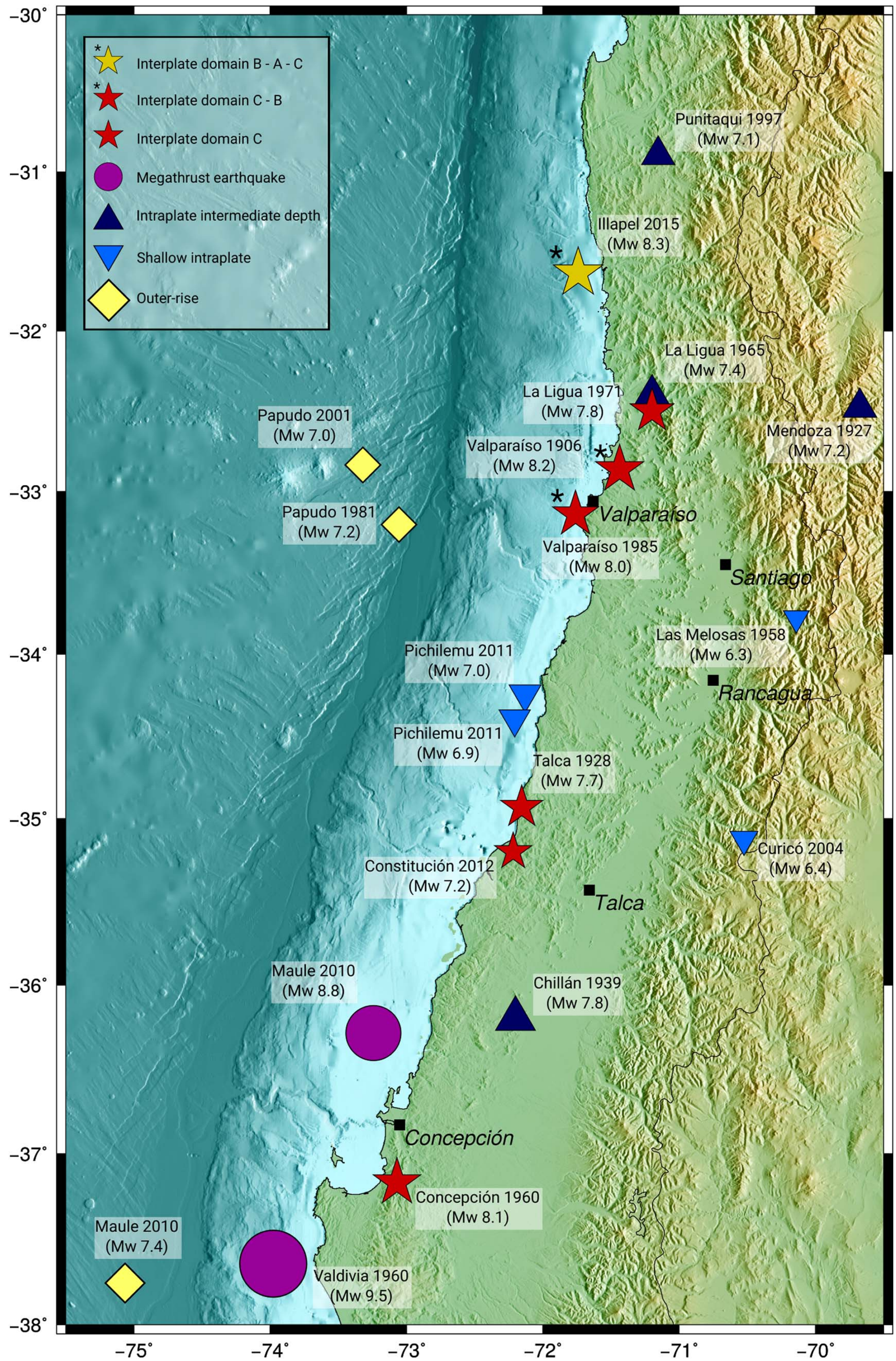

Fig. 6. Hypocenters of main earthquakes since 1900 in Central Chile.

et al., 2011; Ruiz, J.A. et al., 2014). Here, we describe briefly the reported megathrust events, and the previous events of magnitude Mw ~8.0 that occurred in the zones where the 2015 Illapel and 1985 Valparaiso events occurred.

5.1. 1730 and 1751 large mega-thrust earthquakes in Chile Central

The 1730 and 1751 are the largest events reported in the chronicles which generated ground level changes, tsunamis and that cities were relocated (Montessus de Ballore's works, Udías et al., 2012). The rupture extent of both events is larger than 600 km. The 1751 tsunami destroyed old Concepción (now Penco), so that the population decided to move to the present-day location of Concepción. They looked for a higher, inland place, moving next to the Biobio River a safer place for tsunamis (Udías et al., 2012), but a place characterized by site effects that amplified most of the damage in Concepción during the recent Maule 2010 event (Montalva et al., 2016). Udías et al. (2012) propose that this tsunami is the largest in central Chile for the last 5 centuries destroying the main settlement on the Juan Fernández Islands (675 km offshore), killing several people (Montessus de Ballore, 1911–1916), and flooded rice fields in Japan (Tsuji, 2013). The uplift detected in recent paleoseismological studies (Ely et al., 2014) suggests that the southern extension of the rupture zone is larger than that of the 2010 Maule mega-earthquake. The 1730 M-thrust earthquake caused severe structural damage for along ~1000 km from 28°S to Concepción 38°S (Udías et al., 2012; Urbina et al., 2016; Carvajal et al., 2017a). The tsunami devastated the Chilean coast and was also reported in Japan (Soloviev and Go, 1976; Tsuji, 2013). The inferred magnitude, for the modern authors, is larger than M 9.0 (Udías et al., 2012; Carvajal et al., 2017a), in contrast with the older works of Lomnitz (1970, 2004) that proposed an event of magnitude between 8.5 and 9.0. Just as for other historical earthquakes, the Montessus de Ballore (1911–1916) report on the 1730 earthquake did not describe uplift or subsidence, and in the other chronics little information exists about changes in land level (Carvajal et al., 2017a).

5.2. 1835. Darwin's earthquake

This earthquake was well documented by Fitzroy (1839) and Darwin (1851), who arrived in the epicentral zone soon after the mainshock. They reported mainly coastal uplift, tsunami inundation and observed damage. The northward extension of the rupture of this event appears to be less than that of the 2010 Maule earthquake despite similarities in uplift patterns observed in the southern part of the rupture (Wesson et al., 2015). Most of the rupture lengths proposed for this event extend from 35.5°S to 37°S, so that it stops in the North before the zone of maximum slip of the 2010 earthquake. The tsunami run-up extended along Central-South Chile with amplitudes lower than the run-ups observed in 2010 (Ely et al., 2014).

5.3. 1928 and 1906, deep plate interface earthquakes

1928 was an interplate event of magnitude Mw 7.7 (Pacheco and Sykes, 1992; Beck et al., 1998), which generated a moderated damage in adobe houses of nearest towns (Astroza et al., 2002) and did not trigger tsunami or damaging run-ups. We propose that the rupture of this event is located near the bottom of the plate interface in the Domain C, similar to Tocopilla 2007. Finally, we highlight that the 1928 Talca event had similar magnitude to that of the intraplate intermediate depth Chillán 1939 earthquake (Beck et al., 1998) but its destructiveness was much less (Astroza et al., 2002).

The magnitude proposed for the 1906 Valparaiso earthquake by Gutemberg and Richter (1956) was 8.6, the same magnitude was proposed by Lomnitz in his works. Recent studies show that this event had a smaller magnitude, Okal (2005) proposed a magnitude of Mw 8.2 and Carvajal et al. (2017b) confirm this magnitude value, they did not observe large tsunami or run-up, and proposed a magnitude range from Mw 8.0 to Mw 8.2. The largest damage of this event was located in the Almendral neighborhood of Valparaíso a zone composed by sands and artificial soil deposits (Astroza et al., 2008). Some coastal uplifts were reported by Steffen (1907).

5.4. 1880 and 1943. Earthquakes in the Illapel region

This zone was proposed as a possible seismic gap because of the 1730, 1880 and 1943 earthquakes (Nishenko, 1985), despite the significant difference in the length rupture of 1730 in comparison with others events. In September 2015 the Illapel earthquake of magnitude Mw 8.3 occurred in the same sector.

5.4.1. The 1880 earthquake

This earthquake was well described by Machado (1910) and Montessuss de Ballore (1911–1916) summarized Machado's work and proposed Mercalli seismic intensities for the damaged towns: VIII intensity at Ovalle, Quelun, Illapel, Salamanca, Llimpo, Chellepín, Cuncumén, Chalinga, Hierro Viejo, Petorca y Chincolco. The intensities are lower at more distant sites. Greve (1964) assigned a maximum intensity V in the Chilean scale. Lomnitz (1970, 2004) assigned magnitude 7.5 for this earthquake and highlighted a "Deep submarine cable break off the Limarí-River", information described in Machado (1910) when he described the high tides observed in Coquimbo.

5.4.2. The 1943 event

On 6 April 1943 a reverse mechanism earthquake of magnitude Mw 7.9 (Beck et al., 1998) was felt in a large area of Central Chile, however the zone of damaged towns was limited (Greve, 1964). The Illapel earthquake took place in a sparsely populated zone of Central Chile. Greve (1964) proposed an isoseismal map in the context of the maps that Greve generated for all Chilean earthquakes, showing little destruction in comparison with other events. The journals reported briefly on this event. Little information on the tsunami was reported, only a minor damage to a vessel located in Los Vilos (Lomnitz, 1970). We highlight the information of the Zig-Zag journal, where they photographed an important run up of sea water in the bay of Coquimbo, which fortunately at this time was not populated. A wide range of magnitudes has been reported for this event since, Lomnitz proposed a magnitude M 8.3. We prefer the Mw 7.9 reported by Beck et al. (1998) who modeled the teleseismic P waves. The location of this event along the plate interface is difficult to elucidate, however the inferred small tsunami and small structural damage favor the idea of an event located in the middle of the plate interface (Domain B).

5.5. The Central Chile Mw ~8.0 earthquakes

Central Chile between 30°S and 35°S is a very active seismic zone where a large diversity of subduction earthquakes have occurred in the last 50 years, Fig. 6. Before 1985 Valparaiso and 2015 Illapel earthquakes, the largest events were: the 28 March 1965 La Ligua intraplate intermediate depth event Mw 7.4 (Malgrange et al., 1981; Astiz and Kanamori, 1986); 9 July 1971 La Ligua interplate earthquake of magnitude Mw 7.8 occurred near the bottom of the contact zone (Malgrange et al., 1981; Astiz and Kanamori, 1986); 16 October 1981 outer rise earthquake of magnitude Mw 7.2 (Astiz and Kanamori, 1986) and 1997 Punitaqui intraplate intermediate depth earthquake Mw 7.1 (Lemoine et al., 2001; Pardo et al., 2002). Interestingly, one the first physical relations among outer-rise, interplate and intraplate intermediate depth was proposed considering these Chilean events (Malgrange et al., 1981; Malgrange and Madariaga, 1983; Astiz and Kanamori, 1986; Lemoine et al., 2001 and Gardi et al., 2006). This hypothesis has now started to be verified thanks to the data recovered from GPS antennas in Chile and the lower magnitude threshold of seismological catalogs (Ruiz, S. et al., 2014; Bouchon et al., 2016; Ruiz et al., 2016, 2017a; Bie et al., 2017; Jara et al., 2017).

5.5.1. Mw 8.0, 1985 Valparaíso earthquake

The 1985 Valparaiso earthquake had a complex rupture. Foreshocks started 10 days before the mainshock, the precursory events were located in a compact zone near the hypocenter of the 3 March 1985 main event of magnitude Mw 8.0 (Comte et al., 1986). The rupture of the main-shock was modeled by several authors using teleseismic data (Christensen and Ruff, 1986; Korrat and Madariaga, 1986; Choy and Dewey, 1988) and by near-field strong motion records (Ruiz et al., 2011). A slip distribution was also proposed by Barrientos (1988) who inverted the reported permanent near-field deformation and by Mendoza et al. (1994) who used seismological data. The estimated slip distributions differ by several kilometers along dip, Mendoza et al. (1994) solution is located nearer of the trench than that of Barrientos (1988), who located slip near the bottom of the plate interface. We proposed that the Barrientos (1988) solution is the more likely location of this event. Thus, Valparaiso 1985 earthquake corresponds to interplate event located in the middle and deep zone of plate interface (Domain C and B). Recently an event Mw 6.9 occurred in the same place where 3 March 1985 earthquake nucleated, the Mw 6.9 24 April 2017 event was preceded by an intense seismic activity, which was combined with a slow slip event (Ruiz et al., 2017b).

5.5.2. 2015 Illapel earthquake

The Illapel earthquake was a very large event of magnitude Mw 8.3 well recorded by the new CSN network. Also several GPS campaign points deployed since 2004 (Vigny et al., 2009) give important information about the crustal deformation in the region (Ruiz et al., 2016; Klein et al., 2017). This event triggered a small tsunami that affected mainly the Coquimbo bay where in the last decades civil infrastructure had been built in the flood zone. Several works have tried to resolve the proximity of slip distribution to the trench using tsunami and teleseismic data (Melgar et al., 2016; Heidarzadeh et al., 2016; Li et al., 2016; Lee et al., 2016; Satake and Heidarzadeh, 2017 and reference there in). Lay et al. (2016) discuss the complexity in the seismological data by the influence of water phases generated by the Illapel earthquake in the rupture near of the trench. Anyway, it is difficult to model the structure and rheology of the zone near trench, characterized by a small frontal prism and an outermost forearc block composed by eroded and fractured volcanic rocks (Contreras-Reyes et al., 2014, 2015). The largest slip is concentrated in the middle zone of the contact with an small zone that reaches the bottom of the plate interface (Ruiz et al., 2016; Tilmann et al., 2016; Grandin et al., 2016; Shrivastava et al., 2016; and many others). Unfortunately none of the > 40 works about Illapel proposed by different groups reproduces the observed three main energy arrivals in the strong motion records of the near field zone (Ruiz et al., 2016), showing that the present state of the art only reproduces correctly the long period waves. The rupture of 16 September 2015 was somewhat similar to those of the previous 1880 and 1943 events. The 1880, 1943 and 2015 events triggered a small tsunami in Los Vilos and Coquimbo bay. However, 1943 was an event of magnitude Mw 7.9 (Beck et al., 1998) lower than 2015 Mw 8.3; which was confirmed by Tilmann et al. (2016) who studied the seismograms of both events. Poli et al. (2017) proposed that the Nazca plate in this zone is penetred by hydrated fracture zones, which could have acted as barriers for Illapel 2015 and maybe the older events.

5.6. 2010 Maule megathrust earthquake

On 27 February 2010 a giant earthquake of magnitude Mw 8.8 occurred in a zone where a large event of magnitude Mw 8.5 was anticipated (Campos et al., 2002; Ruegg et al., 2009; Madariaga et al., 2010; Kanamori, 2015). The event ruptured a 500 km length segment of the plate interface in an area where two large events had occurred in 1835 and 1751. The rupture area of 2010 is definitely longer than that of 1835 and seems similar to the rupture of the 1751 megathrust event. The 2010 event was well recorded by GPS stations deployed by Chilean, French, German and others international groups (Vigny et al., 2011; Moreno et al., 2012) and some accelerographic stations of the Universidad de Chile, that unfortunately did not have absolute time recording (Ruiz et al., 2012). This mega-earthquake triggered a large tsunami (Fritz et al., 2011) and the main destruction was concentrated in adobe houses (Astroza et al., 2012; Leyton et al., 2013). The area with the largest slip distribution was located near the northern part of the rupture (Delouis et al., 2010; Lay et al., 2010; Vigny et al., 2011; Koper et al., 2012; Ruiz et al., 2012; Moreno et al., 2012; Lorito et al., 2011; Lin et al., 2013; Yue et al., 2014 among many others). The main difference between all the proposed slip distributions concerns the trench-ward propagation of the rupture. Recently, Maksymowicz et al. (2017), using difference swath bathymetric data, proposed that the Maule rupture is compatible with slip extending to, at least, ~6 km from the deformation front at the trench. This result is consistent with those of Yue et al. (2014), Yoshimoto et al. (2016) and others, which used the tsunami data to better define the near trench rupture. The deep contact rupture was well constrained by the inversions that used the GPS coseismic data recorded in the coastal zone (Vigny et al., 2011; Moreno et al., 2012). The 2010 earthquake triggered large aftershocks: an outer-rise Mw 7.4 event that occurred just 1.5 h after the Maule mainshock (Ruiz and Contreras-Reyes, 2015); the shallow normal intraplate Pichilemu aftershocks of magnitude Mw 7.0 and Mw 6.9 (Farías et al., 2011; Ryder et al., 2012; Ruiz, J.A. et al., 2014); the 2 January 2011 Mw 7.1 event located in the southern zone of the Maule rupture, with a bimodal rupture from the interplate contact to the shallow intraplate area (Hicks and Rietbrock, 2015); and the 25 March 2012 Mw 7.2 an interplate event located near of bottom of the seismogenic contact (Ruiz et al., 2013). The lower magnitude aftershocks were mainly located surrounding the largest slip zones (Rietbrock et al., 2012). In summary, the Maule 2010 event was the first giant earthquake that we can study using modern seismological data in the Chilean subduction zone, the previous giant megathrust earthquake was Valdivia 1960 Mw 9.5 which saturated most of seismological records.

The extensive zone affected by the Maule earthquake had not experienced large destructive earthquakes in several decades. The older houses in small towns were built using adobe and most churches were built using combined adobe, timber and stones. This construction type allows us to compare directly with the damage reported in the chronicles. Astroza et al. (2012) described in detail the destruction of these towns. The main characteristic of observed damage is that the churches, by their type of architecture, were always the most heavily damaged during Maule 2010. Astroza et al. (2012) proposed that the main damage correlated with the largest slip observed in the northern zone of the Maule rupture. These new observations may allow us to calibrate the damage described in old chronicles to correlate better with the length and magnitude of historical giant earthquakes in Chile.

6. South Central Chile

In the last 50 years, until the Maule earthquake 2010, deformation of south Central Chile was dominated by the postseismic deformation of the Mw 9.5, Valdivia megathrust earthquake (Plafker and Savage, 1970; Cifuentes, 1989; Barrientos and Ward, 1990; Klotz et al., 2001; Wang et al., 2007; Moreno et al., 2009; Ruiz et al., 2017a), see Figs. 3 and 7. South Central Chile was a scarcely populated region where probably some events of magnitude around 7.0 may not have been reported in the historical chronicles (Ruiz et al., 2017a). Nishenko (1985) proposed that 1575, 1737, 1837, and 1960 were similar events with an average repeat time of 128 ± 62 years. However, since Cisternas et al. (2005), it has been discovered that Southern Chile earthquakes possess a large diversity of rupture size (see Cisternas et al., 2017a and references there in). The 1575 giant earthquake could be a giant event similar to 1960. The 1737 earthquake was an event located

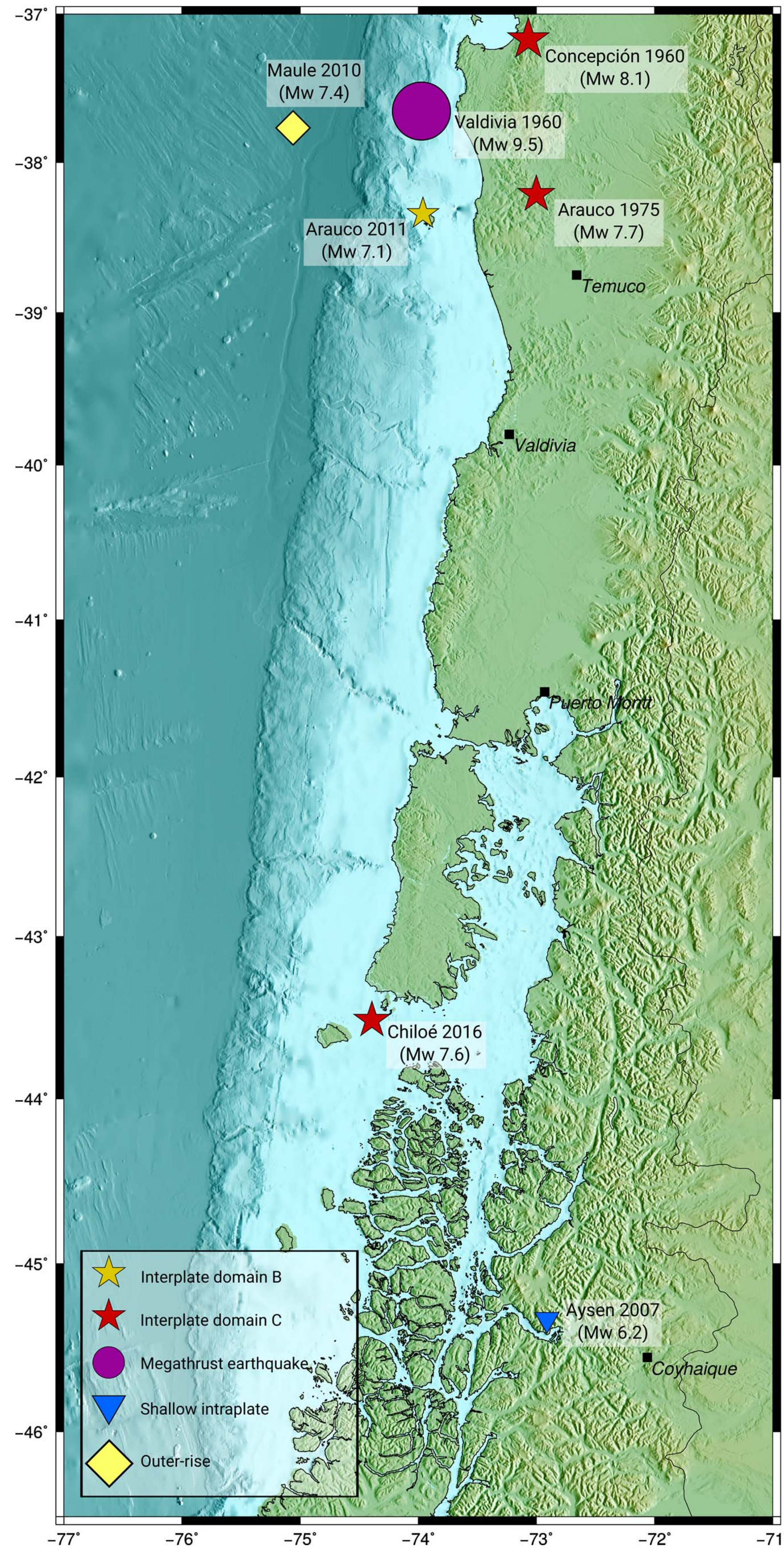

Fig. 7. Hypocenters of main earthquakes since 1900 in South-Central Chile.

in the northern part of the Valdivia earthquakes rupture without information of tsunami. 1837 was an important event with a trans-oceanic tsunami, but the rupture extent was shorter than the giant megathrust Valdivia 1960 earthquake (Cisternas et al., 2017a, 2017b). The South Central zone that extends from 37°S to 47°S accommodates transpressional deformation due to the obliquity of convergence by dextral strike slip on the Liquiñe-Ofqui shallow fault (Cembrano et al., 1996). The most recent earthquake in this active fault occurred in 2007, when a complex sequence of events occurred during several months, with maximum magnitude Mw 6.3 (Mora et al., 2010; Legrand et al., 2011; Agurto et al., 2012; among others). Recently, Kanamori and Rivera (2017) suggested that a slow Valdivia's aftershock of magnitude Mw 7.7 probably took place in this fault. In this section we describe briefly the large magnitude events occurred before the Valdivia megathrust earthquake of 22 May and the 21 May 1960 the Mw 8.1 precursory event in Concepción.

6.1. The 1737 and 1837 earthquakes, the previous events to the 1960 giant megathrust event

Recently Cisternas et al. (2017b) compiled and interpreted first-hand written accounts of the 1737 earthquake. An event that did not trigger a tsunami, but damaged distant towns. Cisternas et al. (2017b) propose that this earthquake was located in the northern part of the 1960 Valdivia rupture, and broke the deeper zone on the plate interface, domain C.

Paleoseismological studies by Cisternas et al. (2005, 2017a, 2017b), Moernaut et al. (2014), among others showed that the 1837 earthquake produced minor regional tsunami deposits in comparison with the 1960 earthquake. The 1837 earthquake is part of the large variability of earthquakes sizes in Central Southern Chile, with a shorter rupture length than the 1960 event (Cisternas et al., 2017b). Lomnitz (1970) proposed a magnitude of 8.0 based on some damage and small local tsunami reports in the Montessus de Ballore's work. In contrast, Abe (1979) based on a large trans-oceanic tsunami (Soloviev and Go, 1976) proposed a magnitude of 9 1/4. Vidal Gormaz (1877) reported changes in the coastal level in the southern Chile islands. Although 1837 is clearly a smaller event than the 1960 megathrust earthquake, the contradictory information between the small local tsunami and large trans-oceanic tsunami, make it difficult to properly quantify the rupture of this earthquake. Cisternas et al. (2017b) based mainly on the reported land-level changes propose a rupture extent of ~500 km in the Southern zone of the rupture of the 1960 giant earthquake the 1837 earthquake ruptured perhaps the Domains A, B and C of the subduction zone.

6.2. 21 May 1960, the often forgotten Mw 8.1 precursor of the 1960 Valdivia megathrust

On 21 May 1960 at 10:02:52 an interplate event of magnitude Mw 8.1 started the Valdivia seismic sequence (Cifuentes, 1989; Cifuentes and Silver, 1989), here we name this event as the 1960 Concepción earthquake. After this event, many other foreshocks were reported (Cifuentes, 1989), including other large magnitude foreshocks of the Validvia megathrust. Among them an event of magnitude Ms 7.8 occurred 15 min before the mainshock (Duda, 1963; Kanamori and Cipar, 1974). The hypocenter of the Concepción earthquake was located near the bottom of the plate interface with epicenter at 37.17°S and 72.96°W (Cifuentes, 1989). Plafker and Savage (1970) reported coastal uplift for this event, and Astroza and Lazo (2010) located the largest damage in the towns around the Arauco Peninsula. Ojeda et al. (2017) performed an inversion of Plafker and Savage (1970) observations and they proposed that this event was an interplate event near the bottom of the plate interface. Unfortunately, the 1960 Concepción event has not been studied or mentioned in many of the modern works on the Valdivia or Maule earthquakes (e.g. Campos et al., 2002). Although Plafker and Savage (1970) separated the deformation of both events, and Cifuentes (1989) and Cifuentes and Silver (1989) identified clearly these two earthquakes. Astroza and Lazo (2010) studied the older reports and newspaper of this time, also observed that the damage was clearly separated for both events.

6.3. 22 May 1960, Valdivia the largest magnitude earthquake in the instrumental period

On 22 May 1960 occurred the Valdivia giant earthquake. The large amplitude seismic waves triggered by this earthquake saturated most of the then existing seismological stations in the world; this made it difficult to reconstruct the rupture process. The Valdivia seismic magnitude was actually determined using the excitation of normal modes of the earth, Mw 9.5 (Kanamori and Anderson, 1975); surface waves Ms 8.3 (Kanamori and Cipar, 1974); low frequency waves Mw 9.6 (Cifuentes and Silver, 1989); the static displacement Mw 9.26 (Barrientos and Ward, 1990) and the tsunami waves observed across the Pacific Ocean Mt. 9.4 (Abe, 1979). There is an important range for the magnitude of the Valdivia megathrust earthquake, but the most accepted value is that proposed by Kanamori and Anderson (1975) based mainly in the normal modes recorded in the Pasadena Press-Ewing seismogram. Plafker and Savage (1970) reported level changes along > 1000 km of the Chilean coast and islands. This work has been essential to propose slip distributions of the earthquake (Barrientos and Ward, 1990; Moreno et al., 2009; Fujii and Satake, 2013). A huge tsunami was triggered by the 22 May 1960 earthquake, generating extensive damage in Chile and in the trans-pacific countries like Japan. Many details were reported in a special volume of the Bulletin of the Seismological Society of America (BSSA) published in 1963.

6.4. Chiloé 2016 earthquake Mw 7.6

The 1960 Valdivia giant earthquake generated postseismic viscoelastic relaxation observed in the regional deformation field many decades after the event (Khazaradze et al., 2002; Hu et al., 2004). It also triggered a dramatic decrease of large events during > 55 years in southern Chile. The reawakening of this zone was marked by the Mw = 7.6 earthquake that occurred at 14:22:23 (UTC) on 25 December 2016 near the southwestern tip of the Chiloé Island. The 2016 Chiloé earthquake is the first large event that has occurred inside the rupture zone of the 1960 earthquake (Melgar et al., 2017; Ruiz et al., 2017a; Xu, 2017; Lange et al., 2018). Ruiz et al. (2017a) observed velocity changes in the continuous GPS stations of southern Chile after the 2010 Maule earthquake. They proposed a link between the changes of GPS velocities and the influence of postseismic deformation of the Maule 2010, somewhat similar to those proposed by Ruiz et al. (2016) and Melnick et al. (2017) for the Illapel 2015 earthquake. The slip distribution of the Chiloé earthquake was modeled by a simple rupture patch of 20 km radius, located in the deeper part of the plate interface (Ruiz et al., 2017a, 2017b).

7. Discussion

7.1. Seismic catalogs and current seismicity

We have reviewed the seismic history of Chile and described the data that are available for the main events that have occurred in the last 400 years. Except for the North-central region (Antofagasta and Atacama), it is now well established that the earthquake "cycle" is controlled by very large and rare tsunamigenic events that occur in Chile at an approximate rate of two per century. Where they are well known (Central and Southern Chile), the recurrence time of these events is of the order of 400 years. Recent paleoseismological and tsunami data confirms this recurrence (Soloviev and Go, 1976; Tsuji, 2013; Dura et al., 2015; Cisternas et al., 2017a, 2017b, and references there

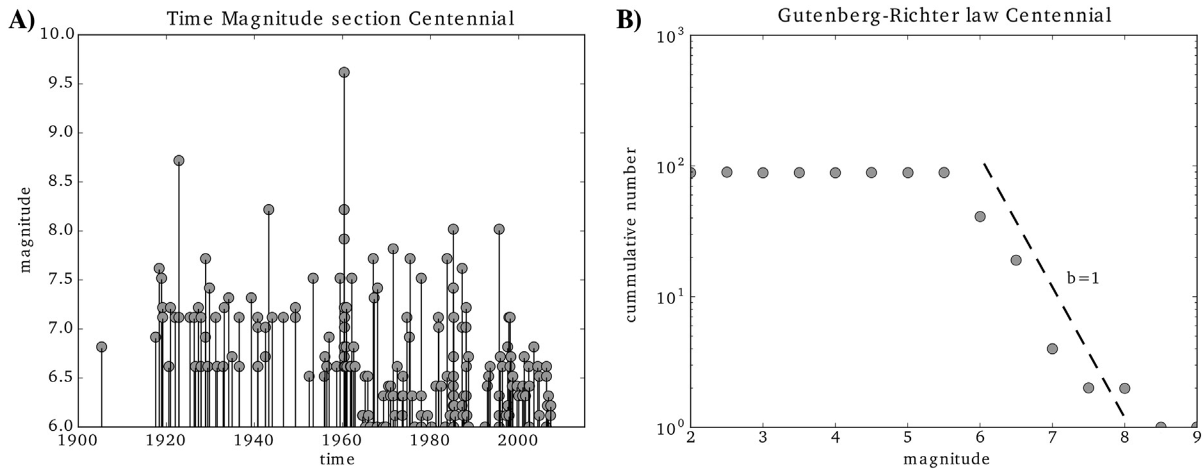

Fig. 8. A) Timeline of events of magnitude larger than 6.0 from the Centennial catalog from 1910 to 2008. B) Gutenberg-Richter law for the Centennial catalog. Cumulative number of events as function magnitude. The segmented black line with a slope −1 is shown as reference.

in). Do catalogs confirm this observation? Unfortunately many of the catalogs available for the 20th century are incomplete and contain many errors for the first part of the 20th century. The most obvious is the error in location and magnitude of the 11 November 1922 megathrust earthquake in Atacama. Catalogs from ISC and USGS list this event as having 70 km depth and some put it near the boundary between Chile and Argentina. For this reason we recommend the Centennial catalog that lists all Chilean large events until 2010 approximately. The Centennial catalog is not exempt of errors, for instance the event of January 1922 located in the middle of the Nazca plate.

Fig. 8a shows the timeline of large earthquakes along the Chilean coast since 1910. Not all events are thrust faults on the seismogenic contact because there are a few normal and reverse fault events inside the Nazca plate or, even fewer, may be crustal events. Separating those events is not possible before 1960 because the fault plane solutions are difficult to obtain. It is clear from the Figure that the smaller events ($6 < M < 7$) are missing in the earlier part of the century, the catalog seems to be complete for $M > 6.0$ only after 1960. This is also clear from the Gutenberg Richter law plotted in Fig. 8b where we observe that the magnitude completeness of the centennial catalog is close to 6. We also notice that near the end of the G-R distribution the number of large events is larger than expected. This may be a permanent feature, or a transient one due to the variations in the large-scale seismicity.

Let us now look at the recent catalogs by USGS, ISC and the Chilean National seismic center (CSN) which are all very similar, although ISC does not include the more recent events. In Fig. 9a we show the Chilean seismicity since 1980 listed by the USGS catalog. Large events discussed in the previous sections are easily identifiable, but we also observe variations in seismic activity in these 35 years. A decrease in seismicity is apparent in the years 1988–1994 and a strong increase starting from the Tocopilla earthquake of 2007. The recent surge of large events since the Maule earthquake of 2010 is even stronger. These features appear also in the Gutenberg Richter law plotted with these data in Fig. 9b. For magnitudes < 7 the GR law shows a slope close to $b = -1$, but from magnitude 8 to 9, there seems to be a bump due to an excess of large events. As we noticed in the data from the centennial catalog, the large seismic events are less rare in this period of time than predicted from smaller events. Whether this is a permanent or a transient feature remains an important question.

7.2. Structural tectonic control of megathrust earthquakes

To estimate the rupture length of historical earthquakes is very difficult in the Chilean subduction zone, because the interpretation is mainly based in the seismic intensity estimated for very sparsely distributed small towns. Most of the inferences were made during the 1980s, when no recent giant earthquake was used as reference. After the occurrence of the 2010 Maule earthquake it is necessary to reinterpret the damage descriptions of historical events. Several attempts to correlate main structures along the Chilean coast and the Nazca plate features have been made to explain segmentation of the Chilean earthquake ruptures (Bilek, 2010; Contreras-Reyes and Carrizo, 2011). Although we think that there exist obvious differences in frictional properties along Chilean subduction zone that may control the dynamic rupture of earthquakes, it is not possible to correlate historically determined source length with these features. During the last years mainly thanks to wide angle seismic marine profiles and gravity profiles, the complexities of Chilean megathrust started to emerge (Ranero et al., 2006; Contreras-Reyes et al., 2010, 2012, 2014, 2015; Maksymowicz, 2015; Geersen et al., 2015) opening a new field to understand the behavior of earthquakes in Chile (Maksymowicz et al., 2015; Álvarez et al., 2014, 2015, 2017). Also along dip we observe different rheology that controls the dynamic rupture process of earthquakes and the seismic wave attenuation. In northern Chile, for instance, León-Ríos et al. (2016) observed the impact of the eroded fore-arc in the rupture of the Iquique 2014 mainshock and the distribution of foreshocks and aftershocks. For the Tocopilla 2007 earthquake Contreras-Reyes et al. (2012) proposed an influence of the along dip geometry of the Nazca plate and Schurr et al. (2012) proposed different friction properties along dip to explain the position of this event near the bottom of the plate interface. Although we believe that segmentation along strike and along dip are important we do not have a clear conclusion for the moment. Finally, we proposed a distribution of main earthquakes since 1900 along dip, Table 1. Most of the events of Mw ~8.0 are deep plate interface events and a few middle plate interface. We do not observe any large trans-pacific tsunamigenic event in the recent historical Chilean seismicity (since 1900), with the exception of the three giant earthquakes listed in the Table 2.

7.3. The characteristic earthquakes

The existence of characteristic earthquakes for each segment is the main hypothesis of the seismic gap model. This hypothesis was tested along strike for the Chilean subduction earthquakes (Kelleher, 1972; Nishenko, 1985), without consideration of along dip slip segmentation. After the 2010 Maule megathrust earthquake, it is clear that only very large magnitude events break the entire plate interface (Lay et al., 2012). Events of magnitude Mw close to 8.0, in general, have slip

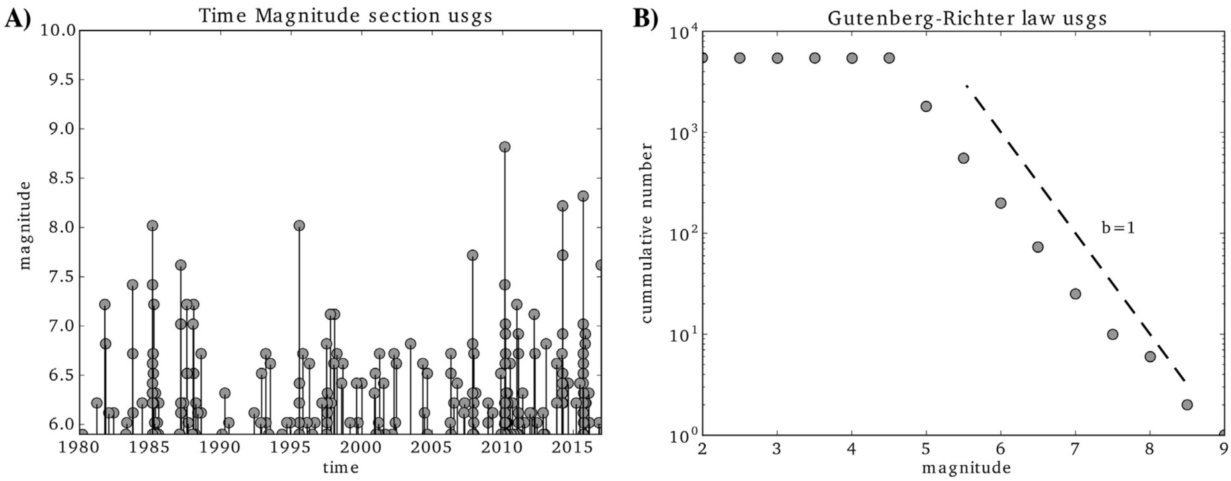

Fig. 9. A) Timeline of events of magnitude larger than 6.0 from the USGS catalog from 1980 to present. B) Gutenberg-Richter law for the USGS catalog. Cumulative number of events as function magnitude. The segmented black line with a slope −1 is shown as reference.

Table 1
Mostly of large earthquakes in Chile since 1900 Mw ~8.0.

Modern earthquakes	Name	Magnitude	Location along dip domain
1 April 2014	Iquique	Mw 8.2	B
3 April 2014	Iquique	Mw 7.7	C
21 December 1967	Tocopilla	Mw 7.4	C
14 November 2007	Tocopilla	Mw 7.8	C
30 July 1995	Antofagasta	Mw 8.0	C
28 December 1966	Tal Tal	Mw 7.7	B
6 April 1943	Illapel	Mw 7.9	B
4 December 1918	Copiapo	Mw 7.8	Probably C
4 November 1983	Copiapo	Mw 7.4	Probably C
17 august 1906	Valparaiso	Mw 8.2	C-B
1 December 1928	Talca	Mw 7.7	C
9 July 1971	La Ligua	Mw 7.8	C
3 March 1985	Valparaiso	Mw 8.0	C-B
16 September 2015	Illapel	Mw 8.3	B-A-C
25 March 2012	Constitución	Mw 7.2	C
21 May 1960	Concepción	Mw 8.1	C
14 October 1975	Arauco	Mw 7.7	C
25 December 2016	Chiloé	Mw 7.6	C

Table 2
Trans-Pacific tsunamigenic earthquakes in Chile since 1900.

Tsunamigenic earthquakes	Name	Magnitude
11-11-1922	Atacama	Mw ~8.5
22-05-1960	Valdivia	Mw 9.5
27 February 2010	Maule	Mw 8.8

distributions concentrated in the middle or near the bottom of the plate interface, see Tables 1 and 2. We suggest that it is not correct to average the time recurrence of giant megathrust earthquakes (Mw > 8.5), which are longer than 300 years, with that of large earthquakes (Mw 8.0), which are shorter and of the order of 80–100 years. Besides, large earthquakes can be located in the same place along strike but at different depth along dip, e.g. the giant 1751, 1835 and 2010 earthquakes of Central-South Chile have important overlap of their rupture areas, however their ruptures seem to be different (Fig. 2).

The data used to compute recurrence in Northern Chile included earthquakes in 1543, 1615, 1768 and 1877, is probably incorrect because the rupture extent of the 1768 earthquake is not known. The Mw 8.2, 2014 Iquique event was the only event of magnitude Mw ~8.0 in a zone where large megathrust events like 1877 occurred. The previous 1877 giant earthquake did not occur in historical time, but probably in 1420. In Central Chile several recurrence times have been proposed. For the Illapel region the events of 1730, 1880, 1943 and now 2015 (Nishenko, 1985); in the Valparaiso region the 1575, 1647, 1730, 1822, 1906 and 1985 events (Comte et al., 1986). These time sequences include the 1730 megathrust earthquake that was > 20 times larger in size than any of the other events considered. The similarity of 1880, 1943 and 2015 may be attributed to the tectonic structure of the Nazca plate that may act as barriers (Poli et al., 2017), although their ruptures are very different as was shown by Tilmann et al. (2016) who compared the seismograms of 1943 and 2015 Illapel events. In southern Chile, the diversity of earthquake sizes was first detected by Cisternas et al. (2005) and corroborated by several paleoseismological works (Ely et al., 2014; Moernaut et al., 2014; Dura et al., 2015; Kempf et al., 2017; Cisternas et al., 2017a; among others) who showed that the 1960 Valdivia earthquake was several times longer than the other events reported in the historical chronicles. It seems to us that those short sequences of earthquakes are not those that define the so-called supercycle (Goldfinger et al., 2013), defined as the time it takes for the larger events to return.

7.4. Intraplate intermediate depth events

Despite high rate of intraplate intermediate depth events in some zones like the Northern and Central Chile, there are few historical events of this type that are well identified. The most probable is the 1647 earthquake in Central Chile (Lomnitz, 2004; Cisternas et al., 2012; Udías et al., 2012) and we propose that 1786 in Northern Chile was also of this type. Determining the type of earthquake for earlier events is difficult since no mechanisms can be computed and depths are very poorly determined. Only damage patterns may be used, but as we saw the original catalogs did not report vertical surface deformation.

8. Conclusion

Our review of past earthquakes shows that there is an undeniable difference between giant earthquakes that break the entire plate interface from the trench to the bottom of the coupled zone and the more frequent Mw ~8 events that break the middle or the bottom of the plate interface. The very large megathrust events have magnitudes of at least 8.4 and usually produce major trans-Pacific tsunamis. These events occur at the average rate of two per century in the entire plate contact zone in Chile. Only one region, North Central Chile near Antofagasta does not seem to have had any event of this kind but this was an almost uninhabited area before the middle of the 19th century.

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