In search for the lost truth about the 1922 & 1918 Atacama earthquakes in Chile

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Abstract

Over the past few decades, precise satellite positioning measurements have revealed variations in the deformation of the Earth's surface along the South American subduction zone. This variable deformation is indicative of the variable coupling on the interface between the two converging plates. In Chile, the 3 major earthquakes of the early 21^{st} century (Maule 2010, Iquique 2014, Illapel 2015) occurred in regions previously identified as strongly coupled. This coincidence supports the classic theory of seismic gaps, in which deformation accumulates in certain zones over long periods of time before being released abruptly by an earthquake. It is therefore natural to postulate that major historical earthquakes obey the same rule, and to ask whether the coupled zones of today's earthquakes also correspond to earthquakes of the past. This question comes up against the uncertainties and imprecision, sometimes errors, in our knowledge of past ruptures. The earthquake of November 11, 1922 (Mw 8.5) in the Atacama region of Chile is often described as the second biggest Chilean earthquake of the 20^{th} century, after Valdivia 1960. In scientific literature, its rupture runs over up to 450 km in length, from 26°S to 30°S. As a result, it seems to have broken two highly coupled segments, Atacama and Chañaral, and crossed a zone of weak coupling, Barranquilla, that were revealed by modern space geodesy. The apparent disparity between the 1922 rupture as described in the existing literature and today's coupling raises an important question: Did the 1922 earthquake, unlike the earthquakes of the 21st century, not respect the coupling, and then why? Or, on the contrary, could the coupling not be constant and change over time? Here, we show how a careful re-reading of the scientific literature of the time has led us to revise various numbers and change our vision of the 1922 rupture. These revisions lead to map a two-times smaller rupture that appears to coincide much better with the current coupling revealed by modern geodetic measurements. The 1922 earthquake, with a rupture reduced to just 200 km in length, corresponds to the Atacama segment positioned between 28°S and 30°S. On the occasion, we also show how another often neglected earthquake, the December 4, 1918, of magnitude ~ 8, also respects the current segmentation by rupturing the second segment of the area. The 1918 earthquake, with a rupture re-evaluated to 100 km in length, corresponds to the Chañaral segment positioned between 27°S and 26°S. The two segments are well separated by the Barranquilla Low Coupling Zone, probably generated by entry of the Copiapó ridge in the subduction, precisely at this latitude.

Keywords: Historical seismicity, Earthquake, Tsunami, Seismic Hazard, Subduction, South-America, Chile.

Introduction

Chile is a seismic country. In less than 60 years, since after the giant megathrust earthquake of 1960 in Valdivia (south Chile), almost the entire length of the Chilean subduction zone ruptured with earthquakes of magnitude 8 or larger. From south to north: Maule 2010 (Mw 8.8), Valparaíso 1985 (Mw 8.0), Illapel 2015 (Mw 8.3), Antofagasta 1995 (Mw 8.1), Iquique 2014 (Mw 8.1) (Ruiz and Madariaga, 2018). Only two portions remain completely unbroken since over a century: North Chile (more precisely, the Loa segment, Métois et al., 2013) holds since 1877 and the Atacama region holds since 1922. The Atacama segment poses an acute seismic hazard since it had also ruptured in 1819, one hundred years before 1922 (Fig. 1). Even though 1819 is a complex sequence made of 3 separate earthquakes occurring on April 3, 4 and 11 (Beck et al., 1998); it suggests a possible recurrence interval of around 100 years for a typical Mw ~8.5 earthquake in this region. Recent GPS measurements reveal this portion of the subduction is strongly coupled, hence accumulating deformation that will have to be released somehow in the future (e.g. Métois et al., 2014; Klein et al., 2018; Yáñez-Cuadra et al., 2022). Simple calculations demonstrate that at the current plate tectonics rate of ~7 cm/yr (e.g. Angermann et al., 1999; Brooks et al., 2003; Vigny et al., 2009), enough deformation has already been accumulated since 1922 to produce an earthquake of magnitude largely above 8. Therefore, this portion of the subduction has been identified as a seismic gap, where a large earthquake may happen anytime soon.

However, the coupling imaged by space geodesy reveal a complex pattern of several smaller contiguous coupled segments, separated by low coupling zones, rather than one single

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long segment (e.g. Métois et al., 2014; Métois et al., 2016; Klein et al., 2018). The portion of the subduction between 26°S and 30°s where the 1922 earthquake occurred is clearly made of 2 segments (Atacama and Chañaral) disconnected by the Barranquilla Low Coupling Zone (LCZ) in the middle (Figure 1). Other more recently published coupling models (Molina et al., 2021; Yáñez-Cuadra et al., 2022; González-Vidal et al., 2023), although they differ slightly because of their inversion methods and their input data, all show the same feature (see Fig. S1). This observation leads to two important questions: First, Would a future earthquake rupture only one or several of these segments? Second, Did the 1922 earthquake rupture the entire length of the seismic gap or only one segment? and then which one?

The earthquake of November 11, 1922 (November 10, 23h45 local time) is the second largest of the 20^{th} century and was felt over a very long stretch of Chile, from Arica to far south of Concepción (Willis, 1929). The tsunami it triggered is known to have caused significant damage over nearly 500 km of coastline, between Coquimbo (30°S) and Chañaral (26°S) and inland cities of Vallenar (28.5°S) and Copiapó (27.5°S) were razed to the ground by the shaking (Sieberg and Gutenberg, 1924; Bobillier, 1926; Willis, 1929). However, its characteristics and rupture length are not well known. In near-field Chile, very few instrumental observations were available. In Copiapó, the seismometer overturned and broke. In Santiago (800 km away), the seismometer needles jumped from the first moment, crumpling and teared the papers, and only an imperfect seismogram could be obtained (Bobillier, 1926). Many witnesses reported that the earthquake lasted a long 11 minutes and the occurrence of several mainshocks, supporting the idea of a multi-segment rupture (e.g. Willis, 1929; Beck et al., 1998). However, attempts to consider and locate two distinct epicenters were made but without success (Macelwane & Byerly work in Willis, 1929, see section 1 of supporting material). Various other attempts resulted in some dispersion but all epicenters fall within a circle of ∼50km radius around the town of Vallenar. They are all far inland and thus share a fairly large depth (Fig. 1).

In the modern scientific literature, it is described as a very large earthquake associated to a very long rupture, said to be ∼ 450 km long, between 26°S-26.5°S and 30°S-30.5°S, in relation to the tsunami-affected area (e.g. Kelleher, 1972; Beck et al., 1998). However, early articles and reports describing the 1922 rupture could suggest otherwise. In order to unravel the truth about the 1922 rupture, we have carefully reread various articles, reports and books from the time of the rupture that detail the earthquake shaking and intensity, and the ensuing tsunami. Similar to our work on the 1877 North Chile earthquake (Vigny and Klein, 2022), we carefully cross-checked the relevant information and, on the basis of a comparison of the various reports, detected unreliable information and factual errors. In the process, we also realized that the earthquake of December 4, 1918 (just 4 years before 1922), which had already destroyed the city of Copiapó, may have played an important and perhaps overlooked role in the region's seismic history. We report here the figures we consider reliable, detailing why, and then explain how these allow us to correct current misconceptions mainly about the 1922 earthquake rupture. Transcripts and translations of consulted articles, reports, and books are available in the supplements section of this work.

1. Description of the scientific literature used in this work

1.1. Sieberg and Gutenberg (1924)

Is in German – 40 pages long – published by the *Veroffentlichungen der Reichsanstalt fur Erdbebenforschung in Jena* (Imperial agency for earthquake research in Jena, Germany), publication n° 137. In this work, Sieberg & Gutenberg analysed the 1922 earthquake in great details. B. Gutenberg collected about 20 seismograms (mostly in Western Europe) and processed them. On the occasion, he discovered long-period surface waves, later named G-waves (Kanamori et al., 2019). A. Sieberg did the macroseismic analysis of the earthquake. For this purpose, he used the material collected by the German foreign service in Chile, conveyed to the *Reichsanstalt* by Prof. Dr. J. Brüggen (a German geologist, founder and head of the Institute of Geology of the University of Chile in 1917). Unfortunately, the exact origin of the information used by Sieberg to establish seismic intensities is lost in the process. Therefore, it is mostly impossible to trace the sources in order to assess their level of reliability and accuracy, a common drawback of Sieberg's work (Albini et al., 2018). However, many sentences describing the damage here and there are identical to those found in other articles and reports, indicating that the sources are most probably the same. Sieberg cautiously evaluated the relation between damage and seismic intensity in the local context. He added a note about the quality of the constructions in North Chile, which he obtained from a technical article, written after the Mw ∼8 earthquake of 1918 in Copiapó (Linneman, 1922). This report indicates that a large number of houses in North Chile were of very poor quality and vulnerable to seismic waves. C. Linnemann, a German engineer, surveyed 1630 houses of which only half were built with the modern and more resistant Brea or Guayaquil cane techniques, the remaining half being build with the cheaper and weaker ancient system of Tapiales or Adobes. He reported that almost 90% of the houses built with the ancient technique were completely destroyed or heavily damaged, when a small 6% of the houses built with the more modern technique suffered the same fate. Therefore, we are quite convinced that the intensities assigned by Sieberg on the Mercalli scale, slightly modified by him for the occasion, are reliable. It's only the interpretations of the earthquake's origin that are more hypothetical. Sieberg & Gutenberg were convinced (actually following Montessus de Ballore's idea, built on the 1877 earthquake in north Chile) that giant Chilean earthquake epicenters are inland and not at sea (Montessus de Ballore, 1911). Accordingly, B. Gutenberg located the epicenter of the 1922 earthquake near the city of Vallenar, 70 km inland, and stated that "*The often spread assumption that the epicenter is to be looked for in the sea is to be rejected*" (Sieberg and Gutenberg (1924); introduction by O. Hecker, director).

1.2. Bobillier (1926)

Is in Spanish – 20 pages long – published in the annual "*Boletín del Servicio Sismológico de Chile*". Carlos Bobillier was an assistant to F. Montessus de Ballore, the founder of the National Seismological Service of Chile (Cisternas, 2009). He became the head of the service after Montessus died in 1923. He wrote a specific section devoted to the earthquake of 1922 in the annual bulletin of the seismological service. In this bulletin, Bobillier mentioned on several occasions another report he had access to, and from which he extracted quantitative information and numbers: an "*Informe del Ingeniero de la Dirección de Obras Públicas, señor Eduardo Aguirre*", so a report by an engineer from the Public Works Ministry. This report is available at the Chilean Ministry of Public Works (MOP) library, and is referred here as Aguirre (1923). Aguirre was commissioned by the ministry to investigate the effects of the earthquake on the different constructions of the devastated area. He travelled to the Atacama region two weeks after the event and visited the localities most affected by the earthquake and tsunami (Chañaral, Caldera, Copiapó, Vallenar, Freirina, Huasco and Coquimbo). Being an engineer, Aguirre relies on facts and quantitative observations. He notices how much these often differ from accounts by "witnesses". He writes "*It was curious to note that many neighbors of a certain education related the events, not as they occurred, but as they believed they would occur according to the knowledge they possessed, acquired in high schools or in later readings. This was especially true in the case of the sea motions*" (Aguirre, 1923, orig. p. 355 - trans. p. 3).

In his 87 pages report, E. Aguirre gives precise figures about the earthquake and the tsunami, explains where they come from and how they are obtained, and provides numerous original photographs. The specificity of Aguirre's work is that he did not rely so much on eyewitness testimonies but on "hard data" and measurements he did himself. At many different places, Aguirre measured the maximum flood level based on marks left by water on identified buildings. He used the topographic maps at his disposal to reference these altitudes with respect to topographic zero. Also, Aguirre explains how he did his measurements and corroborates any average final number by several measurements at different places in the same area. The existence of this report was known, but it had remained untraceable until now. We believe that its discovery, and the use of the figures it contains, is a major contribution to our understanding of the 1922 earthquake and tsunami.

1.3. Willis (1929)

Is in English – 180 pages long – publication n° 382 of the Carnegie Institution of Washington. Bailey Willis was a geological engineer who worked for the United States Geological Survey (USGS). He was head of Stanford geological department at the time of the earthquake. He received a grant from the Carnegie Institution of Washington to lead an expedition to Chile and investigate the causes and consequences of the earthquake. Willis sailed to Chile on January 11, 1923 and returned on September 2. Seven months were spent in Chile, five of them in the province of Atacama. It should be noted that Willis was on site only several months after the event. Some repairs had been made, so he probably did not see the whole damage with his own eyes and many photographs produced in his book are not of his own; also the testimonies he collected were already aging and this may explain some level of confusion, approximation and contradiction. Last, but not least, being a Californian geologist, Willis spent a lot of time (at least 2-3 months) searching for a surface rupture trace in the highlands of the cordillera (Davison, 1929). He travelled uphill Copiapó in the "*quebrada*" that leads to Argentina through the San Francisco pass and to the mines of Potrerillos (26°S) and Chuquicamata (22°S), looking for such a rupture trace, he, of course, never found. He was instead much impressed by the Andean geology. Willis also travelled to San Félix Island. So, in the end, only a relatively small portion of his time was truly devoted to the 1922 earthquake. This shows in his book since he left the work of compiling the hundreds of testimonies regarding the earthquake to a professor of natural science he had met in Copiapó, Don Luis Sierra-Vera. Sierra was well acquainted with earthquakes, possibly a former student of F. Montessus de Ballore. He lived in Copiapó where he was in charge of operating the seismometer installed by the seismological service and had already helped Linnemann with his report on the 1918 Copiapó earthquake. Sierra did the actual work of assigning seismic intensities to each and every report he had received. Being a resident of Copiapó and having lived through the destruction caused by the earthquake of 1918 (only 4 years before), Sierra also knew of the weakness of the region's buildings and of the difference in the vulnerability of buildings depending on the quality of their construction. This point is illustrated by a photography, showing a two-storey house suitably built of panels "*tabique*", intact amidst the ruins of old, single-storey houses poorly constructed of simple adobe (Willis, 1929, orig. plate V-B, p. 13). So, like Sieberg, Sierra was very much aware of Linnemann's report (which is also included in Willis' book) and knew how to take vulnerability into account in the intensities he assigned. Fortunately, Willis included Sierra's work in an appendix to his book and this detailed information is still available, quoted here as Willis (1929, Appendix 2).

We provide in the electronic supplement, digitized copies of the original articles and reports, transcripts in their original languages obtained from Optical Character Recognition (OCR) software, and translations in English realized with Deepl. In addition, we also provide a complete archive of the hundred or so photographs with legends found in Aguirre (1923).

1.4. More recent literature

More recently, the 1922 Atacama earthquake has been the subject of several landmark publications: Lomnitz (1970); Kelleher (1972); Beck et al. (1998).

1.4.1. Lomnitz (1970)

Is a catalog of seismic events that occurred in Chile between 1535 and 1955. The description of the 1922 earthquake is a one-page spread, mostly based on information taken from Willis (1929). Most of the information is correct, except for 2 at both ends of the rupture (Coquimbo: major damage caused by the earthquake and not the tsunami, Chañaral: coastal uplift) which were unfortunately repeated in many later articles. Lomnitz (1970) is the source of the famous story of telegraph communication between Vallenar and Copiapó during the earthquake: *The epicenter was at first believed to be in the vicinity of Copiapó, where the damage was extremely severe; but the telegraph operator at Vallenar was invariably able to forewarn the Copiapó operator of each major aftershock, by keying the words "Esta temblando" (It quakes), upon which the shock would be felt in Copiapó.*

1.4.2. Kelleher (1972)

Is a very famous article compiling rupture zones of the last largest South American earthquakes at the time and establishing the gap theory there. The paragraph regarding the 1922 Atacama earthquake is rather short, but Kelleher (1972) uses information from Lomnitz (1970), Heck (1947) and Berninghausen (1962). Very unfortunately, he picks up on the two very questionable information forms Lomnitz (1970) to infer a very long rupture zone, from Coquimbo to Chañaral (see section 6 for more details). The length of more than 400 km drawn by Kelleher (1972) for the 1922 rupture, associated with a very small estimate for that of 1918 (discussed in a few sentences in his article), will become a reference for all subsequent articles on the subject.

1.4.3. Beck et al. (1998)

Is a very detailed article on the source characteristics of several historic earthquakes along the central section of the Chilean subduction zone. Four events are analysed: 1943, 1939, 1928 and the 1922 Atacama earthquake. Beck et al. (1998) reproduce Kelleher (1972) map of the most recent (at the time) Chilean ruptures and a space-time plot of historical large earthquakes inferred mostly from Lomnitz (1970). Regarding the 1922 event, they collected seismograms and modelled the P-Wave through multi-station omnilinear inversions. The best seismogram, from De Bilt in the Netherlands (DBN) revealed that 1922 was the largest of the four studied earthquakes and that the source was made of three distinct pulses over a total duration of 75s. The three pulses suggested three sub-events, matching well the testimonies of successive shocks reported in Willis (1929) and possibly the three distinct events of 1819 April 3, 4, and 11.

2. Review of tsunami heights along the South American coast

Despite being one of the largest events of the time, the tsunami generated by the 1922 earthquake is poorly quantified. Along the entire coastal length of South America, the International Tsunami Information Center (ITIC) data base at NCEI/NOAA (ITIC, 2023) gives only 4 values: 3 in Chile and 1 in Peru (Fig. 2). As usual, tsunami heights reported by eyewitnesses of the time are often unclear, fluctuating and sometimes exaggerated. Large and inaccurate inundation figures are often reported far away from the earthquake epicenter by the press of the time (León et al., 2019). In consequence, and similarly to the case of the 1877 earthquake and tsunami in north Chile, the earthquake magnitude and its rupture length may be overestimated (Vigny and Klein, 2022). Another difficulty arises from a very common ambiguity between the maximum height reached and the maximal oscillation of the water level. The latter is a crest-to-trough measurement and is close to twice as much as the maximum height, but one is often mistaken for the other. The common challenges faced in defining and reporting tsunami wave heights are fully described in Dunbar et al. (2017).

Another common problem comes with the timing of the tsunami arrival at different locations. Arrival times are extremely confusing because one seldom knows if the witnesses refer to the first arrival or the largest one (which is generally the third one in this instance), and because reported times are extremely different from one witness to the other and often inconsistent between places. Examples found in Aguirre (1923) are eloquent: in Chañaral, a first witness (Sr. Juan Trabucco) stated that the first arrival was at 0h15, the second at 0h30, and the third at 0h45; a second witness (Pr. Scholberg) stated that the largest wave (the third) arrived at 1h25. That is a 40-minute difference at the same place, as noted by Aguirre. In Caldera (closer to the epicenter than Chañaral), the maritime governor states that the first arrival was at 0h10 and the third at 3h, so 1h30 to 2h later than in Chañaral. In Coquimbo, the sailor on duty and his chief engineer stated that the first arrival was half an hour after the shaking and the third at 1 am. By all means, the first arrival must have been difficult to time with precision since the tsunami arrived at night and quite shortly after the shaking stopped. So, we think that the only reliable information here is that most witnesses indicate the first arrival is everywhere (between Coquimbo and Chañaral) between 20 and 30 minutes, undifferentiated between towns and without any distinguishable pattern.

Misguided by dubious travel times, Sieberg and Gutenberg (1924) located the tsunami origin far north of the earthquake's epicenter. This lead them to favor the theory that tsunamis are generated by another source, at some distance, i.e. a submarine landslide (possibly triggered by the earthquake) rather than by the slip on a fault located under the sea. Gutenberg published a second article in 1939, revisiting their result of 1924, to insist on this theory (Gutenberg, 1939). This idea was supported by the different locations he had found for the earthquake epicenter (EP at 28.5°S/70°W, west of Vallenar) and the tsunami origin (TS at 27.5°S/71.5°W, south of Caldera), both depicted on Fig. 3-A inset, showing figure 2 of Gutenberg (1939) taking up figure 1 of Sieberg and Gutenberg (1924). However, TS's location, shifted northwards with respect to EP, is probably an artefact that stems from the dubious tsunami's arrival times at Chañaral in the north (+1h) and Coquimbo in the south (+2h). The sources for the arguable arrival times are two testimonies reported in Willis (1929): one for the arrival time at Chañaral (see section 2.1) and one for the arrival time at Coquimbo (see section 2.4). We find them dubious because they are single testimonies, corroborated by no other, and quite the opposite contradicted by other testimonies in Willis (1929) and other sources Aguirre (1923), who always say 20 to 30 minutes. The latter seems more robust because they are either corroborated by evidence (i.e. a clock jammed at a certain time) or by precise explanations (i.e. the witness explained how he went to the dock and timed the successive arrival with his stopwatch). The discrepancy of the late timings could be due to the fact that they may have reported the time of the later highest wave, but without explicitly saying so. By all means, this hypothesis of a marine landslide-induced tsunami was later debated and rebuked in details by Shepard et al. (1949).

In this section, using information corroborated by observations published in various scientific articles and reports of the time, we discuss the 1922 tsunami heights in various port cities of Chile and Peru. It is well known that testimonies, especially 2nd or 3rd hand, should be taken with caution and there is often no obvious reason to judge one right and the other wrong. However, all testimonies are not equal: some are first hand, others "hear say"; some are vague, others detailed; some are contradicted by others, some are corroborated by others; finally, some are simple testimonies while others are reports of measurements substantiated by evidence. Until now, almost all known 1922 tsunami heights along the Chilean coast came from Willis's book and, therefore, from testimonies obtained several months after the event. These are the figures found in the literature and, therefore, in the ITIC data base. In general, a single figure is attributed to a given location, even if differing testimonies have reported different figures, in which case it's almost always the largest that is adopted. Aguirre's report is the work of an engineer who was on site only days after the event and made actual measurements of tsunami heights relative to topographic zero at many places. He explains how he did his measurements, provided photos of evidence and corroborated a final average number with several measurements at different places in the same area. So in the following sub-sections, we explain where known figures come from and why we sometimes believe them to be dubious, whereas other figures, often slightly smaller, essentially coming from Aguirre (1923) seem more reliable, especially when backed up by detailed measurements or observations.

1. **Chañaral (26.5°S)**. There, the ITIC data base gives a value of 9 meters, taken from Soloviev's article (Soloviev and Go, 1975), which they took from Willis' book (Willis, 1929). Similarly, the scientific literature gives the same figure of 9 meters, also taken from Willis (e.g. Lomnitz, 1970; Abe, 1979; Beck et al., 1998). It is the highest reported tsunami height, an emblematic figure frequently found in the literature, which has become the number associated with the magnitude of the 1922 tsunami. This figure comes from the one testimony, among only 3 in Willis' book, that gives a quantitative description of the tsunami in Chañaral. It is the testimony of a Chañaral primary schoolteacher, Mrs. Maria Isable T. Zeballos (probably misspelled by Willis). She states that the tsunami began 1 hour after the earthquake, that the sea advanced 3 times, and that it rose 9 meters, destroying 14 blocks of houses (Willis, 1929, orig. p. 35). However, Bobillier gives a much lesser figure of only 5.5 meters at Chañaral, referring to Aguirre (1923). Aguirre explains how he measured himself the

maximum inundation height (due to the 3^{rd} wave) at 3 distinct locations: The house of a Dr. Scholberg (2.4 m above the ground floor), the customs building in Freire street (1.9 m above street level), and at hotel Ingles (2.55 m above the ground floor). He found that those 3 values indicate a general rise of 5.5 meters above zero, according to the planimetry map realized by the Geography section of the Public Work ministry (Aguirre, 1923, orig. pp. 358-359; trans. p. 4). A possible explanation for this contradiction with the primary school teacher observation would be that the 9 m figure she gave refers to the total difference between lowest and highest sea levels rather than the inundation level.

A large recess of the sea between the successive waves is attested by all witnesses. In Coquimbo, days after the event, Aguirre measured the depth of rocks that had emerged at the peak of sea retreat and found -5.80 meters (Aguirre, 1923, orig. pp. 364-365; trans. p. 5). A similar recess may have happened in Chañaral, so it could just be a matter of not confusing the maximum height reached by the inundation with the difference between the highest and lowest levels.

The amplitude of the recess at Chañaral should be estimated through proper modeling to check whether the explanation that the witness referred to a crest-to-trough difference rather than to an inundation height holds up. But, because the figure reported by Aguirre is substantiated by measurements and corroborated at 3 distinct locations, we believe this number to be trustworthy and that this figure of 5.5 meters at Chañaral should be retained.

2. **Caldera (27°S)**. There, the ITIC data base gives a value of 7 meters, taken from Soloviev's article (Soloviev and Go, 1975), mixing two testimonies from Willis' book, provided by Sr. Bernado Tornini (who indicated 6 m) and Sr. Guillermo W. Lavan (who indicated 7 m), both commercial passengers on board steamer Flora, anchored in the bay (Willis, 1929, orig. p. 34; trans. p. 11). However, another testimony from Willis' book (Senora Ana S. de Baez, Telegraphs postmaster) indicates a lesser figure of about 5 meters. This lesser number is confirmed by Bobillier (1926), again referring to Aguirre (1923), coming from solid evidence: "*The highest water level left very clear marks at the Caldera railway station [...] 2.40 m above the floor and 2.70 m above the loading dock platform. I calculate [...] a height of 5.50 m with respect to zero.*" (Aguirre, 1923, orig. p. 360; trans. p. 5). In support of his measurements, Aguirre produces a photograph of the railway station warehouse, a long rectangular building, on whose wall the water has left a fairly clear and straight mark at the highest level

reached (Aguirre, 1923, photo. # 96). Therefore we conclude that this lesser figure of 5.5 m at Caldera is a more reliable number.

3. **Huasco (28.5°S)**. There is no number for the tsunami height at Huasco in the ITIC data base. However, Bobillier (1926), again referring to Aguirre (1923), indicates that the same inundation level of 5.5 meters was reached at Chañaral, Caldera and Huasco. This information also comes from solid evidence: "*marks left on the walls of the Torres y Cia. bodegas indicate that the water rose up to 1.20 m above the threshold of the entrance door. That elevation must be at a height above zero very close to those deduced for Caldera and Chañaral*" (Aguirre, 1923, orig. p. 362; trans. p. 5). Therefore we conclude that this figure of 5.5 m at Huasco should be taken into account.

4. **Coquimbo (30°S)**. There, the ITIC data base gives a value of 7 meters, again taken from Soloviev's article (Soloviev and Go, 1975), again reproducing a testimony from Willis' book: *"[...] it reached 7 m above mean sea level at the railway quay [...]"* (Willis, 1929, orig. p. 31). There is only one testimony at Coquimbo in Willis' book. It is attributed to a Sr. Eduardo Olivares Quadra, an employee of the post-office. This man was in his house and gave indications about the earthquake only. But then, Willis aggregates 2 additional notes, from an unknown Sr. Casandra who indicated a different time for the earthquake (11h52 instead of 11h57), and a description of the tsunami. The complete note regarding the tsunami reads: "*About two hours after the earthquake came the maremoto with its three successive waves. The last was the one which did the most damage. It rose to an altitude of 5 meters and attained a distance of 2 km in the lowest part of the coast. Elsewhere parts of the shore suffered not at all from the wave, indicating that the waters were impelled by strong currents from northwest to southeast. (Coquimbo Bay is a cul-de-sac opening toward the northwest. The wave, passing the wide entrance, was low and did not rise high along the eastern or western shores, but the waters were constricted at the southern end and attained an extreme height of 7 meters above mean level at the railroad wharf — B. W.)*". This note is problematic for a number of reasons: i) Willis does not say who is this witness, when he usually does in the most precise terms for everyone else he cites. ii) the elapsed time reported between the earthquake and the tsunami, 2 hours, cannot be right (Bobillier (1926) and Aguirre (1923) report 20 to 30 minutes, everywhere between Chañaral and Coquimbo). iii) the last sentence, between parenthesis and with the very unusual addition of "**- B.W.**" by the end of it, seems to indicate that this last bit of information comes from Willis himself rather than from the witness.

But Willis does not explain how he inferred this figure of 7 meters. Last, the legend of a photography reads *"Coquimbo. Effects of earthquake wave in railroad yard; height of wave 26 feet (8 meters) above mean tide"* (Willis, 1929, plate 3A, p. 8). Willis himself did not notice he was providing two different figures (7 or 8 meters), or did not think it mattered. All these inconsistencies lead us to think that this part of the report is unreliable and should be discarded. On the contrary, we find a trustworthy source for Coquimbo in Bobillier's report: A measurement of 4.6 meters at a custom house (only 5 blocks away from the railroad wharf mentioned by Willis, according to ancient maps of Coquimbo), again reported by E. Aguirre. This figure comes from the testimony of the sailor on duty at the custom house that night (one Fidel Araya), corroborated by the chief engineer (Sr. Luis Aguayo) (Aguirre, 1923, orig. pp. 363-365; trans. p. 5). They say the first wave arrived $\frac{1}{2}$ hour after the earthquake and reached 2.3 meters above the mean sea level, the second wave reached the same height, then, after a deep retreat of 5.8 meters, the sea rose for the third time and reached the elevation of 4.6 meters. This final figure is likely inferred from marks left by the sea on the building wall. Last, Aguirre (1923) wrote *"The most flooded areas were those of the Victoria population, a very poor neighborhood of Coquimbo, located in unhealthy, muddy soil, the formation of which should not have been allowed"*. Therefore, we conclude that the lesser number of Aguirre should be trusted and the tsunami height at Coquimbo should be revised from 7 meters to 4.6 meters.

5. **Callao, Peru (12°S)**. Callao is the harbor of Lima city in Peru. There, the ITIC data base gives a value of 2.4 meters, again taken from Soloviev's article (Soloviev and Go, 1975). The figure at Callao can be found in only one of the 28 sources for the 1922 tsunami heights they refer to: Iida et al. (1967). Similarly, in the more recent literature, Beck et al. (1998) refer to the book of Lockridge (1985), which in turn also refers to Iida et al. (1967). Iida's catalog cites 11 sources (Finch, 1924; Wilson, 1928; Willis, 1929; Bobillier, 1933; Heck, 1947; Gutenberg and Richter, 1954; Iida, 1956; Keys, 1957; Gutenberg, 1959; Berninghausen, 1962; Watanabe, 1964), but none of them reports anything about Callao. So Iida et al. (1967) is the one and only reference where a figure at Callao suddenly pops up, but without any indication of where it might come from. Logically, it should be based on an observation published by the Directorate of Hydrography and Navigation (DHN) of the Peruvian Navy. However, this service have no information on this figure and no record of a tsunami at Callao in 1922 (C. Jimenez pers.com., 2023). The tide gauge was installed there only in 1940, and no document

could be found to substantiate Iida's figure. On the opposite, a comprehensive report of Peruvian CERESIS ("*Centro Regional de Sismologia para America del Sur*") on the historical tsunamis along the coast of south America, does not mention that 1922's tsunami gave rise to an inundation in Peru (Silgado, 1974). Simple linear simulation with a coarse bathymetry reveal that the maximum amplitude would be not greater than 2 meters for a Mw 9.0 earthquake and less than 1 meter for a Mw 8.5 earthquake (Jiménez et al., 2017). Therefore, it seems most likely that the "observation" of 2.4 m at Callao reported in Iida's catalog, is incorrect. It could origin from a mistake of units: a more plausible reported height of 2.4 feet (∼0.7 m) being confused with 2.4 meters.

In summary, it is quite clear that the tsunami affected a long portion of the Chilean coastline. Original numbers showed some degree of variability, with maximum figures at both ends of the rupture: 9 meters at Chañaral and 7 or 8 meters at Coquimbo. The revised numbers are generally slightly smaller and more regular, with a typical value of around 5-5.5 meters. It is quite common that tsunami heights vary from one place to another over small distances, especially along bays with very specific configurations (i.e. closed geometry and/or long peninsulas). It was the case of Puerto Aldea bay behind the "Lengua de Vaca" or Coquimbo bay behind "La Herradura", both affected by the tsunami of 2015 (Aránguiz et al., 2017; Contreras-López et al., 2017). However, at large scale (hundreds of km) along a long portion of the coastline, despite local variability, the average value of the 2015 tsunami is rather stable around 4 meters with a standard sigma of 1.5m (Aránguiz et al., 2017, Fig. 3a). So, the figure of 9 meters, often found in the literature as a "defining" number for the 1922 tsunami seems too large. A smaller number of 5 to 5.5 meters seems more adequate. This number, still significantly larger than the defining number of 4 meters of the 2015 Illapel tsunami, would indicate that the magnitude of the 1922 earthquake is rightly inferred to be larger than that of the Illapel earthquake, i.e. larger than 8.3. Unfortunately, unlike for the 1877 event, in the sources consulted there are no observations describing quantitatively the decay of the tsunami along the Chilean coastline further away from the epicenter (Vigny and Klein, 2022). Thus, the rupture length remains poorly constrained by the tsunami figures available in those sources. Idem, there is no specific information about tsunami inundations in the far field in the sources we consulted. Revisiting all the 22 known numbers in the ITIC data base (see Fig. 2) and collecting other numbers at other places all around the Pacific, is a major endeavor that we did not undertake since it would only make sense in the framework of quantitative tsunami modeling, which is far beyond the objective of this article.

3. Distribution of seismic intensities

We gather here the intensities reported at various locations compiled by the different authors (Table 2). Sieberg and Gutenberg (1924) scale is the Mercalli-Cancalli-Sieberg scale. Bobillier (1926) uses the Mercalli modified scale to quantify the damage that have been reported to him. In its appendix n°II, Willis (1929) provides a large table which summarizes the three hundred answers received to a detailed questionnaire that had been sent out by the Governor of the Province of Atacama. They were compiled by Luis Sierra-Vera, who attributed corresponding intensities in the Rossi-Forell scale to the specific locations where he had damage reports. We converted the intensities into the modified Mercalli scale using the correspondence formula given in Davis (1982) (see supplement for details).

Rossi-Forrel	1	3	5	7.75	8.75	9.5	10
Mercalli modified	I	III	IV-V	VI	VIII	IX	X-XII

We then calculated the average of the various intensities reported at each localities (see supplementary material for intensity scales description and Sierra's table). We reproduce the intensity maps and contour lines of the different authors (Fig. 3).

Despite small discrepancies here and there, the 3 authors agree well (Fig. 3, Table. 2). Especially, Sieberg and Gutenberg (1924) and Bobillier (1926), both originally in Mercalli scale (whether modified or not), attributed the same intensities at 7 locations out of the 10 they have in common. The latter attributed slightly higher intensities than the former at the 3 remaining locations. Willis (1929, Appendix 2) intensities are consistently 1 or 2 notch lesser. It is difficult to know whether this is due to our conversion of scale (from Rossi-Forrel to Mercalli) or if, well aware of the weakness of the buildings in the Atacama region, Sierra didn't systematically revise the reported intensities downwards. Sierra may also have taken into account the embrittlement caused by the previous earthquakes of 1918 and 1920 in the area and of which he was well aware since he had experienced them in person. However, intensity patterns are very similar and the region most affected is clearly the one around the city of Vallenar, $\sim$ 100km south of Copiapó.

Given the large extent of the affected area, the scarcity of inhabited places in the Atacama region and the disparity of observed damages, Willis (1929) could not locate the earthquake epicenter and renounced drawing isoseismal contour lines (Fig. 3-C). On the contrary, both Sieberg and Gutenberg (1924) and Bobillier (1926), driven by their idea that the earthquake epicenter was inland, they drew the outline of the area they felt had been the most affected: the city of Vallenar (28.5°S) (Fig. 3-A,B). Lacking data in the mountain ranges, east of

Vallenar, Bobillier (1926) did not close his contour lines. On the opposite, guided by the existence of a single value in Argentina in the southern part of the affected area (Rodeo, 69°W/30°S, intensity 7), Sieberg and Gutenberg (1924) closed their contour lines. It should be noted that they have no intensity values south of 30.5°S, and that the rather smooth closure of the isolines of level 9 to 6 several hundreds of kilometers to the south (a feature retaken by B. Gutenberg in his article of 1939) is purely hypothetical. Unsubstantiated drawing of isolines is another common feature of Sieberg's work (Albini et al., 2018). Finally, it should be noted that isoline 9 is particularly stretched in a north-south direction because it must include Copiapó (27°S) to the north and Vicuña Rivadavia (30°S) to the south. We show in the following section how this extension is questionable on both sides.

4. Definition of - and search for - the pleistosist area

The pleistoseist area (following the definition by F. Montessus de Ballore) is the area that suffered the greatest damage around the epicenter. In modern terms, this area correspond to the area enclosed by the isoseismal line of intensity 8 in the Mercalli scale. This area also depicts the rupture length since it has been observed that aftershocks following the mainshock remain within this zone. More precisely, the pleistosist area being inland and the rupture being at sea, the rupture length corresponds roughly to the intersection of the isoseismal contour line of level 8 with the coastline (e.g., Dorbath et al., 1990).

1. **Chañaral (26.5°S)** coastal town, is undoubtedly outside of the pleistoseist area. At Chañaral *"the earthquake was not alarming [...] The movements were long, rapid, gentle (suaves) and regular [...] the movements were almost continuous and slow and gentle [...]"* (Willis, 1929, orig. p. 35; trans. p. 12). There, Bobillier (1926) does not give any quantitative estimation but reports that *"the old and tall brick chimneys of the old Edwards foundry have survived the earthquake"*. This specific information comes from Aguirre's report, who provides a photography of the chimneys and also insists on the fact that this is proof of the moderate violence of the earthquake there (Aguirre, 1923, orig. p. 409; trans. p. 14; photo. # 54). This specific fact corresponds to intensities less than 6 in the modified Mercalli scale. This figure of level 6 is the number attributed by Sieberg & Gutenberg in their own Mercalli-Cancali-Sieberg scale. Taking into account these mild intensities (far beyond level 8), we consider it highly probable that the rupture did not reach Chañaral's latitude.

2. **Caldera (27°S)** coastal town, is also most probably outside of the pleistoseist area. All the testimonies reported by Sierra concur in assessing damage between non-existent and slight there (Willis, 1929, Appendix 2). According to many testimonies reported in Willis (1929) the sea rose without noise and without surf. Depending on the source, the time lag between the earthquake and the tsunami first arrival varies considerably, from 20 to 45 minutes, so this information remains inconclusive. But here too, seismic intensities are relatively moderate: from 6 to 7 depending on the author (Table. 2) and all concur that in Caldera, like in Chañaral, damage was done only by the tsunami.

3. **Copiapó (27.5°S)**, 70 km inland. There, the earthquake was very strongly felt. The Wiechert pendulum of the local seismological station weighing 135 kg was overturned; the cemetery was devastated by the earth movement, discovering corpses; many mines in the Copiapó department collapsed; 85% of the houses were either completely destroyed or heavily damaged. (Bobillier, 1926, orig. pp.8-9; trans. pp.5-6). However, the few reinforced concrete constructions that existed there resisted perfectly well without showing any cracks. Sixty to seventy people died and around a hundred more were injured (Bobillier, 1926; Sieberg and Gutenberg, 1924). This figure may seem high, but in relation to the number of inhabitants (11,000) it actually represents a much lower proportion than in the more southerly towns (Huasco, Freirina, Vallenar) (Sieberg and Gutenberg, 1924, orig. p.12; trans. p.2). It seems important to consider that the level of destruction may have been increased by the embrittlement resulting from two recent earthquakes that had occurred nearby in the previous 4 years and had already seriously damaged the city. The 4 December 1918 earthquake of magnitude around 8 and the 28 October 1920 earthquake of unknown magnitude. The 1920 earthquake is not in Lomnitz (1970) (an oversight ?) and therefore disappeared from all subsequent catalogs. However, it was felt from Vallenar to Copiapó and is assigned a *"Grado IV"*, alike the 1918, by Greve (1949) in his list of destructive earthquakes in Chile. In 1920, many houses repaired after the 1918 earthquake fell to the ground (including the Gobernación concrete building in Vallenar), demonstrating the inefficiency of the repairs (Meza-Pizarro et al., 1992). In addition, it is worth noting that the 1922 November 10$^{\text{th}}$ mainshock was preceded by a strong foreshock on the 7$^{\text{th}}$, followed by 3 more earthquakes on the same day, 4 more the 8$^{\text{th}}$ and 2 more the 9$^{\text{th}}$, all strongly felt in Copiapó (Bobillier, 1926). So we tend to consider that the extensive damage in Copiapó is not necessarily solid evidence of the intensity of the earthquake there, but rather of the building's vulnerability & weakening. Therefore, we are inclined to

position Copiapó on the edge of the pleistoseist area, most probably outside of it.

4. **Huasco (28.5°S)** coastal town, seems to be within the pleistosist area. Among the 420 inhabitants, 12 died and numerous were wounded. According to various testimonies reported by Sierra, about half the houses suffered considerable damage or were destroyed (Willis, 1929, Appendix 2). Sieberg reports that almost all buildings collapsed or were heavily damaged. Assigned intensities there range between 8 and 9 depending on the authors (Table. 2).

5. **Freirina (28.5°S)** 15 km inland (2 600 hab.), is clearly within the pleistosist area. All but one of the houses were destroyed and the death toll approached a hundred including the immediate vicinity (Sieberg and Gutenberg, 1924, orig. p.13; trans. p.3). Assigned intensities there range between 8 and 10 depending on the authors (Table. 2).

6. **Vallenar (28.5°S)**, 50 km inland. Nowhere the earthquake was stronger than in Vallenar. Willis wrote *"the maximum apparent intensities were observed in the vicinity of Vallenar (at Vallenar itself, at El Transito east of the city, and at Huasco Bajo west of it)"* (Willis, 1929, orig. p.44; trans. p.23). Bobillier adds *"Undoubtedly, the earthquake was much stronger in Vallenar than in Copiapó [...] The city was totally destroyed, leaving standing, but in bad condition, very few buildings [...] only the church remained in good condition"*. Out of a population of around 6,000, over 300 were killed and 600 injured (Bobillier, 1926; Sieberg and Gutenberg, 1924). The level of destruction was such that the question of rebuilding the town on another site, less exposed to seismic risk, was suggested and considered (Aguirre, 1923). Assigned intensities there range between 9 and 11 depending on the authors (Table 2). Vallenar is clearly at the heart of the pleistoseist area.

7. **La Serena / Coquimbo (30°S)** coastal cities, are most likely also outside of the pleistoseist area. About Coquimbo, Aguirre wrote *"In the ports visited, the destructive action of the earthquake is not noticed [...] because the violence of the movement has been mediocre"*. Willis has a photography (Plate IV-A p11) that shows an intact hut (in spite of the walls being just a pile of stones) near Coquimbo and the legend says *"Near Coquimbo. Hut, on coast 16 miles (25 km) south of city, not damaged by earthquake, showing weakness of shock at this point"*. Sieberg and Gutenberg (1924) are the only one to report an intensity at Coquimbo: they attribute a "mild" figure of 6 despite

the relatively high level of damage. they wrote *"Here the earthquake occurred merely as a "temblor" which did not cause any appreciable damage to buildings, although fissures appeared in the ground in several places. On the other hand, the city suffered from the devastating effects of the seismic waves in a very unusual way"*. Intensities reported at the nearby city of La Serena (no more than 10 km away from Coquimbo) are surprisingly much higher: they range between 7 and 9 depending on the author (Table. 2). An explanation for this may be provided by Aguirre who wrote in the technical section of his report about the few masonry and concrete buildings he surveyed: *"for the private constructions of these cities (nb. Copiapó and La Serena), lime mortar has been used almost exclusively, most of the time with a high proportion of sand. I collected samples of mortars so poor that at the slightest pressure of the fingers they disintegrate."* (Aguirre, 1923, orig. p.405; trans. p.11). So, the greater damage in La Serena than in Coquimbo would be due to specific fragility of many of the buildings in La Serena rather than to the characteristics of the earthquake itself.

8. **Vicuña / Rivadavia (30°S)** 100 km inland, are probably outside of the pleistosist area. The two towns are only 15 km apart in the Elqui valley, uphill La Serena, and they also seemed to have suffered heavy damage (Sieberg and Gutenberg, 1924, orig. p .14; trans. p. 4). For this reason Sieberg and Gutenberg (1924) stretched their isoline 9 far to the south in order to include those two localities (Fig. 3-A). Neither towns were included in the questionnaire and are thus absent from Sierra's compilation. However, in his summary of intensities, Willis (1929) attributed intensities of only 8 to Vicuña and 9 to Rivadavia (in the Rossi-Forel scale he uses) upon his on-site visits (Willis, 1929, orig. p. 44; trans. p. 23). Those correspond to lesser intensities of 7 (Vicuña) and 8 (Rivadavia) in the modified Mercalli scale. Bobillier (1926) has it the other way around... He attributed an intensity 9 to Vicuña, reporting heavy damage there (but only 10 houses fell down and no casualties) and attributed no intensity to nearby Rivadavia since, even though the earthquake was strongly felt there, it did not cause any serious damage (Bobillier, 1926, orig. p .11; trans. p. 7). To add to the confusion, it is not certain that destruction there can be attributed unequivocally to the 1922 earthquake itself or rather to one of the 3 large earthquakes that occurred shortly afterwards at this latitude on 3, 12 and 20 January 1923 (Fig. 4-B, Table. S1 and see section 5); or even to another earlier earthquake: 30 earthquakes were felt in Vicuña between December 24 and 28, with the last one on the 28th causing panic among residents. (Bobillier, 1926, orig. pp .40-41; trans. pp. 17-18). So the inclusion

of both localities by Sieberg and Gutenberg (1924) in the area of major damage caused by the 1922 earthquake alone may be a mistake.

Overall, with the notable exception of Copiapó, the area of intense destruction seems to correspond to the Huasco river valley region: from coast to mountain: towns of Huasco, Freirina and Vallenar were most affected. This is stated in so many words by Aguirre: *"The most violent zone seems to have been the Huasco Valley, due to the greater destruction that is noted in the constructions of Vallenar, Freirina, and Huasco Bajo with respect to the similar ones of Copiapó"* (Aguirre, 1923, orig. p .355; trans. p. 3).

The fact that the destruction seemed so severe inland (Vallenar and Copiapó) and relatively mild along the coast was noted by all authors. It certainly played an important role in the development of the theory in vogue at the time: the epicenter had to be inland and the tsunami generated by submarine landslides (e.g. Gutenberg, 1939). However, this theory was biased by the misconceptions of the time: the theory of plate tectonics was not known, and great Chilean earthquakes were understood as ruptures occurring on structures within the Andes and not on a subduction plane, the existence of which was unknown. In any case, when it comes to assessing the damage inland with respect to along the coast, most investigators have probably underestimated the differences in building and soil qualities. Only Aguirre clearly identifies this has a major issue. In his own words, *"buildings in the inland towns (Copiapó, Vallenar, Freirina) are old, very modest and poorly preserved"* when *"in the ports visited, [...] the constructions, in their great majority, are made of wood or light materials that are well fastened"*; and then in addition, *"Copiapó, Vallenar and, to a large extent, Freirina, are located on a soil with inconsistent bearing capacity"* when *"In the ports visited [...] the violence of the movement has been mediocre, due to the existence of rock on the surface of the ground or at a shallow depth"* (Aguirre, 1923, orig. pp. 366-367; trans. p. 6).

Last, but not least, most may have underestimated the fact that the northern part of the region, where the city of Copiapó is located, had already suffered a major earthquake of magnitude around 8 in 1918, only 4 years before and a second one in 1920, only 2 years before. Repairs may have been unfinished and/or inadequate. Therefore, the inclusion of Copiapó by Sieberg and Gutenberg (1924) and Bobillier (1926), in the zone of major damage caused by the 1922 earthquake alone may be a mistake. In any case, Sieberg's isoline 8, with or without Copiapó included, defines a rupture only 200-250 km long, as it intersects the coast at La Higuera (∼30°S) and Carrizal Bajo (∼28°S).

5. Aftershocks and background seismicity

Recently, the International Seismological Center (ISC) provided a catalog of significant earthquakes that now start as early as 1904 (Bondár and Storchak, 2011). This catalog contains the 1922 sequence: the mainshock of November 11, a foreshock on November 7, and several dozen of events large enough to have been detected and localized, which could be qualified a-priori as aftershocks, only 2 of them large enough for magnitude estimation (Tab. S1). Because the precision of localisation at the time was quite low, most earthquakes (except the largest) are positioned on the nodes of a fairly coarse grid (apparently 1/4 or even 1/2 degree). Therefore, it is difficult to determine precisely the surface area covered by the aftershocks. We tested a randomization of the coordinate localisation with different uncertainties (0.25°, 0.30°, 0.50° and 0.75°). Obviously, the larger the uncertainty the larger the area covered by aftershocks (Fig. S2). However, simply counting the number of events detected and localized roughly at the same coordinates, a simple pattern with 3 distinct clusters emerges (Fig. 4).

(i) Most events (25 out of 35) occurred around the city of Vallenar (71°W, 29°S), within a circle of the localisation uncertainty, probably 1/4 or 1/2 of a degree so around 50km. This is the core of the rupture area.

(ii) A cluster of 7 events occurred north-west of that, almost at the latitude of Caldera (27°S), but quite far out at sea, west of the subduction trench. This suggests that this specific cluster, disjointed from the bulk of the earthquakes around Vallenar, is triggered "outer rise" seismicity rather than real aftershocks. Given their latitude they could be positioned where the Copiapó ridge enters the subduction. It is perhaps this seismicity that has led previous authors to extend the rupture area northwards to at least 27°S. "Outer-rise seismicity" could reveal large near-trench coseismic slip at this latitude (Sladen and Trevisan, 2018). But in the listed cases, outer-rise earthquakes are relatively small (less than Mw 5 for Illapel 2015, and less than Mw 5.5 for Maule 2010), stretched along the trench and mostly occur between 0 and 50 km from the trench. It does not seem to be the case here, where the 7 events are probably above Mw 6 to be detected and clustered almost 100 km away from the trench.

(iii) A small cluster of 3 events occur south-east of Vallenar, at the latitude of La Serena (30°S), but this time very far inland. However, 4 additional earthquakes were detected in this area over seven years bracketing 1922 (Fig. 4-B), suggesting that this is "normal" seismicity unrelated to the 1922 event. They may be deep events occurring inside the slab that is bend at this latitude because of the transition from the flat slab area around 30°S.

This region is nowadays quite a seismic gap, at least for the observational period of the last 50 years (Fig. S4). So there clearly is something peculiar about this region which produced large earthquakes both before and after 1922, and none over at least the last 50 years.

One large aftershock of magnitude 6.6 occurred 6 days after the mainshock, far offshore the *Lengua de Vaca*, a promontory of the Tongoy peninsula, slightly south of La Serena ~30.3°S. It is an isolated event and it is difficult to know whether it occurred within the mainshock rupture area or outside of it. We tend to think that it is outside of it since isolated events of similar size occurred in this area, both long before and long after the 1922 earthquake: one event on Feb 15, 1917 and another one on July 10, 1923 (Fig. 4-B and Table S1). Finally, much further north, (near Chañaral at 27°S) a cluster of 6 events may induce the belief that the 1922 rupture reached this latitude. In reality, these earthquakes date back to 1918. They depict the 1918 Copiapó earthquake sequence, fairly well localized around the epicenter of the mainshock of magnitude around 8.

In summary, the area covered by earthquakes that can be safely described as aftershocks is actually rather small. It extends over ∼ 100 km from 28.5°S to 29.5°S (Fig. 4). Bearing in mind that the networks of the time may only have detected earthquakes of magnitude greater than 6, it is clear that many more undetected smaller events occurred. However, for recent Chilean megathrust earthquakes, the surface depicted by aftershocks of magnitude larger or equal to 6 corresponds well to the surface covered by all aftershocks (Fig. S5). It seems reasonable to think that the same applies for ancient earthquakes.

6. Kelleher's gap seems too long

In his work on South-American seismic gaps, for the rupture of 1922, Kelleher drew an ellipse of ~400 km long from slightly north of Chañaral (26.1°S) to slightly north of Coquimbo (~29.6°S) (Fig. 5 from Kelleher, 1972). He then increased his estimation of the rupture zone by including Coquimbo (30°S) in it, bringing the total length of the rupture to approximately 450 km long (Kelleher, 1972, pp.2098-2099). This figure became a milestone and was reproduced in hundreds of works since, including the famous work of Kanamori (1977) on great earthquakes magnitudes and the work of Beck et al. (1998) on Chilean historical earthquakes. We discuss here the reasons why we think this rupture area is too large and should be reduced by approximately half.

6.1. Southward

Kelleher's arguments for extending the rupture southward down to Coquimbo (~29.6°S) are threefold. i) "considerable damage between about 27° and 30°S [(Willis, 1929)]"; ii)

"tsunami was most destructive in the vicinity of Coquimbo (29.57°S) [(Berninghausen, 1962)]"; and iii) "most of the damage in Coquimbo is related to the earthquake and not to the tsunami [(Lomnitz, 1970)]". All 3 are highly debatable, if not factually incorrect:
(i) Of course there was considerable damage in the Atacama area: Vallenar was destroyed and Copiapó suffered heavily. However, precisely, Coquimbo was not so much affected (see section 4.7). Sieberg assigned an intensity 6 (Mercalli). Willis assigned an intensity 7 (Rossi–Forrel). Bobillier and Sierra did not even bother to assign an intensity given the lightness of the damage there (see section 3 - Tab. 2)).
(ii) Yes, the tsunami was destructive in Coquimbo, but not particularly high. Berninghausen (1962) wrote *"The tsunami was most destructive in the vicinity of Coquimbo, where 3 waves 17 feet high reached $1\frac{1}{4}$ miles inland. The wave at the head of a funnel-shaped bay was 23 feet high"*. This comes from Heck (1947) who took it from Willis (1929), who is therefore the one and only source. But we explained how Willis's figure of 23 feet - or 7 meters could be exaggerated and why we favor a reduced figure of 4.6 meters coming from Aguirre (1923) measurements (see section 2.4).
(iii) The information from Lomnitz (1970) that most of the damage in Coquimbo is earthquake related, is a mistake. It contradicts all other sources (see section 4.7). Last, Kelleher indicates that the S-P data from La Paz suggest an aftershock zone extending southward to about 30.8°S, which leads him to include Coquimbo in the estimated rupture zone. We were not able to review these data, but the ISC catalog shows only 3 earthquakes this far south during the first 3 months after the mainshock. The very large distance between these earthquakes and the bulk of the aftershocks clustered around Vallenar and the previous occurrence of large earthquakes there suggests that they are not directly connected to the 1922 rupture (see section 5).

6.2. Northward

Kelleher's arguments for extending the rupture northward up to Chañaral (∼26.2°S) are also threefold. i) Again, "considerable damage between about 27° and 30°S [(Willis, 1929)]"; ii) "coastal uplift at Chañaral (26.2°S) [(Willis, 1929)]"; iii) "The tsunami source area was significantly to the north, actually near Caldera (∼27°S) (Gutenberg, 1939)". All three are questionable:
(i) Damage north of Copiapó (27.5°S) is the opposite of considerable. Sieberg, Bobillier and Willis, all 3 concur that intensities were below 7 at Caldera (27°S) and below 6 at Chañaral (26.2°S) (see section 3 - Tab. 2). Bobillier (actually, Aguirre) noted that tall old brick chimneys of an abandoned factory & mine in Chañaral had perfectly resisted the earthquake.

Also he acknowledged the fact that several sections of the railway going inland to the mine of Potrerillos (same latitude as Chañaral) had been destroyed, but because of landslides, not because of the earthquake itself. Last, in the technical annex of his report, Aguirre explained at length how houses and bodegas built next to the coastline in Chañaral were destroyed by the tsunami and not the earthquake. So, it is quite clear that there is a steep gradient of intensities between Copiapó (27.5°S) and Caldera (27°S).

(ii) The information of coastal uplift at Chañaral comes from a testimony reported by Willis: *"The day following the earthquake it was observed that the sea had withdrawn, leaving a great extent of the playa uncovered"*. It appears as a fragile argument. First, it is mentioned to Willis by one witness only (among 3) and like a second or third hand information "it was observed that...". Second, Aguirre who went there and measured the inundation height at several different places in Chañaral never mentions this observation nor the possibility of an uplift large enough to change the beach, including in the final pages of his report in which he discussed the reconstruction of the city. Whether it was because he did not observe the phenomena or because nobody mentioned it to him, is unknown. Considering the thorough investigations he conducted everywhere he went, we trust that the absence of such observation in his report is meaningful. Third, coseismic uplift/subsidence results from elastic rebound and are relatively large scale phenomena (at least 10 km). So if the beach had been uplifted, the whole nearby harbor should have been too. Uplift in harbors is usually easily observed because it leaves lines of dead seaweed and shellfish on moles, jetties, dykes, breakwaters, and dock pillars. But none of the like has been reported either in Chañaral nor in Caldera. Therefore, even though uplift is possible, we don't think it occurred in this specific instance. In addition, Bobillier wrote *"It was said that this earthquake and tidal wave had produced upheavals of the seabed and even of the coast. But the soundings carried out by the Navy's "Aguila" scamper proved that no such thing had happened"*. Idem in Huasco (28.5°S), soundings made in 1923 revealed identical to those carried out the year before the earthquake by the same ship. Same in Caldera (27°S), and even the opposite: a survey carried out in the port of Carrizal Bajo (28°S) revealed a small subsidence of the sub-marine floor in the sack of the port. So we consider unlikely that an apparent upheaval of the beach might be attributed to coseismic coastal uplift, but rather to tsunami deposits (for example), if real.

(iii) The fact that the tsunami source seemed to be located far north, comes from the misconception based on dubious tsunami arrival times north (Chañaral) and south (Coquimbo) of the rupture developed in Gutenberg (1939) and taken up in Lomnitz (1970) (see section

2). Last, also based on the S-P data from La Paz, Kelleher indicates that aftershocks occur up to ∼26°S. ISC catalog reveals that there are no large aftershocks this north, but only one cluster of earthquakes around 27.5°S. But these are far at sea and more likely triggered outer-rise earthquakes rather than aftershocks depicting the main rupture area (see section 5).

In summary, we suggest the rupture did not reach Coquimbo southward and did not reach Chañaral northward, and far from it since it did not even reach Caldera. Therefore, we think that Kelleher's ellipse is overextended by a factor of 2. The rupture did not extend over a length of about 400 km, from Chañaral (26°S) to Coquimbo (30°S), but rather only from Carrizal Bajo (south of Caldera) (28°S) to La Higuera (north of Coquimbo) (29.5°S), over a much shorter length of no more than 200km. This reduced length, and its location in the southern half of the gap, matches quite well the aftershock distribution revealed by the ISC catalog.

7. The 1918 "Copiapó" earthquake

Only 4 years before the great earthquake of November 1922, another significant earthquake had occurred nearby: the "Copiapó" earthquake of 4 December 1918. On this first instance, the city of Copiapó had already been razed to the ground (Linneman, 1922). The municipal authorities of the time commissioned an official photographer (José Antonio Olivares-Valdivia) to document the extensive damage. A dozen of these official photographs were published in two magazines of the time by the end of the month of December 1918 (Zig-Zag, 1918; Sucesos, 1918). Other photographs have been published in more recent books (Cáceres-Munizaga, 2018; Cortés and Zalaquett, 2020). It should be noted that in some other books, some photos from 1918 are erroneously attributed to 1922; a very understandable mistake since many pictures are strikingly similar (Monroy-Lopez, 2018; Cáceres-Munizaga, 2018). According to news reports of the time, entire blocks were reduced to a pile of rubble by the 1918 earthquake. The jail and the hospital were destroyed. Many shops were heavily damaged and in drugstores and pharmacies, medicines fell from their shelves to the ground. The statue of Bernardo O'Higgins (bronze bust on pedestal) fell to the ground. Damage was estimated to exceed 5 million pesos of the time, an amount quite similar to that of 1922.

The earthquake also caused considerable damage in Chañaral, despite the port's wooden buildings being more resistant than those made of adobe in the inland towns. The chimney of the French smelting company "*copper mines & factories of Chañaral*" partially collapsed and had to be later destroyed with dynamite. A significant tsunami was also observed there

(Cáceres-Munizaga, 2018).

This 1918 earthquake is often overlooked in the census of Chilean subduction earthquakes for a simple reason: its alleged relatively moderate magnitude $Ms = 7.6$ (Abe, 1981) or $M = 7.7$ (Kelleher, 1972) and its short rupture length: less than 50 km (Beck et al., 1998, Fig. 1) or even a simple dot (Fig. 5 from Kelleher, 1972). Actually, Kelleher did not discuss on the rupture length and just plotted the epicenter, and Beck et al. (1998) did not say anything specific about the 1918 earthquake. Most probably, both believed the 1918 event to be "much smaller" than the 1922 event. However, the original sources of information and the recent re-calculation of the magnitudes of a number of significant earthquakes by ISC-GEM Bondár et al. (2015), may indicate that its size has been underestimated.

First of all, the first magnitude estimation of "$7\frac{1}{2}$+" comes from Lomnitz (1970). Lomnitz does not say explicitly what are his sources, but the wording strongly suggests Linneman (1922). Apart from the report of very heavy destruction in Copiapó, Linnemann says 4 things about the 1918 earthquake: i) there was strong shaking in Caldera; ii) the shaking there lasted 6 minutes (to be compared to the 11 minutes of the 1922 event); iii) a tsunami occurred in Caldera soon, or even almost immediately, after the earthquake; iv) the tsunami reached ~5 meters high (Linneman, 1922, orig. pp. 417-418; trans. p. 6). An inundation is also reported at Chañaral, but without precision (Cáceres-Munizaga, 2018). Thus, a surprising fact: the 1918 earthquake produced a very significant tsunami over almost 100km of coastline, whereas the 1966 Taltal earthquake ($\sim$ 100 km north of Chañaral), of comparable magnitude (Mw = 7.8, Deschamps et al., 1980), did not (Lockridge, 1985). These observations suggest that the 1918 earthquake magnitude could have been underestimated. Finally, the Chilean Seismological National Center (CSN) currently indicates a magnitude 8.2 for this earthquake, unfortunately without indications of the sources and references for this rather high figure (CSN, 2023).

Second, Recent re-estimation of magnitudes by ISC-GEM indicates magnitudes Ms = 7.9 and Mw = 8.0 based on the readings from 8 seismograms (Bondár et al., 2015). There is a large scatter from 7.0 to 8.2, but the data from European stations are clustered around 8, and Ms=7.9 may be reasonable. On the same ISC data base, Ms for the 1922 event ranges from 7.6 to 9.5, but the European data are clustered around Ms=8.5 (*H. Kanamori, pers.comm. about* Bondár and Storchak, 2011). Thus, it may be reasonable to say that the difference in Ms between the 1918 and the 1922 events is about $\frac{1}{2}$ Ms unit. This is coherent with Abe (1981) who gives, Ms=7.6 for the 1918 event and Ms=8.3 for the 1922 event, which yields a ΔMs=0.7 between both events. Therefore, it is probably reasonable to assume that the magnitude difference (either Ms or Mw) between the 1922 and 1918 events is somewhere around 0.5-0.7, and that the magnitude of the 1918 earthquake could be revised to a slightly higher value of Mw∼8 (*H. Kanamori, pers.comm.*).

Accordingly, the rupture length could also be revised to a larger value. Rupture lengths commonly associated to Mw∼8 earthquake can reach ∼100 km, alike the recent 2014 Iquique earthquake (e.g. Ruiz et al., 2014). The commonly used scaling relation between the seismic moment, M_0, and the rupture length, L ($M_0 \sim L^3$), suggests ΔMw ranging between 0.6 and 0.95 for a rupture length ratio of 2 to 3, respectively. This difference is reasonable for the 200 km (1922 event) and 100 km (1918 event) combination. The ratio 300 km (1922) over 100 km (1918) is also within a reasonable range of magnitude difference, but ratios of 4, i.e. 400 km over 100 km or 200 km over 50 km, are too large (*H. Kanamori, pers.comm.*). For these reasons, we believe the 1918 earthquake rupture should also be revised to a longer length of around 100 kilometers.

A slightly larger magnitude around Mw∼8 and a longer rupture length around 100 kilometers would explain better a 6 minute duration, heavy damage in Copiapó, and a significant tsunami in Caldera and Chañaral. Last, the 1918 epicenter and its aftershocks (at least 6 events of Mw larger than 6) are located between 26°S and 27°S by ISC, much closer to Chañaral than Copiapó. This location is clearly north of the 1922 earthquake, but probably not adjacent to, and rather on the other side of the Copiapó ridge that enters the subduction precisely at 27.5°S.

The Chañaral earthquake of 4 October 1983 of magnitude Mw = 7.7 occurred in the same area (Dziewonski et al., 1984). It also caused damage in Copiapó and generated a moderate tsunami (10-20 cm detected at Valparaíso tide gauge). Unfortunately, the source characteristics of this earthquake are poorly defined since both CMT and ISC indicated a magnitude Mw of 7.7 and a depth of ∼ 40 km, but USGS assigned it a significantly smaller magnitude Mw = ∼ 7.4 and a depth of around 15 km. However, a dozen large aftershocks span a region between 25.6°S and 26.8°S, which could be quite similar in extension and localisation to the 1918 event.

8. Discussion

The coupling inferred from GPS allows to identify two strongly coupled 150-200 km long segments: the Chañaral segment (25.5°S - 27°S) to the north and the Atacama segment (28°S - 29.5°S) to the south. The two segments are separated by a zone of low coupling positioned slightly south of Caldera (Barranquilla LCZ, from 27.5°S to 28°S), which corresponds to the entry into subduction of the Copiapó ridge (Fig. 6). So, on the one hand, the 1922 Vallenar earthquake, restricted to a 200 km long rupture would have rupture the Atacama segment (Fig. 6). On the other hand, the 1918 Copiapó earthquake, which was actually located at the latitude of Chañaral according to the ISC-GEM locations of the mainshock and six large aftershocks, would have ruptured the Chañaral segment.

In this situation, the presence of a weakly coupled zone at the latitude of Barranquilla could have prevented a longer rupture by impeding the rupture from propagating through the LCZ, from one coupled segment into the next one. In general terms, a seismic rupture may enter a LCZ over a certain length, but is expected to stop somewhere into it and not cross it. Because in a LCZ coupling is weak but not zero, some slip, possibly slower, can occur in or around it. With a typical coupling value of 0.1-0.2, 10 to 20% of the plate tectonic rate should give way to accumulation of deformation, which, with the Chilean convergence rate of 7 cm/yr, yields 0.7 to 1.4 meters to be released co-seismically (or otherwise) every 100 years. Regarding the 1922 event, the Barranquilla LCZ, immediately north of the Atacama coupled segment and/or any other weakly coupled area next to it could accommodate some slip during a seismic rupture. That would somehow increase the rupture length, depending on how much slip exactly occurs and whether this slip is fast enough to generate strong enough shaking. This is also true for the La Serena LCZ positioned south of the segment. This aspect underlines the difficulty of defining a rupture length at better than several tens of km, i.e. a significant fraction of the width of the LCZs that border the coupled segment. Considering the 1922 event, the seismic rupture itself to which we attribute a length of $\sim$200 km, may have extended northwards (resp. southward) for a few tens of km into the Barranquilla (resp. La Serena) LCZs, including into their down-dip narrow strips of moderate coupling featured in our coupling model. Slow slip there would have increased the earthquake magnitude, without producing strong shaking.

Finally, the large depth of the 1922 epicenter, positioned in the middle of the segment rather than on either edge, and the complex coupling pattern of the segment could also explain the subdivision of the source time function into 3 main distinct pulses (the 3 distinct shocks felt by witnesses) (Beck et al., 1998). This, plus the slightly deeper coupling of the segment ($\sim$ 30 km), relative to the one of the North-Metropolitan segment that produced the Illapel earthquake of 2015 ($\sim$ 20 km), may also explain a relatively deeper and further inland epicenter.

Many attempts have been made to evaluate the magnitude of the 1922 earthquake. This is not an easy task given the complexity of the rupture source and values range from Ms

= 8.3 (Beck et al., 1998) to Mt = 8.7 (Abe, 1979). However, the currently accepted value of Mw = 8.5, is around the very first value proposed in Kanamori (1977), confirmed by tsunami modeling of Carvajal et al. (2017) and the latest work by Kanamori et al. (2019). A magnitude Mw = 8.5 corresponds precisely to 7 meters of slip on a fault that is 200 kilometers long and 100 kilometers wide (with a rigidity coefficient of 0.4). So, if this study suggests a revision of the rupture length from 400 km to 200 km long, it does not imply a revision of the magnitude, on the contrary.

Therefore, based on the convergence speed of the Nazca and South American plates (7 cm/yr), we can estimate that a recurrence interval of $\sim$ 100 years for an earthquake of magnitude around 8.5 on the Atacama segment is likely. This duration corresponds well to the elapsed time between the 1819 and the 1922 earthquakes. We conclude that an earthquake of equivalent size on the Atacama segment is probable and imminent. Additionally, regarding the Chañaral segment, if 1983 is similar to 1918, this would define a recurrence of around 60-70 years for a characteristic magnitude $\leq$ 8 earthquake on this segment, disconnected from the Atacama segment by the Copiapó ridge and the Barranquilla LCZ.

9. Conclusion

The revision of original articles and reports on the 1922 earthquake led us to propose that its rupture length is not 400-450 km but rather only 200 km. This corresponds extremely well to the Atacama segment depicted by the coupling inferred from recent geodetic measurements. On the other hand, there's no reason to revise its magnitude, 8.5 corresponding very well to the accumulation on this segment at the current tectonic rate.

However, on the occasion we also suggest a revision of the magnitude, rupture length (both larger than thought) and localisation of the 1918 earthquake. It does not seem to have ruptured the northern part of the 1922 rupture but on the contrary ruptured another disconnected segment to the north of the Atacama segment. Thus, these two segments, Atacama to the south and Chañaral to the north, would have different seismic cycles with different characteristic earthquakes and different recurrence time: a Mw $\sim$ 8 earthquake every 60-70 years in the Chañaral segment (1918 and 1983 being the 2 last events there) and a larger Mw $\sim$ 8.5 earthquake every $\sim$ 100 years in the Atacama segment (1819 and 1922 being the 2 last events there).

A strong coincidence between present day coupling inferred from geodetic measurements and recent earthquakes in Chile have been established (Métois et al., 2016). On two occasions, we find this coincidence to hold for historical earthquakes ruptures, once their estimation is corrected from long lasting misconceptions: this work for 1922 and our previous work for 1877 in north Chile (Vigny and Klein, 2022). This finding raises the interesting question of the reason for the permanency of coupling throughout the seismic cycle, since earthquakes are supposed to obliterate the asperities at the origin of the coupling along the plate interface.

References

Abe, K. (1979). Size of great earthquakes of 1837–1974 inferred from tsunami data. *Journal of Geophysical Research: Solid Earth*, 84(B4):1561–1568.

Abe, K. (1981). Magnitudes of large shallow earthquakes from 1904 to 1980. *Physics of the Earth and Planetary Interiors*, 27(1):72–92.

Aguirre, E. (1923). Los materiales y los procedimientos de construcción en la región afectada por el terremoto del 10 de Noviembre de 1922 (Continuación). *Anales del Instituto de Ingenieros de Chile*, (6):355–376.

Albini, P., Antonucci, A., Locati, M., and Rovida, A. (2018). Should Users Trust or Not Trust Sieberg's Erdbebengeographie(1932)? *Seismological Research Letters*, 90(1):335–346.

Angermann, D., Klotz, J., and Reigber, C. (1999). Space-geodetic estimation of the nazca-south america euler vector. *Earth and Planetary Science Letters*, 171(3):329–334.

Aránguiz, R., González, G., González, J., Catalán, P. A., Cienfuegos, R., Yagi, Y., Okuwaki, R., Urra, L., Contreras, K., Del Rio, I., et al. (2017). The 16 september 2015 chile tsunami from the post-tsunami survey and numerical modeling perspectives. *The Chile-2015 (Illapel) earthquake and tsunami*, pages 219–234.

Beck, S., Barrientos, S., Kausel, E., and Reyes, M. (1998). Source characteristics of historic earthquakes along the central Chile subduction Askew et alzone. *Journal of South American Earth Sciences*, 11(2):115–129.

Berninghausen, W. H. (1962). Tsunamis reported from the west coast of South America 1562-1960. *Bulletin of the Seismological Society of America*, 52(4):915–921.

Bobillier, C. (1926). Boletín del Servicio Sismológico de Chile - XVI - Año de 1922 - terremoto de Atacama. *Talleres de El Diario Ilustrado, Santiago de Chile.*

Bobillier, C. (1933). Historia de los maremotos acaecidos en Chile desde el año 1562-hasta el año 1932. *Boletín del Servicio Sismológico de Chile*, (23):34–41.

Bondár, I., Engdahl, E. R., Villaseñor, A., Harris, J., and Storchak, D. (2015). ISC-GEM: Global Instrumental Earthquake Catalogue (1900–2009), II. Location and seismicity patterns. *Physics of the Earth and Planetary Interiors*, 239:2–13.

Bondár, I. and Storchak, D. (2011). Improved location procedures at the International Seismological Centre: Improved location procedures at the ISC. *Geophysical Journal International*, 186(3):1220–1244.

Brooks, B. A., Bevis, M., Smalley Jr, R., Kendrick, E., Manceda, R., Lauria, E., Maturana, R., and Araujo, M. (2003). Crustal motion in the Southern Andes (26°-36°S): Do the Andes behave like a microplate? *Geochemistry, Geophysics, Geosystems*, 4(10).

Cáceres-Munizaga, M. (2018). *Atacama sísmica: un compendio de eventos telúricos ocurridos en la región de Atacama desde el siglo XVIII.* Ediciones on demand, (www.edicionesondemand.cl).

Carvajal, M., Cisternas, M., Gubler, A., Catalán, P., Winckler, P., and Wesson, R. L. (2017). Reexamination of the magnitudes for the 1906 and 1922 Chilean earthquakes using Japanese tsunami amplitudes: Implications for source depth constraints. *Journal of Geophysical Research: Solid Earth*, 122(1):4–17.

Cisternas, A. (2009). Montessus de Ballore, a pioneer of seismology: The man and his work. *Physics of the Earth and Planetary Interiors*, 175(1–2):3–7.

Contreras-López, M., Winckler, P., Sepúlveda, I., Andaur-Álvarez, A., Cortés-Molina, F., Guerrero, C. J., Mizobe, C. E., Igualt, F., Breuer, W., Beyá, J. F., et al. (2017). Field survey of the 2015 chile tsunami with emphasis on coastal wetland and conservation areas. *The Chile-2015 (Illapel) Earthquake and Tsunami*, pages 235–253.

Cortés, G. and Zalaquett, R. (2020). *Copiapó 1918: El registro de una Catástrofe.* ediciones del museo regional de Atacama.

CSN (2023). Centro Sismológico Nacional de Chile (CSN).

Davis, J. F. (1982). Earthquake planning scenario : For a magnitude 8.3 earthquake on the San Andreas fault in Southern California. California Department of Conservation, Division of Mines and Geology, Special Publication n°61(Special Publication n° 61).

Davison, C. (1929). The Chilean Earthquake of 1922. *Nature*, 124(3123):391–392.

Deschamps, A., Lyon-Caen, H., and Madariaga, R. (1980). Etude du tremblement de terre de Taltal (Chili 1966) à partir des ondes sismiques de longue période. *Annales Geophysicae*, 36(2):179–190.

Dorbath, L., Cisternas, A., and Dorbath, C. (1990). Assessment of the size of large and great historical earthquakes in Peru. *Bulletin of the Seismological Society of America*, 80(3):551–576.

Dunbar, P., Mungov, G., Sweeney, A., Stroker, K., and Arcos, N. (2017). Challenges in Defining Tsunami Wave Heights. *Pure and Applied Geophysics*, 174(8):3043–3063.

Dziewonski, A., Franzen, J., and Woodhouse, J. (1984). Centroid-moment tensor solutions for October–December, 1983. *Physics of the Earth and Planetary Interiors*, 34(3):129–136.

Finch, R. H. (1924). On the prediction of tidal Waves. *Monthly Weather Review*, 52(3):147–148.

González-Vidal, D., Moreno, M., Sippl, C., Baez, J. C., Ortega-Culaciati, F., Lange, D., Tilmann, F., Socquet, A., Bolte, J., Hormazabal, J., et al. (2023). Relation between oceanic plate structure, patterns of interplate locking and microseismicity in the 1922 atacama seismic gap. *Geophysical Research Letters*, 50(15):e2023GL103565.

Greve, F. (1949). Determinacion del coeficiente de seguridad antisismico para las diferentes zonas de Chile. *Anales de la faculdad de ciencias fisicas y matematicas de la universidad de Chile*, (5):3–19.

Gutenberg, B. (1939). Tsunamis and earthquakes. *Bulletin of the Seismological Society of America*, 29(4):517–526.

Gutenberg, B. (1959). *Physics of the Earth's Interior.*

Gutenberg, B. and Richter, F. (1954). *Seismicity of the Earth and Associated Phenomena.*

Hayes, G. P., Moore, G. L., Portner, D. E., Hearne, M., Flamme, H., Furtney, M., and Smoczyk, G. M. (2018). Slab2, a comprehensive subduction zone geometry model. *Science*, 362(6410):58–61.

Heck, N. H. (1947). List of seismic sea waves. *Bulletin of the Seismological Society of America*, 37(4):269–286.

Iida, K. (1956). Earthquakes accompanied by tsunamis occurring under the sea off the Islands of Japan. *J. Earth Sri.*, 4:1–43.

Iida, K., Cox, D. C., and Pararas-Carayannis, G. (1967). *Preliminary catalog of tsunamis occurring in the Pacific Ocean.* Hawaii Institute of Geophysics, University of Hawaii Honolulu.

ITIC (2023). International Tsunami Information Center / National Geophysical Data Center / World Data Service / NOAA National Centers for Environmental Information : Global Historical Tsunami Database.

Jiménez, C., Carbonel, C., and Rojas, J. (2017). Numerical Procedure to Forecast the Tsunami Parameters from a Database of Pre-Simulated Seismic Unit Sources. *Pure and Applied Geophysics*, 175(4):1473–1483.

Kanamori, H. (1977). The energy release in great earthquakes. *Journal of Geophysical Research*, 82(20):2981–2987.

Kanamori, H., Rivera, L., Ye, L., Lay, T., Murotani, S., and Tsumura, K. (2019). New constraints on the 1922 Atacama, Chile, earthquake from Historical seismograms. *Geophysical Journal International*, 219(1):645–661.

Kelleher, J. A. (1972). Rupture zones of large South American earthquakes and some predictions. *Journal of Geophysical Research*, 77(11):2087–2103.

Keys, J. (1957). History of the Tsunamis in Samoa. *Apia Obs., Samoa.*

Klein, E., Métois, M., Meneses, G., Vigny, C., and Delorme, A. (2018). Bridging the gap between North and Central Chile: insight from new GPS data on coupling complexities and the Andean sliver motion. *Geophysical Journal International*, 213(3):1924–1933.

León, T., Vargas, G., Salazar, D., Goff, J., Guendon, J. L., Andrade, P., and Alvarez, G. (2019). Geoarchaeological records of large Holocene tsunamis along the hyperarid coastal Atacama Desert in the major northern Chile seismic gap. *Quaternary Science Reviews*, 220:335–358.

Linneman, C. (1922). Informe sobre el terremoto de Copiapó del 4 de diciembre de 1918. *Boletín Minero de la Sociedad Nacional de Minería*, 279:412–420.

Lockridge, P. A. (1985). *Tsunamis in Peru-Chile*, volume 39. The Center.

Lomnitz, C. (1970). Major earthquakes and tsunamis in Chile during the period 1535 to 1955. *Geologische Rundschau*, 59(3):938–960.

Métois, M., Vigny, C., Socquet, A., Delorme, A., Morvan, S., Ortega, I., and Valderas-Bermejo, C.-M. (2014). Gps-derived interseismic coupling on the subduction and seismic hazards in the atacama region, chile. *Geophysical Journal International*, 196(2):644–655.

Meza-Pizarro, A., Muñoz-Barraza, M., and Whittaker-Roa, M. A. (1992). *Historia de las catástrofes ocurridas en la region de Atacama.* Tesis para optar al título de Profesor de Educación General Básica con mención en ciencias sociales y al grado de Licenciado en Educación, Departamento de Educación, Universidad de Atacama, Copiapó, Chile.

Molina, D., Tassara, A., Abarca, R., Melnick, D., and Madella, A. (2021). Frictional segmentation of the chilean megathrust from a multivariate analysis of geophysical, geological, and geodetic data. *Journal of Geophysical Research: Solid Earth*, 126(6):e2020JB020647.

Monroy-Lopez, O. (2018). *Terremoto y maremoto en el Norte de Chile.* Gráfica Pamela Diaz Castro EIRL, Santiago, (pdia@dyproducciones.cl).

Montessus de Ballore, F. (1911). *Historia sísmica de los Andes meridionales, segunda parte: Terremoto y Maremoto del 9 de Mayo de 1877 en Chile septentrional y Perú meridional, 1911-1916*, volume 2. Sociedad Chilena de Historia y Geografia, editorial Cervantes, Santiago, Chile.

Métois, M., Socquet, A., Vigny, C., Carrizo, D., Peyrat, S., Delorme, A., Maureira, E., Valderas-Bermejo, M.-C., and Ortega, I. (2013). Revisiting the North Chile seismic gap segmentation using GPS-derived interseismic coupling. *Geophysical Journal International*, 194(3):1283–1294.

Métois, M., Vigny, C., and Socquet, A. (2016). Interseismic Coupling, Megathrust Earthquakes and Seismic Swarms Along the Chilean Subduction Zone (38°–18°S). *Pure and Applied Geophysics*, 173(5):1431–1449.

Ruiz, S. and Madariaga, R. (2018). Historical and recent large megathrust earthquakes in Chile. *Tectonophysics*, 733:37–56.

Ruiz, S., Metois, M., Fuenzalida, A., Ruiz, J., Leyton, F., Grandin, R., Vigny, C., Madariaga, R., and Campos, J. (2014). Intense foreshocks and a slow slip event preceded the 2014 Iquique Mw 8.1 earthquake.

Science, 345(6201):1165–1169.

Shepard, F. P., MacDonald, G. A., and Cox, D. C. (1949). The tsunami of April 1, 1946. *Bulletin of the Scripps Institution of Oceanography*, 5(6):6–33.

Sieberg, A. and Gutenberg, B. (1924). Das Erdbeben in der chilenischen Provinz Atacama am 10. November 1922. *Veroffentlichungen der Reichsanstalt fur Erdbebenforschung in Jena*, 137.

Silgado, E. (1974). Historia de los Grandes Tsunamis producidos en la Costa Occidental de América del Sur. *Centro Regional de Sismología para América del Sur.*

Sladen, A. and Trevisan, J. (2018). Shallow megathrust earthquake ruptures betrayed by their outer-trench aftershocks signature. *Earth and Planetary Science Letters*, 483:105–113.

Soloviev, S. and Go, C. (1975). A catalog of tsunamis on the eastern shore of the Pacific Ocean (1513-1968). *Nauka Publishing house, Moscow, USSR (in Russian); Can. Transi. Fish. Aquat. Sci. 5078, 1984 (in English).*

Sucesos (1918). El terremoto de Copiapó. *Revista Sucesos. Valparaíso, Chile.*, Edición 19 Diciembre.

Vigny, C. and Klein, E. (2022). The 1877 megathrust earthquake of North Chile two times smaller than thought? A review of ancient articles. *Journal of South American Earth Sciences*, 117:103878.

Vigny, C., Rudloff, A., Ruegg, J.-C., Madariaga, R., Campos, J., and Alvarez, M. (2009). Upper plate deformation measured by GPS in the Coquimbo Gap, Chile. *Physics of the Earth and Planetary Interiors*, 175(1–2):86–95.

Watanabe, H. (1964). Studies on the Tsunamis on the Sanriku Coast of the Northeastern Honshu in Japan. *Geophys. Mag*, 32(1):120–127.

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., and Tian, D. (2019). The Generic Mapping Tools Version 6. *Geochemistry, Geophysics, Geosystems*, 20(11):5556–5564.

Willis, B. (1929). Earthquake conditions in Chile. *Publication of the Carnegie Institution of Washington*, 382.

Wilson, R. M. (1928). A year of the tide gauge operation. *Monthly bulletin of the Hawaiian Volcano Observatory; USGS, Honolulu*, 16(3):17–25.

Yáñez-Cuadra, V., Ortega-Culaciati, F., Moreno, M., Tassara, A., Krumm-Nualart, N., Ruiz, J., Maksymowicz, A., Manea, M., Manea, V. C., Geng, J., and Benavente, R. (2022). Interplate Coupling and Seismic Potential in the Atacama Seismic Gap (Chile): Dismissing a rigid Andean Sliver. *Geophysical Research Letters*, 49(11).

Zig-Zag (1918). La desgracia de Copiapó. *Revista Zig-Zag. Santiago, Chile.*, Edición 21 Diciembre.

Acknowledgments

Maps are made with Generic Mapping Tools GMT (Wessel et al., 2019). Ancient articles transcripts were done with online OCR software (e.g. ocr2edit, pdftowordconverter). Translations were done with the DeepL translator. We thank Hiroo Kanamori and Matias Carvajal for very thorough and detailed reviews that greatly helped improving the manuscript. Special thanks to Domenico Di Giacomo from ISC for explaining the arcanes of ISC data base and to Luis Rivera for very enlightening discussions, to Miguel Cáceres, Omar Monroy and Rodrigo Zalaquett and many others for their help with libraries, compilations and books that kept the seismic history of Atacama alive. This work was supported by CNRS, ANR grant number ANR-19-CE31-0003 and Agencia Nacional de Investigación y Desarrollo through scholarship ANID-PFCHA/Doctorado Nacional/2020-21200903.

Data availability

Scans, transcripts and translations (if relevant) of four ancient articles (Linneman, 1922; Sieberg and Gutenberg, 1924; Bobillier, 1926; Willis, 1929), one report (Aguirre, 1923), two magazines (Sucesos, 1918; Zig-Zag, 1918) and the appendix of Davis (1982) are available as electronic supplements. Further citations of this work or use of transcripts or translations should also refer to the original articles.

Supporting Information

Linnemann_BoletinMinero_1922_original.pdf
Linnemann_BoletinMinero_1922_transcript.pdf
Linnemann_BoletinMinero_1922_translated.pdf
Aguire_AnalesIIC_1923_original.pdf
Aguire_AnalesIIC_1923_transcript.pdf
Aguire_AnalesIIC_1923_translated.pdf
Seiberg_NovaActa_1924_original.pdf
Seiberg_NovaActa_1924_transcript.pdf
Seiberg_NovaActa_1924_translated.pdf
Bobillier_BoletinSSC_1926_original.pdf
Bobillier_BoletinSSC_1926_transcript.pdf
Bobillier_BoletinSSC_1926_translated.pdf
Willis_Carnegie_1929_original.pdf

Willis_Carnegie_1929_transcript.pdf

Aguire_1923_Photos.pdf

Willis_1929_Photos.pdf

ZigZag_1918.pdf

Sucesos_1918.pdf

Location Name	Latitude (°S)	Longitude(°W)	ITIC	This work
Callao	12.05	77.15	2.4	0.7 ?
Chañaral	26.38	70.67	9	5.5
Caldera	27.07	70.83	7	5.5
Coquimbo	29.95	71.34	7	4.6
Huasco	28.46	71.22	-	5.5

Table 1: **Tsunami heights along the South American coastline.** Summary of tsunami heights in South America from ITIC data base and revised from this work. heights are in meters. Tsunami heights are the highest level reached by the inundation usually above the lowest tide level, but sometimes above the mean sea level. In the Atacama region of Chile, the difference is no larger than 0.5 meters

site	lat(°S)	lon(°W)	Intensities (Mercalli Modified)		
			Sieberg & Gutenberg (1924)	Bobillier (1926)	Willis (1929)
El Salado	26.367	69.750			
Chañaral	26.367	71.717	6	≤6[(1)]	
Potrerillos	26.450	69.500			7.2
Caldera	27.050	70.883	7	≤7[(2)]	6.8
Puquios	27.183	69.917			7.8
Copiapó	27.367	70.367	9	10	8.2
Tierra Amarilla	27.483	70.300	10	10	7.8
San Antonio	27.889	70.044	10		
Yerba Buena	28.000	70.000	9		
Carrizal Bajo	28.067	71.200	8		6.7
Carrizal Alto	28.085	70.901	8	10	
Huasco	28.450	71.283	9	9	8.2
Freirina	28.500	71.100	10	10	7.8
Gut Loncomilla	28.534	70.905	11		
Vallenar	28.583	70.800	11	11	8.9
El Tránsito	28.871	70.280	10		9*
San Félix	28.939	70.462	10		
La Serena	29.917	71.250	8	9	7.4
Coquimbo	29.969	71.336	6		
Rivadavia	29.978	70.560	9		8*
Vicuña	30.033	70.712	9	9	7*
Rodeo	30.216	69.143	7		
Ovalle	30.583	71.200		8[(3)]	

Table 2: **Intensities of the 1922 Atacama earthquake.** Summary of intensities reported at specific places by the different authors. Sieberg and Gutenberg (1924) is in Mercalli-Cancali-Sieberg scale. Bobillier (1926) is in Mercalli modified scale. Both being slightly but marginally different. Willis (1929) is converted from the Rossi-Forel scale they used into the Mercalli modified scale using Davis (1982) correspondence (see supp. section 5 for details). For all places but three, we use the compilations of intensities attributed by Sierra at every location (in Willis's appendix II) and first converted them, then computed an average value at each location. This average is the source of the decimal values. Note that the distance to the nearest integer gives an indication of the consistency of the figures at a given location. Numbers marked with an asterisk are for the remaining 3 locations (El Tránsito, Rivadavia and Vicuña), provided by Willis (1929) in the main text, and also converted in the Mercalli modified scale.

[1] This study, no figure given in ref. Justification: *"All old chimneys resisted the earthquake perfectly"*

[2] This study, no figure given in ref. Justification: *"Strong oscillations but no damage (solid constructions there)"*

[3] Exaggerated ? Only a single figure in one table, no details given in main text. Justification: *"Destruction: only few houses of poor conditions"*

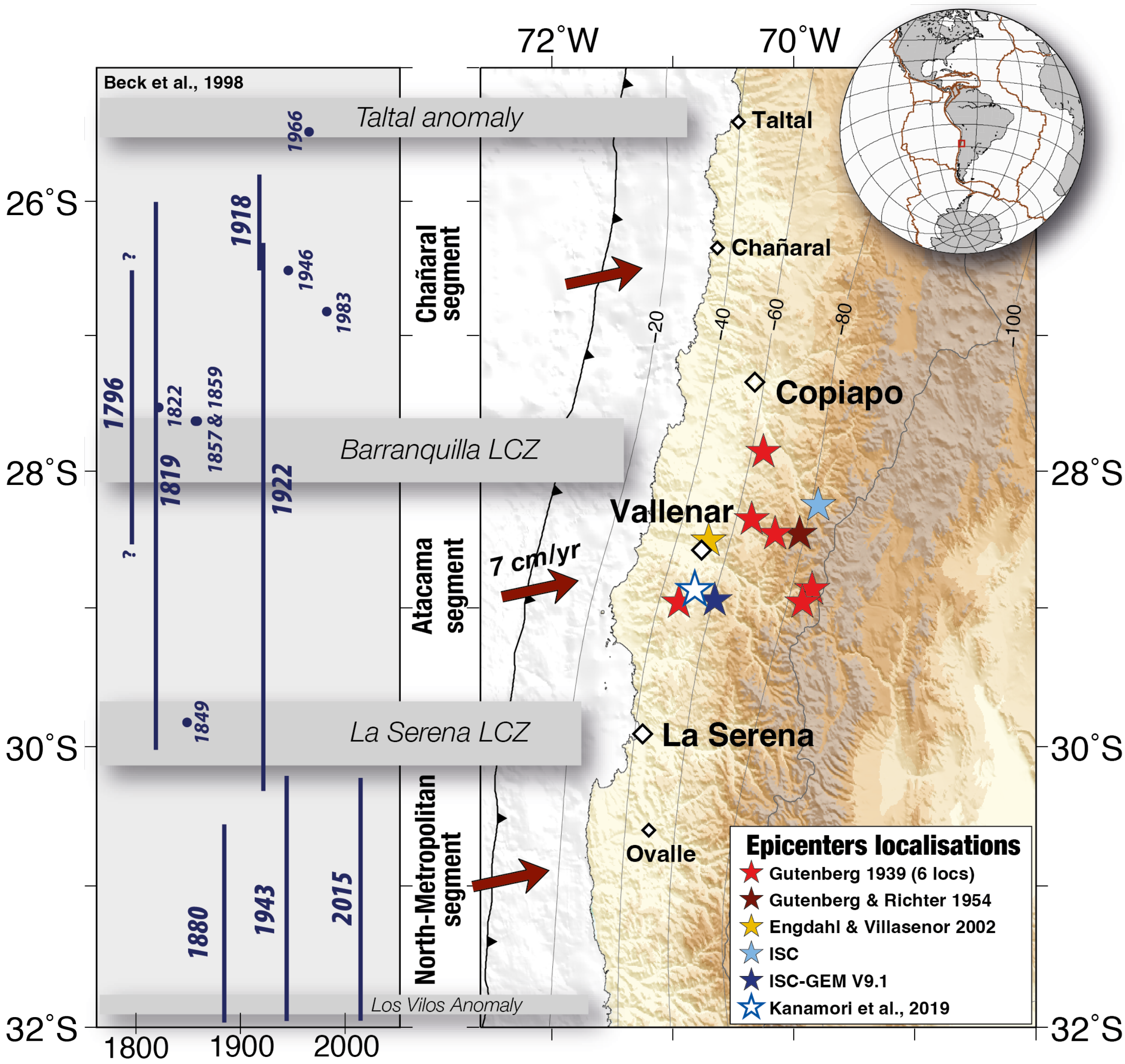

Figure 1: **Localisation map and space-time plot of megathrust earthquakes along the coast of north-central Chile, Modified after Beck et al. (1998)**. On the left panel, bar lengths depict rupture lengths of largest earthquakes. Dots represent smaller events of unknown rupture lengths. 1819 bar includes three events (April 3,4 and 11). 1796 bar represents two events (March 30 and August 24). Labels with the LCZ acronym indicate the localisation of the Low Coupling Zones inferred from recent geodetic measurements (Métois et al., 2016; Klein et al., 2018). On the right panel, the main localities mentioned in the text are depicted by diamond symbols. Colored stars depict the different localisations of the 1922 epicenter. The dark red arrow depict the Nazca-SouthAmerica plate convergence at 7 cm/yr. Slab2.0 isodepth from Hayes et al. (2018).

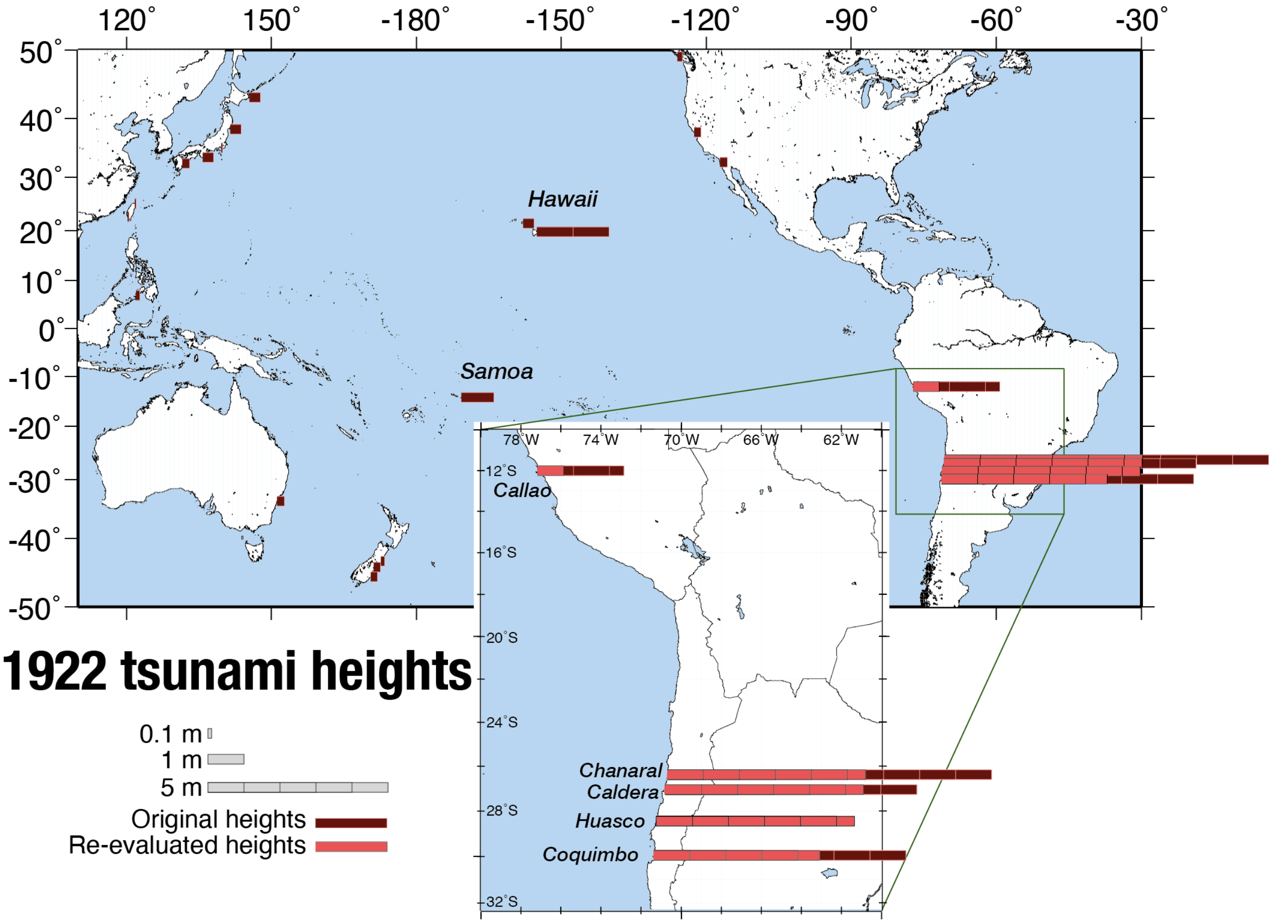

Figure 2: **1922 tsunami heights worldwide**. Dark red rectangles depict ITIC data base values (22 worldwide - only 4 along the coastline of South America). Light red rectangles depict revised values along the South American coastline according to this work.

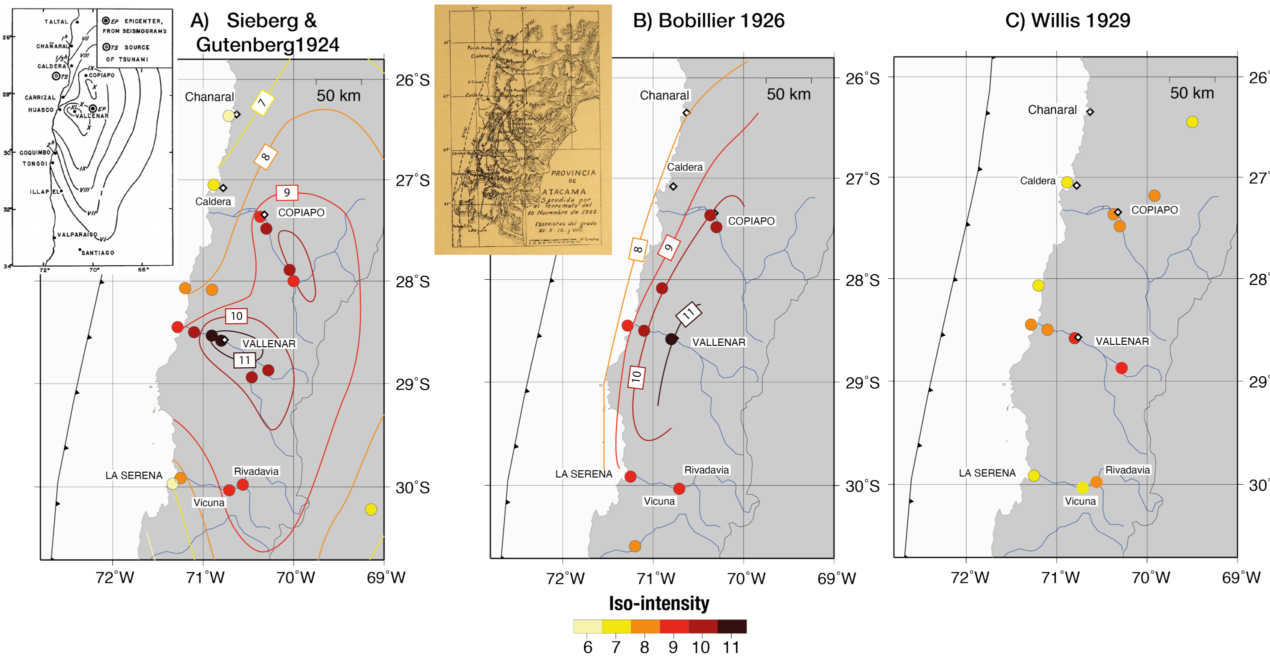

Figure 3: **Comparison of intensities attributed by A) Sieberg and Gutenberg (1924) ; B) Bobillier (1926) and C) Willis (1929)**. The same color scale for intensity is used for figures A, B and C. Insets depict the original figures from the corresponding articles.

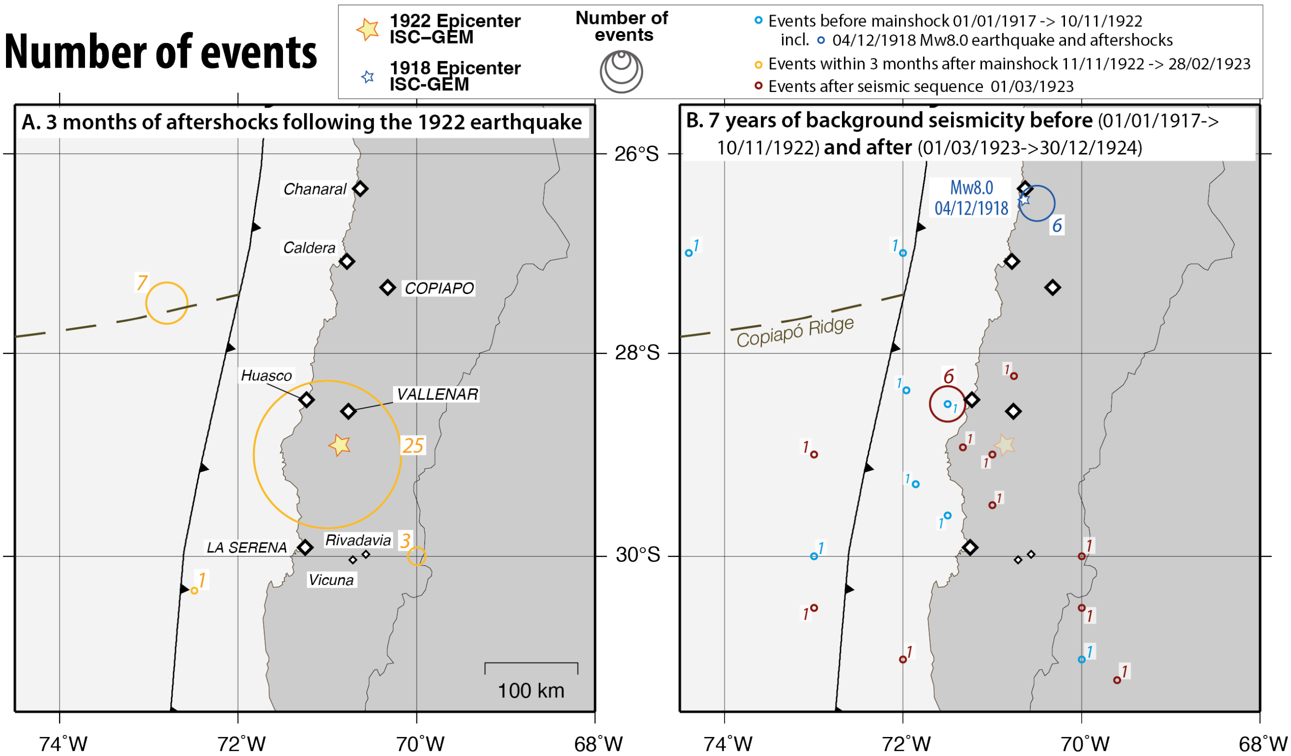

Figure 4: **Localisations & number of events, according to the International Seismicity Catalog, Bondár and Storchak (2011).** Because the precision of localisation at the time was quite low, most earthquakes (except the largest) are positioned on the nodes of a fairly coarse grid (apparently 1/4°). So, we represent the number of events at each localisation with circles of size proportional to the number of events at that coordinate. They range from 1 event (smallest circle) to 25 events (the largest circle close to the city of Vallenar). The number of events is also indicated. See table S1 for complete list of events. A. Aftershock seismicity over the 3 months following the 1922 earthquake, represented in yellow. The star depicts the mainshock epicenter (ISC-GEM, Bondár et al., 2015). B. 7 years of seismicity between 1917 and 1924, excluding the aftershocks 3 month-period. Events occurring before the 1922 earthquake are represented in blue. They include the Copiapó magnitude 8 earthquake of 4 Dec. 1918, depicted by the dark blue star, from (ISC-GEM, Bondár et al., 2015) and its own aftershocks (dark blue). Events occurring after the 1922 earthquake are represented in dark red. They include a "cluster" of 6 events offshore Huasco, 4 of these occurring within 3 weeks between July and August 2023. Since only significant magnitude events are detected (Mw $\geq$ 6), many more smaller events probably happened which could be evidence of a seismic swarm.

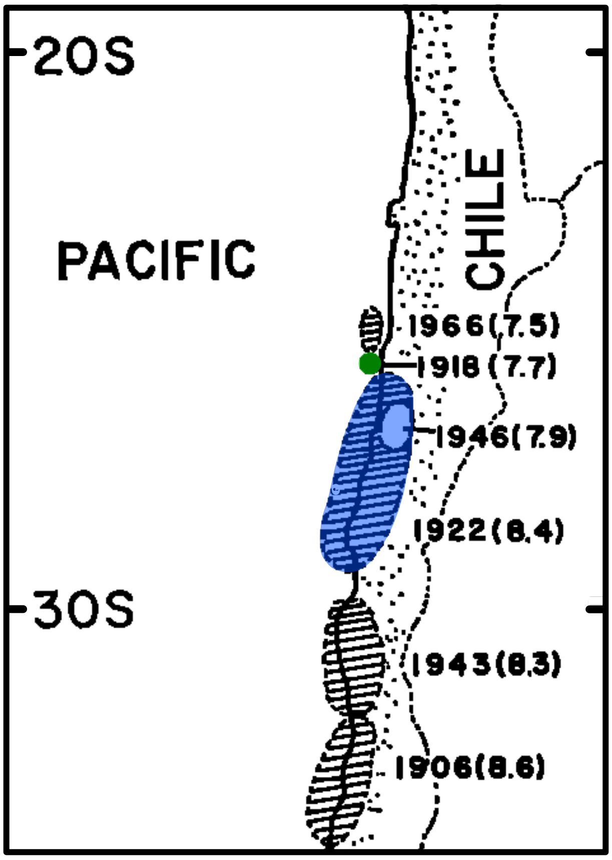

Figure 5: **North-Central Chile zoom of Fig.1 from Kelleher (1972)**. Hatched areas represent estimated rupture zones of large (M $\geq$ 7.7) Chilean earthquake of the 20^{th} century, among which 1922 is highlighted in blue. The green solid circle represent the epicenter of the 1918 earthquake. Magnitudes are in parentheses.

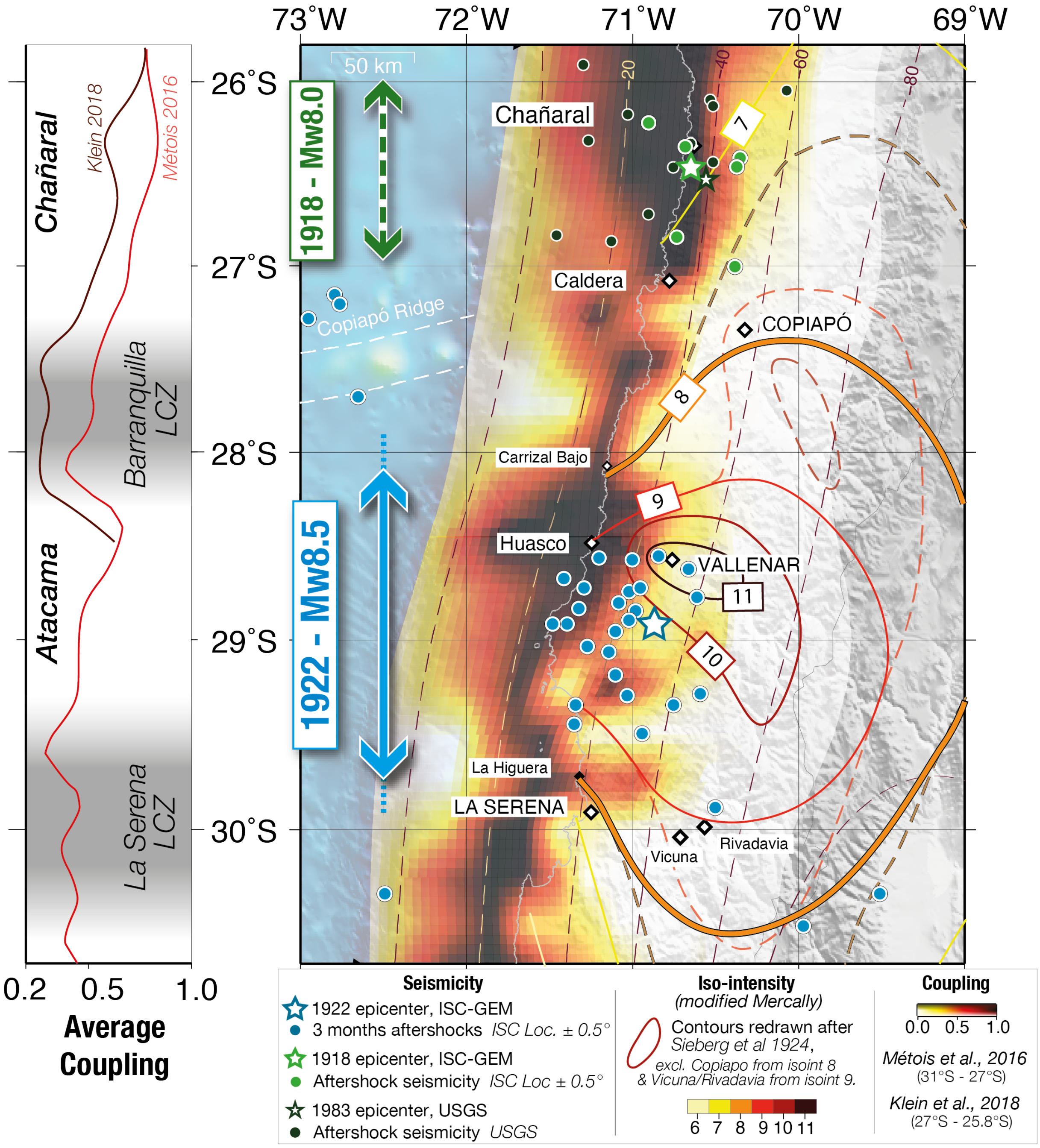

Figure 6: **Earthquake ruptures, coupling and segmentation**. Earthquakes rupture length and position are inferred from this work. On the left panel, the average coupling is depicted as a function of latitude: light red (Métois et al., 2016) and dark brown (Klein et al., 2018). Scale ranges from 0.2 to 1. The two areas (La Serena and Barranquilla LCZs) where coupling is relatively low are shaded in grey. On the right panel, map depicting the coupling combined from (Métois et al., 2016) and (Klein et al., 2018). Colour scale indicates the amount of coupling (white=0-red=50%-black=100%). Superimposed on the coupling map, events of 1918 and 1922 are depicted by a) their rupture lengths: 1918/1922 - dashed green / solid blue arrow; b) their epicenters 1918/1922 - green/blue star; c) their aftershocks: 1918/1922 - green/blue dots. Because the precision of localisation at the time was quite low, most aftershocks are positioned on the nodes of a fairly coarse grid (apparently 1/4 degree); to avoid this artefact of many aftershocks falling on the same node at the same coordinates, we artificially degrade their coordinates by a random 0.5 degrees (∼ 50 km in latitude and longitude). The 1983 Mw 7.7 earthquake epicenter and aftershocks (USGS source) are also depicted (dark green star and dots). Iso-lines of seismic intensities from (Sieberg and Gutenberg, 1924) are depicted with color codes (yellow to dark red), the iso-line VIII in orange is enhanced. Iso-line X south of Copiapó is suppressed and iso-lines VIII and IX are modified inland (North-South extension is reduced) in order to take into account the too excessive intensities attributed at Copiapó and Rivadavia/Vicuña. Slab isodepth from Hayes et al. (2018)