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The 1877 megathrust earthquake of North Chile two times smaller than thought? A review of ancient articles

Christophe Vigny *, Emilie Klein

Laboratoire de géologie - CNRS UMR 8538, Ecole normale supérieure - PSL University, Paris, France

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ABSTRACT

The 1877 North Chile megathrust earthquake is commonly considered as one of the largest historical earthquakes that occurred on the Chilean subduction zone. The literature generally attributes it a magnitude close to 9, associated with a rupture of about 500 km long. Because it occurred nearly a century and a half ago, the area is often described as a mature seismic gap, that is to say, a place where a great subduction earthquake similar to that of 1877 would be imminent. A careful study of historical articles describing the earthquake and subsequent tsunami shows that the size of the rupture has most likely been greatly overestimated. First of all, it seems that the area of severe shaking, corresponding to intensity VIII on the Mercalli scale, has been artificially increased. Secondly, it appears that once errors and exaggerations are corrected, nowhere was the subsequent tsunami actually higher than 10 m. It also appears that the initial exaggerations have been further amplified in the modern literature to reach today's estimation of the earthquake size. In reality, all historical observations, i.e. the intensities of destruction on the continent due to the earthquake itself and the characteristics of the subsequent tsunami, concur to attribute to the earthquake a rupture of only ~225 km long, located between 20.5°S and 22.5°S. Both this reduced length and its localization match very well the patchy coupling revealed by recent GPS measurement in the area and support the hypothesis of a rupture of the Loa segment alone. The estimation of an earthquake magnitude from the subsequent tsunami is always difficult because the amplitude of the tsunami at a given place depends on many more parameters than the seismic moment alone. The source localization which changes the azimuth and path towards a given receiving place, the source depth, the rupture velocity, all play a role. They remain largely unknown for the 1877 event. However, the comparison of the 1877 revised figures with recent tsunamis suggest the magnitude should also be lowered to around 8.5 : slightly larger than Illapel 2015, significantly smaller than Maule 2010. In all cases, the seismic hazard of the region should be revised downwards: the next expected earthquake in the region should be either significantly smaller than feared (magnitude ~8.5 rather than ~9), or occur much later than announced.

Introduction

A major earthquake, of magnitude close to 9, is said to have occurred in 1877 on the subduction in Northern Chile (e.g. Abe, 1979; Kausel, 1986; Comte and Pardo, 1991). This earthquake is known as the Great North Chile earthquake or the Arica-bend earthquake. Arica is the city located at the present day border between Peru and Chile where the subduction makes a curve – a bend – which connects the N-S trending Chilean section to the NW-SE trending Peruvian section. As no other very large earthquake has occurred in this region since that date, the area is considered as a seismic gap worth watching: deformation accumulating at a rate of about 6–7 cm/yr for nearly a century and a half, the gap seems ripe to produce soon a very large earthquake capable of releasing at once the 10 m of deformation accumulated since 1877 (e.g. Hayes et al., 2014). At first sight, the location of the gap seems to correspond with the strong and homogeneous coupling assessed from surface deformation quantified by space geodesy in the area (e.g. Chlieh et al., 2011). This would confirm the gap theory developed in the 70's and 80's (e.g. Kelleher, 1972; Nishenko, 1985). Interpretation is simple: earthquakes occur where the subduction is blocked because that is where the deformation accumulates.

However, as new data were acquired in the area with improving resolution, a variety of coupling models were produced (e.g. Béjar-Pizarro et al., 2013; Métois et al., 2013; Li et al., 2015; Métois et al., 2016; Hoffmann et al., 2018; Jolivet et al., 2020). These newer models depict a more complex pattern of coupling than a single large patch of intense coupling. As the resolution of the data improves, the models

* Corresponding author.
E-mail address: vigny@geologie.ens.fr (C. Vigny).

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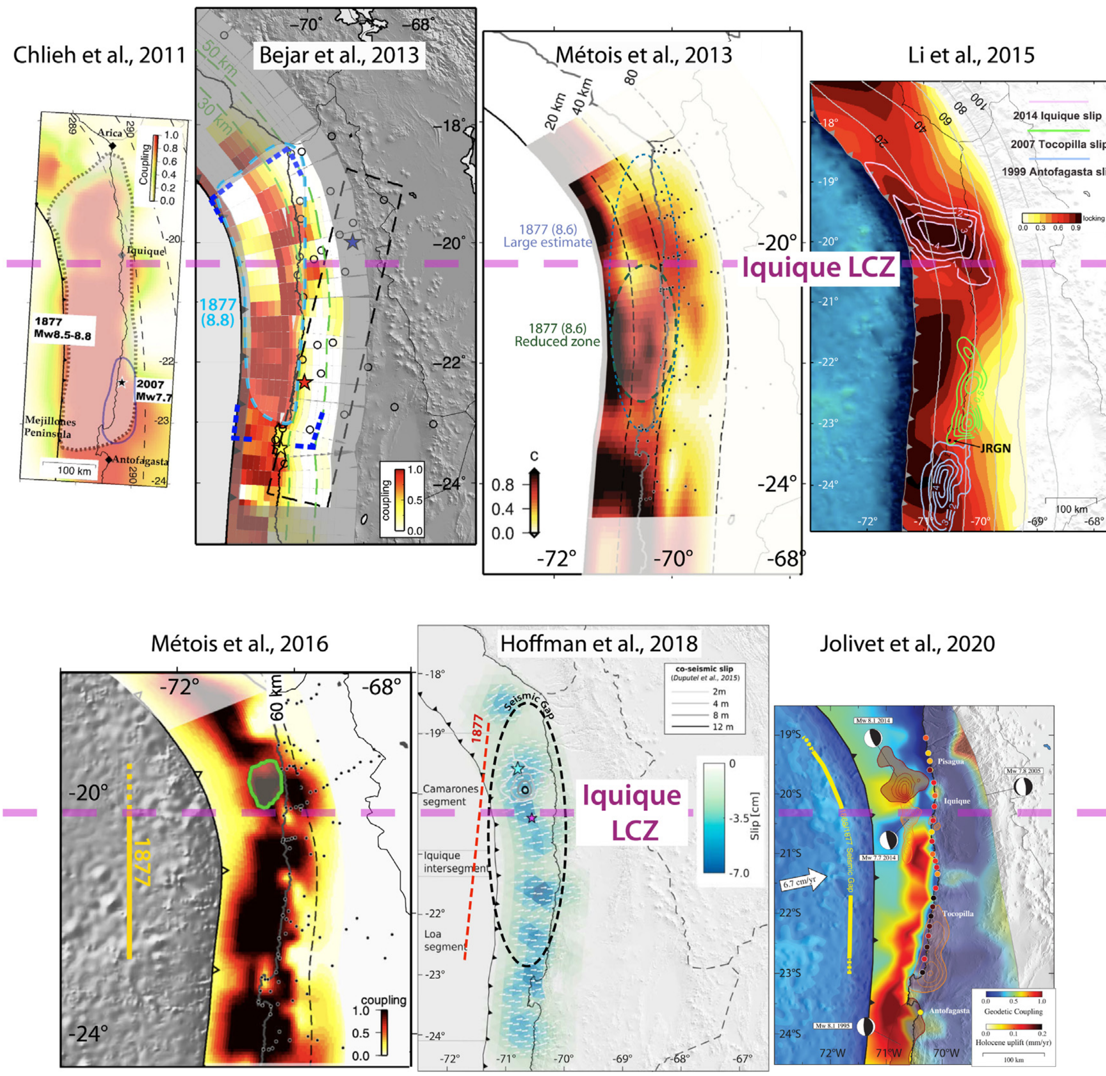

Fig. 1. Comparison of coupling models inferred in North Chile from the present-day geodetic measurements. From left to right top row: elastic backslip 3-plates model inferred from GPS by Chlieh et al. (2011); elastic backslip 2-plates model inferred from combined GPS and InSAR by Béjar-Pizarro et al. (2013); elastic backslip 3-plates model inferred from GPS by Métois et al. (2013); visco-elastic coupling model inferred from GPS by Li et al. (2015); bottom row: elastic backslip 3-plates model inferred from GPS by Métois et al. (2016), elastic backslip 3-plates model inferred from GPS by Hoffmann et al. (2018) and elastic backslip 2-plates model inferred from combined GPS and InSAR by Jolivet et al. (2020). All figures, extracted from original publications, were rescaled and rotated to be aligned. Figures from Chlieh et al. (2011) and Jolivet et al. (2020) show the extension of the 1877 North Chile earthquake. When available, we reported the rupture zone exactly as it was drawn on other figures of the articles (from Fig. 1 of Béjar-Pizarro et al. (2013), Fig. 5 of Métois et al. (2013), Fig. 2 of Métois et al. (2016) and Fig. 1 of Hoffmann et al. (2018)). The purple dashed line is located at the same latitude on both rows and highlights the latitude of the Iquique LCZ.

show a more and more heterogeneous patchy coupling (Fig. 1). In particular, starting with Métois et al. (2013), confirmed by Li et al. (2015) and Métois et al. (2016), coupling models consistently reveal a “bottleneck” of coupling at the latitude of Iquique (~20.5°S). Hoffmann et al. (2018) depict the same feature (in terms of slip rate rather than coupling coefficient), but oddly enough locate it ~100 km south of every other models. Here, the discrepancy is probably due to an unconventional way of estimating inter-seismic velocities: the average over 3 distinct time windows mixing the inter and post seismic periods of 2 earthquakes (Tarapaca and Tocopilla). However, in the end, all models yield the same pattern, independent of the data and whether they use simple elastic or more complex visco-elastic rheology.

The presence of such a low coupling zone in the middle of the North-Chile gap is unexpected and surprising: it cuts the long gap in two. Worse, coupling in the northern part of the gap seems to decrease a lot and even become evanescent north of Pisagua (~19.5°S) (Jolivet et al., 2020). So what remains is a much shorter length of strong coupling than the alleged rupture of 1877, and only in its southern part (Fig. 1). The coupled segment appears to be about 250 km long, from slightly north of Antofagasta (23°S) to slightly south of Iquique (20.5°S), while the alleged 1877 rupture length is almost double with 500 km from Antofagasta to Arica (23.5°S-18.5°S). According to these models, the alleged 1877 rupture seems to include the coupled segment in its southern part, but its northern extension covers areas where coupling is variable, alternating relatively strongly and weakly coupled patches over several hundreds of kilometers. This finding has led to doubts about coupling maps accuracy, and even to question the gap theory. But how do we know the length of the 1877 rupture ? In fact, its estimation is problematic. A careful reading of the literature shows how the length of this rupture has been overestimated and increased surreptitiously article after article. Thus, a return to the source of the ancient articles on the 1877 earthquake and subsequent tsunami is in order to clarify the question.

For this work, we reanalyzed 5 ancient scientific articles from which everything originated. First and foremost, Geinitz (1878) (hereafter G); then Vidal-Gormaz (1878) (VG), Milne (1880) (M), Harnecker (1895 &1897) (H), Montessus de Ballore (1911) (MdB). We also include 2 more recent articles Soloviev and Go (1975) (S) and Kausel (1986)

(K). Finally, we discuss how the 1877 rupture was introduced in the modern scientific literature by Comte and Pardo (1991). Except for Milne (1880), and a translation of Soloviev and Go in English (in 1984), the ancient articles are in German or Spanish, quite difficult to find and not always easy to read. We were able to access the original documents (or scans of the original documents), transcript and translate them using automated Optical Character Recognition (OCR) and translation software (DeepL). English translated transcripts of these articles are provided in the Auxiliary material. We evaluated and sorted the credible information in the light of a careful and thorough cross-examination. This also brought out typos, errors, recopying errors and their possible transmission from one article to the next. Finally, we extracted and summarized the information relevant to our original question about the 1877 rupture length.

1. Description of the scientific literature used in this work

1.1. Geinitz (1878)

Is in German – 80 pages long – published in Nova Acta, the journal of the German Academy of Science. Eugen Geinitz was German. He obtained his PhD from the University of Leipzig in 1876 with a dissertation on mineral pseudomorphs and became a professor of mineralogy & geology at Rostock university, Germany. In this work he compiles information about both the earthquake and the subsequent tsunami. He gathered all sorts of information (Earthquake time, shaking intensity, tsunami description, timing and wave amplitudes, ..) through two main sources: (a) contemporary press articles and (b) a questionnaire he drafted and had distributed to local authorities through the German (imperial) consular network, very present in South America at the time. Various newspapers also published the questionnaire. Geinitz also collected reports from ship captains (The merchant navy is very present at that time because of the trade of metal ore and nitrate) and from other unknown individuals whom he lists in his acknowledgments.

At the time, little was known about earthquake ruptures and seismic waves. So, a good part of his work is devoted to finding the point (*das centrum*) of the "explosion". For this matter, Geinitz observes that the time at which the earthquake shock is reported varies from place to place. This is an indication of the varying seismic waves travel time and should in principle allow the determination of the location of the origin. However, Geinitz rapidly realizes this is impossible to do because of poor clocks, unable to provide any kind of accurate timing. XIXth century clocks are not precise and more importantly not synchronized. So differences of 5–10 minutes mean nothing. At Caldera for example, there are two official clocks: one at the lighthouse, operated by the harbor authorities, and one at the railway station. The first one is set by sextant or sundial observations by a naval officer. The second one is set by observations of sunrise and sunset. There is a 6-minute difference between them. What remains is the assumption that the directions of the displacements observed at a particular location indicate the direction from which the waves come, and thus locating the origin should become a relatively simple exercise of geometry. Obviously, this particular effort also fails due to the ignorance of the diverse polarization of the various seismic waves, and even more important the ignorance of the fact that the seismic source is not a single point and cannot be reduced to an explosion. However, Geinitz concludes to a general feeling that the origin of the seismic waves is located at sea and somehow South-West of the city of Iquique.

Another good part of his work is devoted at analyzing the tsunami travel time, first along the South-American coastline and second across the Pacific Ocean. The first part (near field) yields no results, again because of poor clocks unable to provide any kind of accurate timing over short duration. In 1877, most clocks are pendulums clocks. Geinitz reports that Clock-makers of Tacna (near Arica) indicated that most of the pendulums of the clocks stop swinging during the earthquake, only those oriented in the direction of the waves kept ticking (!). So 1 to 6 minutes of the elapsed time between the earthquake and the tsunami are commonly lost at many locations. Last, rather than a single large wave, the tsunami is a succession of waves of variable amplitude. What is more, in the near field, the tsunami happened immediately after the earthquake, that is to say at night and in an instance of great confusion. Therefore, the reported tsunami time can be the one of any of the incoming waves, sometimes the first, possibly the highest, but rarely the true first motion of the sea. The second part (far field) yields better results, albeit difficulties with local time conversions, and allows him to quantify the "average" depth of the Ocean along the paths of the tsunami.

It can be difficult to sort through the mass of information from Geinitz (1878) and sort out the facts from the exaggerations, not to mention the pure inventions. With today's eyes, we conclude that the most credible information is usually provided by port authorities, conveyed to Geinitz through answers to his questionnaire. On the opposite, press articles (from journals like "*The South Pacific Times*", "*Das Valparaisoer Deutsche Nachrichten*", "*El Mercurio del Vapor*", "*La Revista del Sur*", "*The Hawaiian Gazette*", "*The Lyttelton Times*", "*The Japan Gazette*", "*The Hiogo News*",…) report events that are very often second or third hand, sometimes even based on hearsay, described in vague words, often exaggerated, sometimes completely invented (no corroboration by any other first-hand source) and in blatant contradiction with the more technical reports. The worst examples being provided by the "*Comercio de Lima*" and "*El Nacional de Lima*", whom reported a tsunami of 19.75 m at Arica (65 feet) ("*La gran ola subió 65 pies*") when the port authorities only reported 8.6 m to Geinitz, with the precision that this height came with the second last wave (*die vorletzte/la penúltima*) at 4 h (G trans.p17). Trustful information extracted from Geinitz 1877 is summarized in Tables 1 and 2.

Hilliger's report

Last, Geinitz's article contains a golden nugget: a report of a few pages produced by a certain J.C. Hilliger. Nothing is known about Hilliger, except that he lived in Valparaiso (he felt the earthquake there) and that he went in person to observe the effects of the tsunami along the South American coast between Coquimbo (30°S) and Callao (12°S) during a two-month trip between May and June 1877. His report is a marvel of conciseness (3 pages) and precision. In a first paragraph, after brief considerations on the extension of the seismic zone, he gives explanations on the feeling of the earthquake in Valparaiso, including a precise value of the direction and amplitude of the oscillations of a suspended lamp: N20°W–S20°E, 3 inches on each side. He deduced an epicenter located at 22°S/78°W, recognizing it seemed too far of-coast and acknowledging he could not ascertain the western deviation by less than 5° by all means. In a second paragraph he discusses the time lag between the earthquake and the tsunami and quickly concludes that this discussion is irrelevant since clocks are not precise enough and not synchronized. In a third section, he gives his evaluation of the tsunami heights at every single location where he could measure it. Very unfortunately he says nothing about his methodology, but his numbers are very consistent: they smoothly increase from South to North until they reach an apex in the epicentral area and then decrease again. They are also quite smaller than all other numbers, except in several places where they match the smallest number reported otherwise. In the last paragraph, Hilliger relays an important observation: heavy rain falls had occurred all along the Chilean/Peruvian coastline for several weeks, both before and after the earthquake (1–2 years of rain in a couple of weeks). We will use this information to suggest an alternative explanation to an important piece of information later provided by Vidal-Gormaz. In conclusion, he demonstrates his good judgment and critical thinking by writing "*[…] What has been written of unusual heat in the mines of Cobija and Tocopilla are fables. Likewise, the burial of many miners in these mines. There may have been 3 or 4 people killed in the mines […].*" Geinitz calls Hilliger's report "*detailed and remarkable*" and fortunately reproduced it as is and in-extenso.

Table 1
Near field 1877 tsunami Characteristics summarized from Geinitz (1878).

City	Latitude	Earthquake time[a]	Tsunami time[b]	Delta Ts-Eq[c]	1st wave sign[d]	Nbr of waves	Highest waves	Sea level rise (m)	
								Various reports	Hilliger[e]
Pisco/Chincha ls.	S 13°43'	20 h 30	23 h 30			2	1	1–2[f]	3
Ilo	S 17°37'	20 h 30	20 h 50	~ 1/4 h	–	3	3	6	3.6–4.5
Arica	S 18°28'	20 h 15	21 h		–	8	7	8.6[g]	4.5/6–7.5[h]
Pisagua	S 19°36'	20 h 20	23 h (?)		–	4	2	4.9	3.6–4.5
Mejillones del Peru	S 20°09'	20 h 15	21 h 10		–	4	4		2.4
Iquique	S 20°12'	20 h 15	20 h 50	+5'	–	6/8	6/8	5–6	3.6–4.5
Pabellon de Pica	S 20°57'	20 h 15	20 h 25		+	6			7.5–9
Chanabaya[i]	S 21°	20 h 20	20 h 40	+20'	+/–	3	2	10.5	7.5–9
Punta de Lobos	S 21°05'	20 h 30	20 h 30		+/–	2	2	10.5	7.5–9
Guanillos[j]	S 21°10'	20 h 15	20 h 30		–	3	1	9	7.5–9
Tocopilla	S 22°	20 h 30	20 h 45	+8'	+				9
Cobija	S 22°34'	20 h 30	20 h 38		+			9	7.5–9
Caleta		20 h 20	20 h 40		+			18	
Mejillones de Bolivia	S 23°6'	20 h 15	20 h 45			3	2	21	9–10
Antofagasta	S 23°40'	20 h 30	20 h 40		–	4	4	2.5[k]	6
Chañaral[l]	S 26°21'	20 h 40	21 h 10		–	3	3	4	3.6–4
Caldera	S 27°4'	20 h 30	21 h	+35'	–		3	2	2.5–3
Coquimbo	S 29°55'	20 h 30	22 h 30		–			2	1.5

Summary of relevant information at specific places along the coastline of Chile, Bolivia and Peru gathered in Geinitz (1878). Numbers provided in the consular reports are preferred over those given in the press when there were inconsistent. Earthquake and tsunami times are given in local (Iquique) time and mark the perception of first arrivals. Delta(Ts-Eq) gives the elapsed time between the end of the earthquake and the first motion of the sea, when it is specifically given. First wave sign depicts whether the first arrival is a crest, resulting in inundation (+) or a trough, marked by a retreat of the sea (–). Sea level rise is the highest level above sea level reached by the inundation: the first column (*various reports*) summarizes the most credible information, the second column (*Hilliger*) summarizes Hilliger's report (cf note e).

[a] The earthquake time cannot be determined with precision at any location because clocks are inaccurate and not synchronized (cf section 1.1).

[b] The tsunami time is even more difficult to determine, because of poor clocks and because of confusion between successive tsunami waves (cf section 1.1).

[c] Elapsed time between the earthquake and the first tsunami wave only when reported precisely by officials at the harbor offices and ignoring vague timing indicated in the newspaper. It is probable that, when specifically reported, this duration was measured precisely with a stopwatch, independently of the absolute arrival times. In most reports, this duration refers to the time elapsed between the end of the earthquake and the beginning of the tsunami.

[d] Sign of first arrival (initial rise or withdrawal) is sometimes unclear, in particular near the rupture. Because it is dark and because the first arrival is often small, it may have gone unnoticed, even more if it is a short duration harmless withdrawal rather than a spectacular rise. (cf section 4).

[e] J.C. Hilliger is an unknown person. He provided a brief report (3 pages) to the general consulate of Valparaiso whom conveyed it to Geinitz (cf section 1.1 Hilliger's report).

[f] Inundation heights are not easy to decipher: Heights are given indifferently relative to the lowest sea level, the highest sea level, the mean sea level, or without any indication. The tide level at any particular location at the precise time of the highest wave is often difficult to determine. Here, the report says "*At Chincha Islands (of coast Pisco) [...] the highest tidal wave occurred at 1 am and overcame by 1/2 foot the highest tide which is 10 feet [...]*". Then, the report from national boat "Amalia" at Pisco harbor says "*[...] 2 large waves, 1st highest at 1 h 45, 2nd at 3 am at high tide [...]*". From these we infer a) high tide was around 3 am, b) the tide was rising at 1 am, missing 2 h, c) the sea level was at ~9/12 of its highest level of max 10 feet. So Chincha Island report indicates a possible height ranging between 1/2–10 1/2 feet (0.15–3.15 m), when the second report allows to infer a plausible height between 1–2 m, assuming the tide of this particular day was an average one.

[g] Discrepancies about Arica's tsunami: the report of Tacna's consulate mentions the largest wave was the 7th (out of 8) at 4 am and reached 12–13 m (40–45 feet). Arica Harbor authorities report is consistent regarding the number of waves (8) and the timing of the largest (7th at 4 h 30 am) but gives a much lesser height of 8.6 m. Hilliger reports an even lesser height of 4.5 m (cf following note).

[h] Hilliger reports two different numbers at Arica: the lesser one (4.5 m) is Arica city, the larger one (6–7.5 m) is taken on the north side of the Island in front of the harbor.

[i] Latitude of Chanabaya is slightly wrong. Chanabaya and Pabellon de Pica are nearby and close to 21°S, but Chanabaya is North of Pabellon rather than south of it.

[j] Name and exact latitude are uncertain. Geinitz uses Guanillo, Milne uses Huanillos, both have the same latitude (21° 10' or 21° 15'). Vidal–Gormaz uses Huanillo and a different latitude (22° 28') which is probably mistaken since Guanillo/Huanillos is unequivocously only slightly over 100 km south of Iquique (~20°).

[k] Actual measurement in Antofagasta harbor (cf section 3–6).

[l] Chañaral is wrongly positioned in Geinitz's article. He uses a latitude of 29° 2' instead of 26° 20', which makes a difference of ~ 300 km. This mistake is also present in Geinitz's map. Hilliger gives the correct position for Chañaral in his report. Similar but smaller mistake for Tacna, located at 18° 36' by Geinitz (South of Arica) and 18° 17' by Hilliger (rightly North of Arica).

1.2. Vidal-Gormaz (1878)

Is in Spanish - 30 pages long. Francisco Vidal-Gormaz was an explorer and writer, officer of the Chilean Navy and director of the Chilean Hydrographic Office. His report on the 1877 earthquake is part of one of the many books he published in the "*Anuario hidrografico*" of the Chilean Navy. Not being a geologist nor a seismologist, he simply compiled information about the earthquake, refraining from interpreting them. Many come from the same sources Geinitz used: Press articles, consular and port authorities reports, and are identical (errors and typos excepted). However, being a sailor himself, he focused on the tidal wave and brings new information produced in particular by naval officers on board ships, along with information at smaller places unknown to Geinitz. In particular his report is the only one to mention changes in bathymetry in several harbor bottom, but with incredibly large figures that are difficult to believe. About Pisagua for example, he quotes a local report which indicates that the sea bottom in a given spot of the bay is now to be found at 18 m depth, instead of 45 m before the earthquake...(VG trans.p15). He also gives more credentials to the testimony of the officer in charge aboard armored battleship *"Blanco Encalada"*, moored in Antofagasta, who actually measured the depth of the water below the ship's keel during the night of May 9 to 10: one of the few, if not the only, direct and indisputable measure of the height of the tsunami there: 3.5 m (VG trans.p9). Last, he is also the first to mention the destruction of ancient Indian (Inca) monumental buildings in the mouth of the Loa river (VG trans.p11).

1.3. Milne (1880)

Is in English - 50 pages long. John Milne was an Englishman and graduated as a mining engineer from the Royal School of Mines in London. He was hired by the Meiji government of the Empire of Japan as a foreign advisor and professor of mining and geology at the Imperial College of Engineering in Tokyo from 8 March 1876. He was a pioneer in seismology and inventor of his famous horizontal pendulum seismograph. He had just arrived in Japan at the time of the 1877 earthquake and traveled immediately after the tsunami along the eastern coast of Japan, from Yedo to Hakodate. Milne says that, while on his journey,

Table 2
Far field 1877 tsunami Characteristics summarized from Geinitz (1878).

City	Latitude	Longitude	Tsunami arrival time[a]	Tsunami travel time[b]	1st wave sign	Nbr of waves	Highest wave	Sea level rise (m)	Crest-to-trough heigh (m)
Acapulco, GE, Mexico	N16°51'	W99°50'	05/10–10 h am	15 h 35'	+	> 10	1	1	1
SanLuisObispo, CA, USA	N35°10'	W120°40'	05/10–7 h 10 am	14 h 05'	+	3		3.6[c]	
Nuka-Hiva, Marquesas	S 8°55'	W140°06'	05/10–4 h am	12 h 15'	+	> 10		4	
Apia, Samoa	S13°49'	W171°41'	05/10–5 h 30 am	15 h 30'	?	3–4	1–3	0.8–1.2[d]	
Hilo, Hawaï	N19°44'	W155°03'	05/10–4 h am	14 h 00'		> 10	2	4-9[e]	4.2
Honolulu, Hawaï	N21°28'	W157°55'	05/10–5 h 20 am	14 h 25'	–	> 4	1		1.4[f]
Kahului, Maui	N20°31'	W156°43'	05/10–4 h 45 am	14 h 05'	–	> 4	1,4	1.4	
Tauranga, NZ	S37°37'	E176°11'	05/11–8 h am		+		1	1	
Gisborne, NZ	S38°40'	E178°01'	05/11–7 h am			5			
Wellington, NZ	S41°06'	E174°30'	05/11–7 h am	18 h 15'	+	20	1	1	1.5
Lyttelton, NZ	S43°37'	E172°45'	05/11–9 h 05 am[g]	18 h 23'	+	> 10	1	0.9	
Newcastle, Australia[h]	S33°04'	E151°45'	05/11–5 h 20 am	18 h 07'	–	> 10	3,4		2
Sydney, Australia	S33°51'	E151°15'	05/11–5 h 20 am	18 h 10'	–	> 10	3		2.4
Kamaishi, Japan	N39°16'	E141°53'	05/11[i]–9 h am	22 h 55'		> 10		1.65[j]	3
Hakodate, Japan	N41°50'	E140°50'	05/11–11 h 30 am	25 h 00'	–	> 10			0.9–2.4[k]
Kadsusa, Japan	N35°20'	E140°40'	05/11–12 h 00 am	25 h 15'	+	> 10			3[l]

Summary of relevant information at specific places scattered around the globe (North America, Pacific Islands, Japan, New-Zealand and Australia) gathered in Geinitz (1878). The tsunami arrival time is the local time at which the first variations of the sea level are reported, format is month/day hour minute. The tsunami travel time is the elapsed time between Earthquake and tsunami arrival, calculated by Geinitz using unspecified time lags. First wave sign depicts whether the first arrival is a crest, resulting in inundation (+) or a trough, marked by a retreat of the sea (–). Sea level rise is the highest level above sea level reached by the inundation but is often difficult to infer from the reports in the absence of precise tide information: time and amplitude at this particular place on this particular day. Crest-to-trough height depicts the height difference between the lowest and highest level reached by the sea level during the entire sequence.

[a]Local time, usually May 10 in the Pacific, May 11 in Australia, New-Zealand and Japan.

[b]Tsunami travel time calculated by Geinitz who converted all local times in Iquique time.

[c]Highly doubtful number, most probably invented (cf section 3–9).

[d]35 inches above spring high tides, 49 inches above ordinary high tides according to fisherman post.

[e]Wave of 30 feet reported but conflict with measurement of only 13.5 feet above lowest tide level made by a Mr. Severance, whom provided a complete report with heights and timing of successive waves.

[f]58 inches difference between lowest and highest level according to pilot Babcock.

[g]Inconsistency between this time (~9 am) and the time at other places in New-Zealand (~7 am), in spite of which Geinitz finds a similar travel time of ~18 h to different locations in New-Zealand.

[h]Tide-gauge records are available at Newcastle and Sydney, Australia and plots are included in Geinitz article. Oscillations last several days. Sydney's tide gauge configuration & build causes filtering of the high frequencies visible in Newcastle's records. Timing is precise and exact. Beware, the numbers reported by Geinitz (6–7 feet of maximum height, G-trans.p30–31) refer to the total amplitude (tide+wave) reached at high tide (which is 6 feet above lowest sea level). Amplitudes are somehow dampened with respect to the true sea level because of the tide-gauge low-pass filter inherent to their design, but Newcastle's oscillation maximum amplitude is 25 inches (75 cm) around 11 am and Sydney's is only 9½ inches (30 cm) around 14 h 45.

[i]Geinitz reports that most Japanese newspapers and a letter from Prof. E. Knipping to <<Geogr. Mittheilungen>> (1877, p. 894) give the date of May 14th (sic!) for the tsunami.

[j]As marked upon a jetty, the water rose about 5½ feet above ordinary high water mark (Milne).

[k]Two conflicting numbers here, the smaller one actually originating from another location (cf section 3–10).

[l]Possible confusion here with a river flooding figure (cf section 3–10).

he collected many records of sea waves series which came in at many different places. However, he states that of these, there are only two of any value: observations made in Kamieshi and Hakodate, already available to Geinitz in 1878, and writes nothing about the rest of his original data. His article is mostly about an "inversion" scheme, dedicated at locating the earthquake epicenter based on tsunami waves and/or seismic waves arrival time, disregarding waves amplitude. He uses the data collected by Geinitz and like him, he stumbles on the problem of inaccurate and non-synchronized clocks (and sometimes incorrect location coordinates – including his own – e.g. wrong latitude for Kamieshi, p.61). However, after eliminating outliers and selecting the most reliable times, he still manages to find a reasonable location (S21° 22′ / W71° 5′), using the tsunami waves. Oddly, this reasonable location is associated to a reasonable sea wave velocity (350 feet/s = 380 km/h) but to a much too slow seismic wave velocity (1 000 feet/s = 0.3 km/s). In summary, despite his trip along the coast of Japan, almost no original data on the 1877 earthquake & tsunami is to be found in Milne's work.

1.4. Harnecker (1895 & 1897)

Are in fact the same article - 24 pages long, the latter being a German translation of the first one, written in Spanish. Otto Harnecker was a German engineer who lived in Chile, in Tocopilla, where he owned copper mines and a smelter company. His publication is a long theatrical complaint about the devastating consequences of the earthquake and tsunami in Tocopilla where he lived, concluded with a theory on the causes of earthquakes. There is almost no usable quantitative information. He simply reports that after the main shock occurred at 8h30pm, the maximum level reached by the first inundation in the bay of Tocopilla was 10–15 ft (3–4.5 m) higher than it was in the calmer part of the harbor, where it was either 1–2 ft (0.3–0.6 m) here or 6–8 ft (1.8–2.4 m) there (H trans.p9). Then he reports a large aftershock occurred around 10pm followed by a second inundation, 3–4 ft higher than the first one. These figures are contradicted in the very next paragraph, in which he reports 30–45 ft (9–15 m) as a generic height, without any precision on the place or time (H trans.p10). Perhaps of interest, a comment about the sedimentary plain in which a myriad of small cracks opened up, cracks that filtered the superficial layer of soil and dust like a sieve. A possible observation of local ground liquefaction ?

1.5. Montessus de Ballore (1911)

Is in Spanish - 40 pages long. Fernand Montessus de Ballore was a Frenchman and graduated from the *"Ecole Polytechnique"* in Paris. He became fascinated with earthquakes after a trip in central America in the early 1880s, and went to Chile in 1907 to become Director of the Seismological Service. Under his direction, the service build and operated one of the best seismological networks of the time. Montessus de Ballore was a prolific writer and publisher and he carried out an impressive work of collecting earthquake data (Cisternas, 2009). His book on the seismic history of the Andes includes a specific chapter on the 1877 earthquake. Unfortunately, he does not provide so much original data but rather a compilation of previous publications. Compilation associated with a critical reading based on the reorganization of information by topic rather than by geographical location and cross-referencing.

In the first part of his publication, being a seismologist, Montessus de Ballore puts more emphasis on the earthquake itself than on the tsunami, and tries to asses the level of damage caused by the earthquake only. The destruction inland seemed more important to him than that along the coast. He reports in particular that according to the verbal testimonies he was able to collect in 1909 near some old inhabitants, the village of Chiu-Chiu was completely ruined. Whereas on the contrary, according to the testimonies collected near the old inhabitants of Arica for example, the losses there resulted only from the tidal wave. Consequently, he develops this interesting theory that what he calls the pleistoseist area (namely the area that suffered the greatest damage around the epicenter) is completely included in the mainland and does not reach the shores of the Pacific. Therefore, he refutes the conclusions of Milne who positioned the epicenter about 100 km offshore, to assert that if the latitude is correct the longitude cannot be, and that the epicenter of the earthquake is necessarily under the continent. Back to the North-South extension of the pleistoseist area along the coast line, he considers that since there does not seem to have been considerable damage in Mejillones del Peru (Mejillones del Norte), nor in Iquique, the northern limit of the area of severe shaking (he writes "greatest violence") should be set here, around 20°S. On the other side, he states that it is clear that Caracoles (far inland, near San Pedro de Atacama) and Mejillones del Sur (on the coast, present day Mejillones) are adjacent but out of the pleistoseist area. So the southern limit must be set around 22.5°S.

In the second part of his publication, Montessus de Ballore focuses on the tsunami. Here he simply repeats information already available in Geinitz and Vidal-Gormaz, until his expert seismologist skills allow him to solve the enigma of an apparent large tsunami in central Peru. He recognizes that there was another tidal wave (possibly two) on the 14th in the ports of Ancon, El Callao and Chala, generated by two tremors on the 14th, distinct from the main shock.

1.6. Soloviev and Go (1975)

is in Russian - 200 pages long - published by *"Nauka Publishing House, Moscow"*. An English translation was made in 1984 by the *Canadian Translation of Fisheries and Aquatic Sciences*, under n° 5078, and is available through the *"Canada Institute for Scientific and Technical Information National Research Council"*. Sergey Soloviev was a Russian seismologist, head of the laboratory of seismology at the Institute of Oceanology of the Russian Academy of Sciences, director of the IUGG tsunami Commission, member of the Russian academy of science. Together with Go Chan Nam, he published a series of tsunami catalogues in all the seas of the world. In this specific publication, 20 pages are devoted to the 1877 earthquake and tsunami (pages 99–117). Probably because it was published in Russian and at the time of the Cold War, this article remained unnoticed for a long time by western scientists. There is no reference to his work in neither Kausel (1986) nor Comte and Pardo (1991). However, Soloviev and Go did an excellent work trimming the tsunami heights reported by Geinitz and attributing intensities on the Mercalli scale according to the descriptions reported by Geinitz and Montessus de Ballore (Fig. 2A). The area affected by iso-intensities VIII or larger is centered on the Loa river mouth, by 21.4°S, and extends over ~225 km long, between 20.5°S to 22.5°S (length A0 - Fig. 2A).

1.7. Kausel (1986)

is in Spanish - 5 pages long - published in the "*Boletin de la Academia Chilena de Ciencias*". Edgar Kausel-Vecchiola was a Chilean seismologist, head of the department of geophysics (DGF) at University of Chile, Santiago, member of the Chilean Academy of sciences. Unaware of a similar and earlier work by Soloviev & Go, he determines the length of the 1868 and 1877 ruptures through the determination of the area affected by intensities above VIII (severe shaking associated with significant destruction) in the Mercalli scale. The assumption in vogue at the time links rupture length and intensity VIII (e.g. Dorbath et al., 1990): Basically, modern earthquake aftershocks cover an area that depicts the main shock rupture and also correspond to the iso-intensity VIII observed in the field. Therefore, the iso-intensity VIII of historical earthquakes should depict the area affected by their aftershocks, hence the rupture length. The intensities are estimated according to the descriptions reported mostly in Montessus de Ballore (1911). Overall, Kausel often assigns intensities 1 notch higher than those of Soloviev & Go (Fig. 2-B). But these estimates are delicate: it is not uncommon for different intensities to be reported in nearby villages. Thus, the northern and southern termination of the rupture are difficult to establish.

The rupture Kausel finds first stretches from Cobija (22.5°S on the coast) to Tarapaca (20°S inland), i.e. ~290 km long (length A1 - Fig. 2-B). In a second step, following the more or less doubtful information reported in Vidal-Gormaz that the correspondent of the journal "*el comercio de Lima*" in Pisagua had witnessed ground subsidence there, Kausel extends the rupture to Pisagua in the North (19.5°S) and increases its length to ~360 km (length A2 - Fig. 2-B). In his article, Kausel writes that he has doubts about this information contradictory with the low level of destruction observed in Pisagua, but still takes it into account ... in a third step, he extends the rupture 40 km south of Cobija and brings the length to ~400 km between 19.5°S and 23°S (length A3 - Fig. 2-B). It is on the basis of these successive extensions that he draws his "iso-intensity VIII" zone (pink area in Fig. 2-B). This length of 400 km matches well the large magnitude Mw 8.9 he favors.

It should be noted that even though he had attributed slightly higher intensities than Soloviev, Kausel would have found a similar length than Soloviev if he had sticked to its original raw data. Not including Iquique nor Pisagua (both intensities < VIII) in the north and not extending beyond Cobija in the south, yields a length of ~225 km (length A0 on both maps). The only difference would have been a larger width, because of high intensities far inland at places like Calama and Chiu-Chiu, that Soloviev ignored (Fig. 2-A-B). Soloviev probably ignored those because he was aware (like Kausel) that the constructions in the saltpeter exploitation area often consist of walls formed by salt crust blocks that have even less resistance than adobe houses.

1.8. Comte and Pardo (1991)

Is in English, - 22 pages long - published in Natural Hazards. They analyze 22 earthquakes that occurred in Northern Chile and Southern Peru between 1513 and 1878. About one page is devoted to the 1877 earthquake. The rupture they describe is ~420 km long (length A4) and runs from south of Cobija to far north of Pisagua (Fig. 2-C). Based on the occurrence of previous earthquakes in the same area in 1543, 1615 and 1768, they establish a return period of 111 +/- 33 year (i.e. maximum of ~ 150 years). This article, written in English in an international journal, becomes a milestone, cited in over 300 subsequent publications. Unfortunately, as it describes many other earthquakes, the paragraph on 1877 is a brief summary of Kausel's conclusions and his doubts and inaccuracies are not mentioned. After this article, it will be commonly accepted that the 1877 earthquake magnitude is close to 9 and its rupture length is largely over 400 km, sometimes up to 500 km, extending roughly from Mejillones to Arica.

2. The extension of the 1877 rupture to Pisagua by Kausel

The decision made by Kausel in 1986 to include Pisagua (19.5°S) in the area of iso-intensity VIII, and thus in the rupture area, instead of terminating it south of Iquique (~20.5°S), is absolutely crucial,

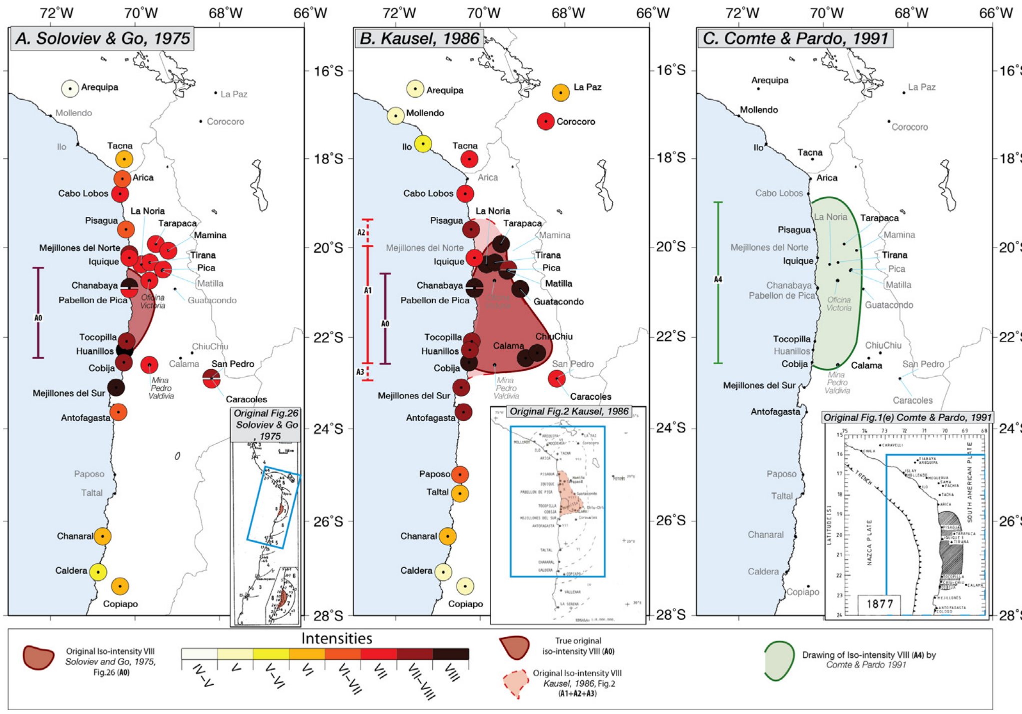

Fig. 2. Comparison of intensities attributed by Soloviev and Go (1975) (A); Kausel (1986) (B) and Comte and Pardo (1991) (C). The same color scale for intensity is used for figures A and B. Insets depict the original figures from articles; in which light blue squares frame the region of interest in North Chile and Southern Peru. Lengths A0 in (A) and A0 & A1 in (B), later interpreted as "the rupture length", depict the N-S extension of the area of intensities larger than VIII. Lengths A2 & A3 in (B) depict the rupture length extensions to Pisagua to the North and to Mejillones to the South mentioned in Kausel (1986). Length A4 depicts the extended rupture length of Comte and Pardo (1991). All locations with intensity reports are indicated on maps A and B, but those ignored by a specific author are in light gray. Note Chiu-Chiu is mislocated in Comte and Pardo (1991) Fig. 1e.

and everything that followed rest on it. Is it substantiated ? on what grounds ?

Arguments in favor are threefold:

1. Earthquake is felt strongly in Pisagua, possibly even stronger than in Iquique.
2. Tsunami is high in Pisagua, similar to the one in Iquique.
3. An important subsidence has been reported in Pisagua (and actually also in Iquique). In Pisagua "*[...] at high tide the sea now floods previously dry lands [...]*"; in Iquique "*[...] usually emerged rocks of the harbor are now permanently under water, even at low tides [...]*".

Arguments against are twofold:

1. No matter how it felt, all reports concur that the intensities did not exceed level VII on the Mercalli scale, neither in Pisagua nor in Iquique. Kausel and Soloviev agree on this point.
2. few aftershocks near Pisagua, much less than near Iquique by all means

So, what to think of the 3 arguments in favor, and in particular the third one that weighed so heavily in Kausel's decision ?

1. Strong Ground motion. Can be explained by an important site effect. Montessus de Ballore notes *"These reports do not report damages, from which we have the right to deduce that if there were damages in Pisagua, it was due to unfavorable circumstances of the terrain or the corresponding reports have been greatly exaggerated"* (MdB trans.p8). This point could be verified checking accelerations generated by the Mw 8.1 Iquique 2014 earthquake at Pisagua.

2. High Tsunami. Can be explained by the geometry of the bay of Pisagua and refraction around the very long East-West peninsula that "protects" Pisagua to the South (*punta Pichalo*). In reality, the elongated peninsula is more likely to amplify a tsunami coming from the South, through refraction around it. This amplification effect will remain localized in a small area around the northern side of the peninsula's root, precisely where the city and the harbor reside. This is exactly what happened with the tsunami caused by the Illapel earthquake of 2015 in Puerto Aldea, near Tongoy, with a similar configuration (Lagos et al., 2015; Tomita et al., 2016). Puerto Aldea, hidden in a cove behind the *lingua de Vaca* peninsula was hit by a much higher wave (almost 8 m at the harbor slipway according to local testimonies) than Tongoy, only a dozen of km away further north (2–3 m max). But this very high wave touched only a rather short portion of the coast, less than a kilometer.

3. Significant Subsidence. On the one hand, it is possible: Maule earthquake of 2010 (Mw 8.8) did cause a subsidence of about 50 cm at 150 km from the trench (the distance from the trench at the latitude of Pisagua) (e.g. Vigny et al., 2011). Iquique earthquake of 2014 (Mw 8.1) also caused subsidence at Pisagua, as revealed by the cGPS station there (PSGA) which shows a co-seismic step of around -30 cm (e.g. Klein et al., 2022). Therefore the co-seismic effect at Pisagua of a nearby subduction earthquake can indeed be a subsidence of a few tens of cm. But then, one should have also noticed a rise of at least the same amplitude when closer to the trench (around 100 km), i.e. around Mejillones and Antofagasta. Coastal rise is usually very visible: sea-shells suddenly emerged on the raised rocks and harbor dikes immediately die and dry, and are therefore immediately reported. But nothing of the like here... besides, are a few tens of cm compatible with the reported observation "*the land has dropped considerably*"?

On the other hand, the information is highly doubtful. (a) it is second hand information conveyed from a Lima newspaper correspondent, reported in Vidal-Gormaz, taken up by Kausel, but unknown to Geinitz and especially Hilliger. Montessus de Ballore, who was aware of this "information" in 1911, explains that these are typical exaggerations frequently encountered and that they should not be believed (MdB trans.p14). He insists on the fact that the same journalist also reported that a volcano had emerged from the sea in Pisagua (sic!) and the same journal reported a tsunami height of ~20 m in Arica when it was only ~5 m at the very most... Montessus de Ballore also dismisses the report of subsidence in Iquique's harbor by the governor of the port. The latter indicates that rocks usually emerged in the harbor are now not visible, even at low tide, which suggests subsidence of at least the height of the tide (~1 m), but Montessus de Ballore argues that nothing says the rocks are still there, sunken under water. He regrets that no hydrographic survey has been conducted in either ports of Pisagua or Iquique, so that these alleged changes in level are doubtful (MdB trans.p14). (b) Vidal-Gormaz reports the opposite of harbor subsidence. On the contrary, he mentions a rise of sea bottom of nearly 30 m in Pisagua's harbor (sic!) *" [. . .] in places, anchor depth would now be found at −18 m instead of −45 m before [. . .]* (VG trans.p15). Ground uplift at sea is completely contradictory with subsidence on land because the two "observations" are nearby. If by any chance, both observations were real, they may have an alternative explanation: a landslide (*aluvión*) triggered by the heavy rainfall that occurred both before and after the earthquake. Pisagua is located at the mouth of a large "*quebrada*" (Tiliviche), and a flash-flood landslide there is plausibly capable of modifying the coastline, allowing the entry of the sea at high tide more inland than before, and changing the sea bottom topography in the harbor through fills deposits. These two things happened in exactly this way in Chañaral, located at the mouth of the "*rio salado*", during the flash-floods of 2015 (Aránguiz et al., 2018). By all means, a flash-flood land-slide (or the tsunami itself !) are more likely to have significantly altered the coastal landscape and the harbor sea bottom topography than the co-seismic rebound is to have produced simultaneously uplift and subsidence at the same location.

In the light of all these consideration, we conclude Pisagua should not have been included in the rupture area. Nor should have been Iquique according to the information reported by Vidal-Gormaz and echoed by Montessus de Ballore that, in Iquique, the earthquake of 1877 was not as strong as the one of 1868 (VG trans.p14). In reality, Kausel felt the "need" to increase the rupture length because of Abe's scaling law, popular at this time, and to which he refers in his article. Abe's formula relates the magnitude (M) to the rupture length (L) very simply: M~L3 (Abe, 1979). According to this formula, a rupture length of 290 km (his initial estimate A1) is very insufficient to produce the magnitude ~9 Abe and Kausel attribute to the 1877 earthquake, and a length of at least 400 km (his last A3) is necessary. Today we know that this formula is not correct: It would assign a magnitude 10 to the 2004 Sumatra earthquake (1300 km long), instead of 9.2, and a magnitude 8.5 to the 2011 Japan earthquake (250 km long), instead of 9.0.

3. Frequent misconceptions about the 1877 tsunami

Since 1878, a number of errors have been circulating about the height of the waves here and there. Some of these wrong numbers still contaminate the International Tsunami Information Center (ITIC) data base at NOAA (ITIC, 2022). The idea that, since it is associated with immense heights, the tsunami of 1877 is absolutely gigantic becomes very common. It is a current misconception that needs to be rectified. Here we list the errors (sometimes simple typos), confusions and exaggerations that have lead to these misconceptions and indicate what is the most probable correct number instead.

1. **Arica : 20 m**. Wrong. This number comes from a press article stating: The great wave rose 65 feet (19,75 m) *"La gran ola subió 65 pies" (El nacional de Lima, May 13)* echoed in VG (trans.p16) and MdB (trans.p21). The impression here is worsened by the *"Wateree"* famous story. A US steam ship that had been brought inland by the 1868 tsunami and transported again in 1877. Many understand the wreck was transported 2 miles inland in 1877, but this is incorrect. *Wateree* was carried 400 m inland, *2 miles North of Arica* in the lowlands around the mouth of Lluta river by 1868's tsunami, and the wreck was simply retaken and brought back near the coastline in 1877. The mouth of the Lluta river covers more than 171 hectares and the wetlands are barely 4 m above sea level. The German consulate reported 40–45 feet (12–13.5 m) and local Port authorities only 8.6 m at maximum (G trans. p17). Hilliger reports that the tide rose about 20–25' (6–7.5 m) north of the island in front of the harbor, and about 15' (4.5 m) high at the town (G trans.p13). Therefore, we consider that the correct number is **4.5 m**.
2. **Guanillos : 18 m**. Wrong. This number comes from Soloviev who wrote *[...] The height of the largest among them, the first tide, was 9 m (30 feet) [...]* but also *[...] According to other sources, the height of the strongest wave was 18 m (60 feet) [...]*, without any further precision or reference (S p102). The first number (30 feet or 9 m) comes from the Maritime Governor's report (G trans.p7), echoed in Montessus de Ballore (Mdb trans.p18). This number is confirmed by Hilliger who noted 25–30 feet (G. trans.p12). The number of 60 feet is of unknown origin, but contaminates the ITIC data base which has 18 m at this location. Therefore, we consider the correct number is **9 m**.
3. **Tocopilla : 24 m**. Wrong. This number comes from Soloviev who wrote *[...] The height of the rise was estimated at 24 m (80 feet) [...]*, without any further precision or reference (S p102). Harnecker (who witnessed the tsunami at Tocopilla) indicates vaguely a very uncertain number : 30–45 feet (9–15 m) as a generic height around Tocopilla (H trans.p10). Apart from that, he states that the level reached by the inundation in the bay of Tocopilla was at a maximum of 23 feet (~7 m) (H trans.p9). Hilliger reported 30 feet (9 m) (G trans.p12). The wrong number of 80 feet may come from a copy error, the 3 of 30 being mistaken for an 8. Despite Soloviev tagging it with a question mark (S p115), this wrong number contaminated the ITIC data base. Therefore, we consider the correct number is **9 m**.
4. **Mejillones : 21 m**. Mixed up. Geinitz describes 3 waves : the 1st one, 30 min after the earthquake reaching 35 feet; the 2nd one, 15 min later reaching 70 feet; and a 3rd one, 45 min later with no height indication (G. trans.p7). Vidal-Gormaz gives a different story : Also 3 waves, but the 1st is only 7 m and the 2nd (also 15 min later) is only 11.5 m; the 3rd is also 45 min later, also without height indication (VG trans.p10). Unfortunately, in this instance, neither Geinitz nor Vidal-Gormaz give any indication of their sources. Then Montessus de Ballore compiles both sources : 2 waves from Geinitz (with correct numbers of 35 and 70 feet), and 2 waves from Vidal-Gormaz, the 1st one with the correct number of 7 m but the 2nd one with a mistake : 19.6 m instead of 11.5 m ! It is a typo made while re-copying Vidal-Gormaz. Soloviev, probably misguided by Montessus de Ballore mistake, picked up on Geinitz's largest number of 70 feet or 21 m (S p103, p115), and this number is in the ITIC data base. However, Hilliger report states : *[...] The site is about 30' above sea level, yet part of it was washed away, consequently the tide rose 30–35' vertical. [...]* (G trans.p12). Note that Hilliger wrote "part of it" and not "all of it", consistent with Vidal-Gormaz who wrote that the first two rows of blocks facing the sea (*and only those 2 rows*) were destroyed. In conclusion, we think that the large figure of 70 feet of unknown origin, echoed by Montessus de Ballore typo, must be discarded in favor of the lesser figure of 30–35 feet or 11.5 m indicated by the most reliable sources: Hilliger, who is the only one to have been to the field and Vidal-Gormaz, director of the Chilean Hydrographic Office with access to official records. Therefore, we consider the correct number is **11 m**.
5. **Caleta : 18 m**. Highly doubtful. A number of 60 feet is found in Geinitz (G trans.p7). It is just one sentence. The source is the journal "South Pacific Times of May 21, in which Capt. G. Massey of steamship "John Elder" who was navigating at sea, 23 nautical miles from the coast, during the earthquake

and tsunami, is quoted for having said *“We later learned that there had been a wave of 60 feet high at caleta”*. No location is given, just this name "caleta" and there is no direct witness. Hilliger did not report a number nor even mentions this location. Vidal-Gormaz says nothing. Montessus de Ballore echoes the information simply stating "*a caleta between Cobija and Mejillones*" (MdB trans.p19), but he also indicates that no credit should be given to the press article of 21 May, which he calls apocryphal (MdB trans.p11). So actually, nobody knows where that is and where this information actually came from. This probably wrong number at an unknown location also contaminates the ITIC data base. Therefore, we consider the Caleta figure should not be taken into account.

6. **Antofagasta : 10 m**. Exaggerated. Some confusion emerges with respect to the earthquake & tsunami in Antofagasta. An account of the events by Don Ramon 2nd Arancibia (writer, book reviewer and journalist), alderman of Antofagasta, was published in many journals at the time. In his own words the earthquake was terrifying, the tsunami monstrous and the damage immense. His novelist writing style and his dramatic words made their mark. However, according to all other accounts (German consul, port authorities, officers aboard navy ships) the damage was much less in Antofagasta than in other places. Moreover, Antofagasta harbor is one of the few places, or even the only one, where the tsunami was actually measured. Leftenant V. Cueto, aboard dreadnought battle ship *“Blanco Encalada”*, anchored in the harbor, repeatedly measured the depth below the ship with a sound line. We do not have the entire record, only the number corresponding to the maximal elevation : +3.5 m (VG trans.p9; MdB trans.p19). This figure is consistent with the number conveyed to Geinitz by the German consulate : 2.5 m above highest sea level. ITIC data base has been partially contaminated by the press exaggeration and gives an intermediate height of 6 m at Antofagasta. Therefore, we consider the correct number is **3.5 m**.
7. **Ilo-Chala, Peru : 3–6 m**. Possible confusion with another earthquake & tsunami. These numbers of 6 m in Ilo (17.6°S) and 3 m in Chala (15.9°S) are provided by port authorities (G trans.p17-18). However Arequipa authorities tagged the tsunami at Chala with the date of May 14 and Geinitz indicates he thinks the date is mistaken and one should read May 10. However, Vidal-Gormaz indicates that other inundations were also reported on May 14 in Peru, up to Calao and Ancon (~ 12° S) (VG trans.p16). Compiling these informations (which include the feeling of several large seismic shocks on that day in Peru), Montessus de Ballore concludes on the occurrence of at least two other earthquakes on May 14, near Chala and Ancon. Each of these earthquakes large enough to have generated a local tsunami (MdB trans.p24). Thus, abnormal heights in this area should not be attributed to the May 9 earthquake & tsunami. Reliable reports that can be attributed to the tsunami of May 10 without ambiguity indicate heights of 1–1.5 m. Therefore, we consider the correct number is **1 m**.
8. **Hilo, Hawaii : 10 m**. Exaggerated. Hilo is located on the East coast of Big Island, the easternmost island of the Hawaiian archipelagos, hence the most exposed to tsunamis arriving from the South-American coast. A wave of 30 feet (9 m) has been reported by the journal *“Hawaiian Gazette”* and echoed by Geinitz (G trans.p26), but without any concrete evidence to support it. On the contrary, measurements carried out continuously during the whole day at Hilo bay by an individual (M. Severance) yield a maximum height of only 13.5 feet (~ 4 m) above lowest tide level (G trans.p26). The height of the tide at the time of the observation is not indicated, but tides are of the order of magnitude of 1 meter at Hilo, so it would correspond to 3 m above highest tide level. Everywhere else on the Hawaiian Islands, heights of only a few feet (~ 1 meter) are reported. A boat pilot (M. Babcock) measured a maximum difference between high and low levels of 58 inches (1.7 m) in Honolulu (G trans.p26). Finally, this lesser figure of 3–4 m at Hilo is identical to the one reported at the Marquesas Islands, even more exposed to South-Americans tsunamis (V trans.p20, MdB trans.p32). An hypothesis for the exaggeration would be confusion with the very important damages caused by catastrophic floods due to torrential rains over those Islands during the whole month of May (VG trans.p20). ITIC data base has not been contaminated by this exaggeration and gives the correct number of **3.7 m**.
9. **Gaviota, San Luis Obispo, California : 3–4 m**. Highly doubtful, possible confusion with another earthquake & tsunami. Geinitz (G trans.p20), echoed by Montessus de Ballore (MdB trans.p23), reports that *"here at 7 o’clock 10 min. a. m. of the 10th the sea rose 12 feet, then receded, and within 20 min rose and fell three times"*, according to a press article with no further precision. The *“History of San Luis Obispo County, California, 1883”* gives exactly the same story with identical details (3 waves, 1/2 hour, 12 feet), quoting the San Luis Obispo Tribune, but occurring at another date : 16 April rather than 10 May (sic !) and at a different place : Cayucos, 100 miles north of Gaviota (re-sic !) (Angel, 1883, p. 330). They also report that an earthquake was felt there on the morning of April 16. An article entitled “The Tidal Wave” was indeed published in the San Luis Obispo Tribune of 19 May 1877 (Tribune, 1877). But the article reminisce about 1868 and is so poorly redacted that it is quite difficult to decipher whether the 12 feet refer to 1877 or 1868 or even to the tidal wave of April 16 observed at Cayucos ... *"[...] The trouble noticed in the waters at Cayucos last week, and reported to us by Mr. Cass, proves to have been the effect of a tidal wave, and was noticed at different points all along the southern coast [...] We believe that the wave of 1868, as observed on the coast of California, did not anywhere show greater fluctuation than on the 10th inst., at Anaheim, where there was a rise of twelve feet in a few minutes [...]"*. More important, San Francisco tide gauge (Sausalito, at the entrance of the bay) reveals waves of no more than 1 feet (0.3 m) on 10 May 1877 (Lander et al., 1993). Soloviev tagged the 3–4 m number with a question mark (S p117) and ITIC data base gives an intermediate number of 1.83 m at Gaviota. Therefore, we consider the Gaviota number should be ignored and the correct number to be taken into account is the tide gauge record at Sausalito : **0.3 m**.
10. **Japan: 3 m**. doubtful, possible confusions. Geinitz uses Japanese newspapers to report tidal waves at 3 locations : (i) Hakodate (southern Hokkaido), (ii) Kamaishi (northern Honshu) and (iii) Kadsusa (Central Honshu, on Chiba peninsula East of Tokyo) (G trans.p31-32).

    (i) At Hakodate, Geinitz reports two conflicting numbers... According to the *“Japan Gazette”* and *“Hiogo News”* we learn the following : “[...] *On May 11 at 11h30am the sea suddenly dropped very low, but after 10 min rose above 7 feet. Around 2h30 pm the wave reached its greatest height. The greatest difference between the highest and lowest water is given as about 8 feet* [...]”. So, this is the first and largest figure. But Geinitz adds another newspaper release (transmitted to him by a prof. E. Naumann in Yeddo) that states “[...] *a little later than 4 pm the sea water fell by about 1 foot and began to rise again rapidly by about 2 feet* [...]”. So this gives a second and lesser figure. However, the article goes on about the testimony of an old man living opposite the bridge Eitaibashi of Fukagawa. This is a neighborhood of Tokyo and we infer that Geinitz got somehow mislead into thinking this 2nd report was about Hakodate when it was really about Tokyo (Yeddo). So crest to trough variations of 8 feet (2.4 m) at Hakodate and 3 feet (0.9 m) at Tokyo.

    (ii) At Kamaishi, Geinitz refers to a letter from Professor E. Knipping in the *“Geogr. Mittheilungen”* of 1877, which unequivocally

states that the sea rose and fell 10 feet every 5 min. However, Milne who traveled along the Japanese coast after the tsunami reports a lesser number of 5 ½ feet (1.65 m) above ordinary high water, marked upon a jetty.
(iii) At Kadsusa, Geinitz cites a reports that states : *"on the 11th, large waves came in at 12 am [...] and again at 4 pm [...] People were dragged away with the waves to the sea"*. No height is given, but the report goes on : *"On the 12th, the floods came again suddenly in Yokohama [...] Also in the vicinity of Mori-oka, heavy rain began and the water volume of the Kitagamigawa River increased [...] On the 13th, the water exceeded the usual height by 10 feet"*. We understand the reports aggregates the tidal wave at Kadsusa on the 11th, with a flood in Yokohama on the 12th and an Iwate province (500 km north of Tokyo and Kadsusa) river flooding on the 13th... We infer that Geinitz took this figure of 10 feet as a measurement of the tidal wave at Kadsusa, when it really refers to the unrelated Kitagamigawa River flooding.
Therefore, the final numbers are : Hakodate **2.4 m**, Kamaishi **1.65 m**, Tokyo **0.9 m** and Kadsusa unknown.

In conclusion, then (as now), impressions are often reported as facts, giving free rein to fantasies and exaggerations. Confusion over reports that mix different things is also quite common. Today, the large number of precise measurements carried out in-situ or by satellite makes it possible to correct this. At the time, very few measurements were carried out. However, in spite of their small number, wherever they exist, they indicate heights much lower than those reported otherwise. A careful and thorough review of ancient reports exposes errors and exaggerations. It reveals that nowhere in near field the tsunami exceeded 10 m (Table 3, part 1). In the far field, figures vary from 1–4 m at exposed Pacific Islands to 0.5–2.5 m in Japan, Australia and New Zealand (Table 3, part 2). Obviously, the tsunami of 1877 is significantly smaller than what the writings of the time have let believe (Fig. 3).

4. Polarity of first tidal wave and rupture length

Some accounts of the tsunami evoke a negative first arrival : the sequence initiates with a withdrawal of the sea. Others evoke a positive first arrival : a wave, a sudden flooding, without prior withdrawal. At some places, it is even more complicated: some witnessed an initial withdrawal, some did not. It would be easy to infer that testimonies are unreliable... and ignore them. However, when sorting testimonies along the South-American coast with latitude, a pattern emerges: the withdrawal is always noted when one is far south and far north of the earthquake, but it is near the epicenter that the reports are conflicting or that a sudden wave without initial withdrawal is reported (Table 1). How to explain this ?

In a simplified schematic framework, the polarity of a tsunami generated by a major subduction earthquakes is well known: because the co-seismic rebound of the upper plate is directed towards the trench, the first wave should be positive towards the exterior (the open sea) and negative towards the interior (the coast). Therefore at the coast, one should always and everywhere see an initial withdrawal. However, at short distance from the rupture, the withdrawal can be small and of short duration. When the sea returns, the positive wave can be very high and arrives very quickly, the closer from the rupture, the quicker. In Chile, the coast is typically no more than 100 km away from the trench at many places and the tsunami arrives no more than 10 min after the earthquake (e.g. Melgar et al., 2016). The delay between the initial withdrawal and the first positive wave can thus be reduced to less than 1 min. Consequently, the initial withdrawal

Table 3
Revised values for the 1877 tsunami heights.

Location	Latitude	Longitude	Height (m)	Range (m)	Reference
Ancon, Peru	−11,73	−77,15	1,00	1–1,5	This work. Section 3–7
Callao, Peru	−12,05	−77,13	1,00	1–1,5	This work. Section 3–7
Pisco, Peru	−13,71	−76,18	1,50	1–1,5	This work. Section 3–7
Chala, Peru	−15,85	−74,26	1,50	1–1,5	This work. Section 3–7
Mollendo, Peru	−17,02	−72,02	2 ,5	2–3	Geinitz (G tr.p18)
Ilo, Peru	−17,67	−71,35	1,50	1–1,5	This work. Section 3–7
Arica	−18,48	−70,31	4,50	4,5–7,5	This work. Section 3–1
Pisagua	−19,60	−70,21	4,00	3,6–5	Hilliger (G tr.p13) & Geinitz (G tr.p17)
Mejillones (del Norte)	−20,15	−70,16	3,00	2,4–3,9	Hilliger (G tr.p13) & Geinitz (G tr.p16)
Iquique	−20,23	−70,14	4,00	3,6–6	Hilliger (G tr.p13) & Geinitz (G tr.p4–5)
Chanabaya	−20,90	−70,14	10,50	–	Geinitz (G tr.p6)
Pabellon de Pica	−20,91	−70,14	8,50	7,5–9	Hilliger (G tr.p12)
Guanillos	−21,17	−70,11	9,00	7,5–9	This work. Section 3–2
Tocopilla	−22,09	−70,20	9,00	7–15	This work. Section 3–3
Cobija	−22,56	−70,26	9,00	7,5–9	Hilliger (G tr.p12) & Geinitz (G tr.p7)
Mejillones (del Sur)	−23,10	−70,45	11,00	9–11,5	This work. Section 3–4
Antofagasta	−23,65	−70,40	3,50	–	This work. Section 3–6
Paposo	−25,01	−70,46	2,75	2,5–3	Vidal–Gormaz (V tr.p8)
Chanaral	−26,35	−70,62	3,80	3,6–4	Hilliger (G tr.p12) & Geinitz (G tr.p10)
Caldera	−27,07	−70,82	2,50	2–3	Hilliger (G tr.p12) & Geinitz (G tr.p9)
Coquimbo	−29,96	−71,34	1,75	1,5–2	Hilliger (G tr.p12) & Geinitz (G tr.p11)
Acapulco, Mexico	16,84	−99,83	1,00	–	Geinitz (G tr.p20)
Sausalito, Ca., USA	37,86	−122,49	0,30	0,25–0,35	This work. Section 3-9
Nuka-Hiva, Marquesas	−8,92	−140,01	4,00	–	Geinitz (G tr.p20)
Apia, Samoa	−13,82	−171,66	1,00	0,8-1,2	This work Table 2-footnote 16. Geinitz (G tr.p25)
Hilo, Hawaii	19,73	−155,05	3,70	2,7–3,7	This work. Section 3–8
Honolulu, Hawaii	21,45	−157,92	1,40	1,4–1,7	This work. Section 3–8
Kahului, Maui	20,88	−156,46	1,40	1,2–1,5	Geinitz (G tr.p26)
Taraunga, New Zealand	−37,62	176,18	1,00	–	Geinitz (G tr.p27)
Wellington, New Zealand	−41,10	174,50	1,00	–	Geinitz (G tr.p28)
Lyttelton, New Zealand	−43,62	172,75	0,90	–	Geinitz (G tr.p28-29)
Newcastle, Australia	−33,06	151,75	0,75	–	This work, Table 2-footnote 20
Sydney, Australia	−33,85	151,25	0,30	–	This work, Table 2-footnote 20
Tokyo, Japan	35,53	139,89	0,90	0,7–0,9	Soloviev (S p113). This work Section 3–10
Kamaishi, Japan	39,27	141,88	1,65	–	Milne p61. This work Section 3–10
Hakodate, Japan	41,83	140,83	2,40	–	Geinitz (G tr.p32). This work Section 3–10

List of corrected tsunami heights after careful cross examination of references described in Section 3. Heights and uncertainty ranges are in meter.

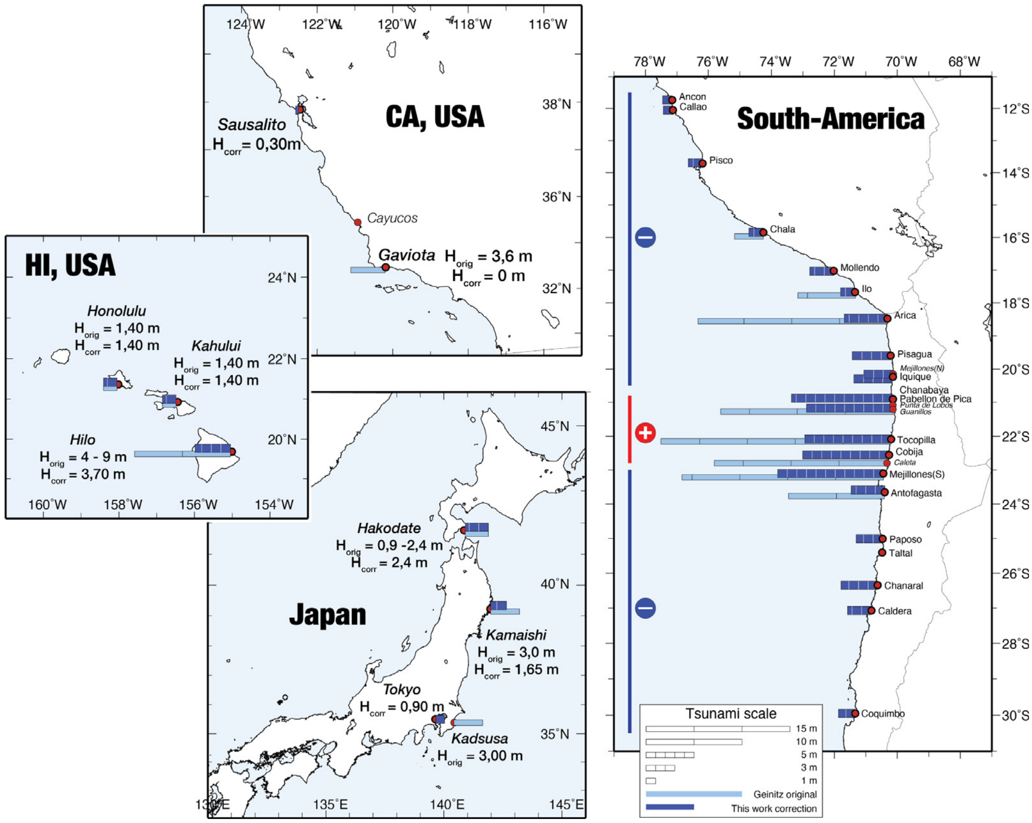

Fig. 3. Tsunami heights : original vs revised numbers. Original heights reported by Geinitz (1878) are depicted in light blue (values listed in Tables 1 and 2). Revised numbers according to discussion in Section 3 are depicted in dark blue (values listed Table 3). The same scale is used for all 4 maps. The plus symbol & red line and the minus symbol & blue line along the Chilean & Peruvian coastlines (South-America inset) depict the polarity of the first arrival : - correspond to the report of an initial withdrawal of the sea, + correspond to the report of a sudden flooding (cf. Table 1).

can be unnoticed, because it is small (relative to the following waves), of very short duration, and all the more so as the earthquake occurs at night, after many lights have been destroyed by the earthquake. It appears legitimate that many inhabitants, in the confusion of the severe earthquake shaking that had just occurred in the near field, emerging from the rubble to fight the fires that started to break out everywhere, did not notice the brief initial withdrawal of the sea before it returned in force. On the contrary, hundreds or thousands of kilometers away from the rupture area, the tsunami will arrive hours after the earthquake and the initial withdrawal can last several minutes or more. Therefore, when far away from the rupture, i.e. far north or far south in Chile, the initial withdrawal lasts longer and the positive tsunami is proportionally weaker. If the withdrawal lasts long enough and if it occurs in the daylight, it is conceivable that the inhabitants will even spread the information and will come to witness it. All effects concur to make the initial withdrawal conspicuous and reported.

To conclude, it can be inferred from the above that places along the coast where the withdrawal is important enough to be reported are far away from the rupture area, while places where it is not reported are in front of the rupture. In the case of the 1877 earthquake & tsunami, this area appears to be limited between slightly north of Pabellon de Pica (20.5°S) and slightly south of Cobija (22.5°S) (Table 1, Fig. 3). This length of ~200–250 km, that we will call $LTsu$ (Figs. 3 and 5), matches very well the length A0 estimated by Soloviev and Go (1975), and even Kausel (1986), had he stuck to his original intensities (Fig. 2).

5. Comparison with recent Chilean tsunamis

Three large earthquakes occurred on the Chilean subduction over the last decade : Maule 2010 (Mw 8.8), Iquique 2014 (Mw 8.1) and Illapel 2015 (Mw 8.3). All three triggered powerful tsunamis that flooded significant sections of the Chilean coast and were recorded all around the Pacific Ocean. Extensive surveys were conducted and inundations were accurately measured at many locations.

In the near field, along the Chilean coast, a straightforward comparison of the 1877 tsunami with those three recent ones reveals that 1877 is comparable or only slightly larger in size and amplitude with the 2015 Illapel event (Fig. 4). Inundation heights are of the same order of magnitude (~10 m) and the length of the affected coastline is comparable (~1000 km). The 2010 Maule event is larger, and the 2014 Iquique event is smaller.

In the far field, the comparison is less straightforward because the local inundation depends not only on the earthquake magnitude but also on its location, since the azimuth of the incoming tsunami matters. At the Pacific islands where 1877 was noted (Marquesas, Samoa and Hawaii), at first sight, 1877 seems comparable to Maule 2010, or even bigger (Fig. 4, inset panels). But 1877 occurred 2000 km north of Maule 2010, which is much more effective in generating higher waves towards these islands. The clue comes from the comparison between the 3 recent events : In Hawaii, at Kahului and Hilo, the 3 earthquakes generate similar inundations (Iquique 2014 : 0.5–0.6 m; Illapel 2015 : 0.6–0.9 m; Maule 2010 : 0.9–1 m) despite their large difference in magnitude (8.1, 8.3, 8.8). In the Samoa islands, at Apia, Maule 2010 (0.4 m) is twice as large as Illapel 2015 (0.2 m) and four times as Iquique 2014 (0.1 m); But at PagoPago, Maule 2010 (0.7 m) is similar to Illapel 2015 (0.68 m) and both are twice as large as Iquique 2014 (0.35 m). In the Marquesas islands, the latitudinal effect is also at play : At the same tide gauge of Taiohaë (Nuka-Hiva Island), Iquique 2014 generates 0.5 m, Illapel 2015 1.37 m and Maule 2010 only 0.95 m. It should be noted that in 2010, the tide gauge saturated and different measurements spread in the same bay of Taiohaë give quite different heights, ranging 2.40–3.78 m.

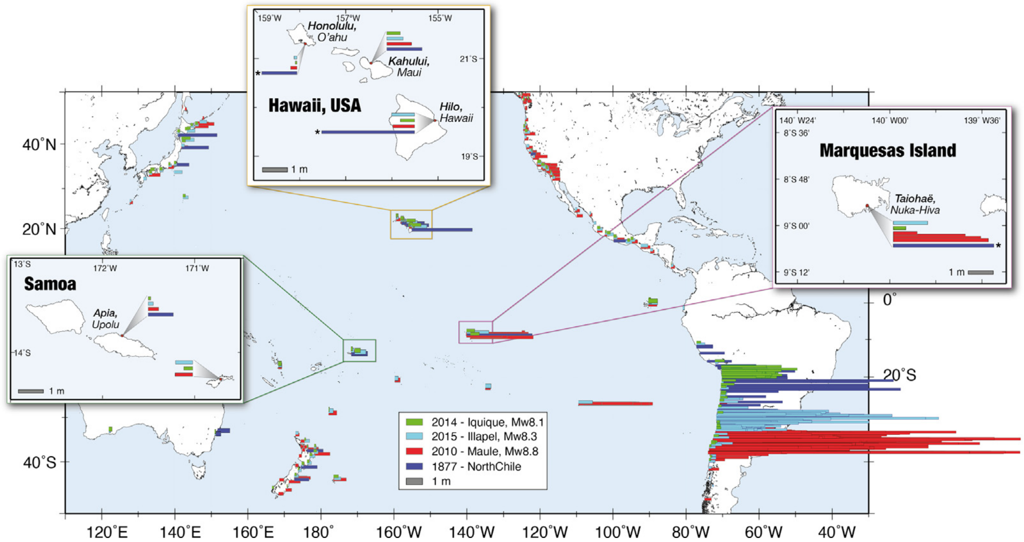

Fig. 4. Comparison of 1877 tsunami heights with the 3 recent Chilean earthquakes & tsunamis of 2010, 2014 and 2015. 1877 is in dark blue (values listed in Table 3). 21st century tsunami heights are from the International Tsunami Information Center (ITIC) data base at NCEI/NOAA (ITIC, 2022). Maule 2010 Mw8.8 (red), Iquique 2014 Mw8.1 (green) and Illapel 2015 Mw8.3 (light blue). The scale is identical for the 4 tsunamis, depicted by the 1 meter gray drawbar located in the central legend-box for the trans-pacific map and in the lower left corner of each inset map. Maule 2010 largest heights (2 values above 20 m) have been truncated.

Eventually, a Mw 8.1 earthquake (Iquique 2014) generates half of the inundation of a Mw 8.8 (Maule 2010) at PagoPago (Samoa) or Maui and Hilo (Hawaii), and a fifth at Nuka-Hiva (Marquesas), simply because it is located more to the North of the Chilean coast and despite its seismic moment being 10 times smaller. Therefore, the fact that at many different places the inundations of 1877 are of the same order of magnitude as those of 2010 (Fig. 4), despite the more efficient location of 1877 epicenter, is an indication that its magnitude is in fact significantly smaller than 2010.

Even further, in California, Japan, New Zealand and Australia, the comparison becomes very difficult for a variety of reasons. (i) Numbers become small and relative uncertainties become high. (ii) Uncertainty over the exact reference (lowest tide, highest tide, mean tide, crest-to-trough measurement, …) becomes critical. (iii) Local effects become really predominant, including the anthropogenic changes between the XIXth and the XXIst century, like the construction of a pier to protect a harbor, for example. (iv) The difference in efficiency relative to the variation in azimuth of the incoming tsunami is increasingly marked. However, the rationale remains true for the most part: 1877 is not higher than Maule 2010, despite its more favorable position.

An earthquake of given magnitude will also generate different tsunamis depending on two additional parameters: its depth and the speed of its rupture. These are largely unknown for the 1877 event, even though one can suspect a deep rupture if the observation by Montessus de Ballore (epicenter below the continent) is correct. So, there is no simple and direct way to estimate 1877 magnitude from the comparison with other earthquakes tsunamis. However, it is most probably larger than Iquique 2014 and Illapel 2015, and smaller than Maule 2010. Hence, its magnitude would likely range between 8.5 and 8.7. This reduced estimate appears also in better agreement with the estimate by Lomnitz (1970) of a Richter magnitude (Ms) between 8 and 8 1/2.

6. The 1877 earthquake in the modern literature

As of today, a total number of 311 publications, out of which 205 research articles, cite Comte and Pardo (1991) (GoogleScholar, 2022; Scopus, 2022). Among them, almost a hundred research articles refer to it specifically for the rupture length and magnitude of the 1877 earthquake. Even though Comte and Pardo (1991) specifically mention a rupture length of 420 km (cf Fig. 2-C), many of these publications depict the rupture with an extremely long length, up to 500 km and more, stretching from Mejillones (23°S) to Arica (18.5°S) (e.g. Pritchard and Simons, 2006; Chlieh et al., 2011; Béjar-Pizarro et al., 2013; Hayes et al., 2014; Jara et al., 2018; Jolivet et al., 2020). These drawings have lead to the frequent misconceptions that (i) 1877 was a giant magnitude 9, (ii) it had ruptured the entire northern Chile stretch, up to the Arica bend, (iii) it was contiguous to the 1868 Peruvian earthquake that had reached the Arica bend from the north. Last, because Comte and Pardo (1991) had established a recurrence of 150 years at most, it became quite frequent to "predict" the imminent occurrence of a giant earthquake in northern Chile (e.g. Casarotti and Piersanti, 2003; Chlieh et al., 2011; Schurr et al., 2014). These predictions clashed with recent coupling maps revealed by GPS measurements in the region, which do not depict a 500 km long coupled segment (e.g. Métois et al., 2013).

7. The 1877 rupture and present-day coupling revealed by Geodetic measurements

Recent GPS & INSAR measurements revealed a more complex pattern of coupling than initially thought (e.g. Métois et al., 2013; Béjar-Pizarro et al., 2013; Li et al., 2015; Métois et al., 2016; Klein et al., 2018; Jolivet et al., 2020). Between 18°S and 23°S the coupling appears patchy rather than uniform (cf. Fig. 1 for comparison of various coupling models). More recent models all show a large low coupling zone (LCZ) that interrupts the coupling at the latitude of Iquique (20.5° S) and draws two segments on either side : The Camarones segment to the North and the Loa segment to the South (Figs. 1 and 5). The Camarones segment consists of two different portions: the actual bend between Arica and Pisagua (18°S–19°S), poorly coupled with low seismicity, and the Pisagua–Iquique section (19°S–20°S) that is coupled and precisely ruptured in 2014 (e.g. Ruiz et al., 2014). On the contrary, the Loa segment is depicted by a large patch of rather homogeneous high coupling that runs over ~200 km between Iquique and Mejillones. Positioned between Iquique (20.5°S) and Cobija (22.5°S), the reduced length of ~225 km of the 1877 rupture (A0) matches well the Loa segment alone. Both, also match length $LTsu$, the length of coastline where no initial withdrawal of the sea was reported at the occasion of the 1877 tsunami (cf Section 4, Fig. 3, Fig. 5). The observation that a reduced 1877 rupture would better match the coupling pattern inferred from geodesy had been done earlier (Métois et al., 2013). This

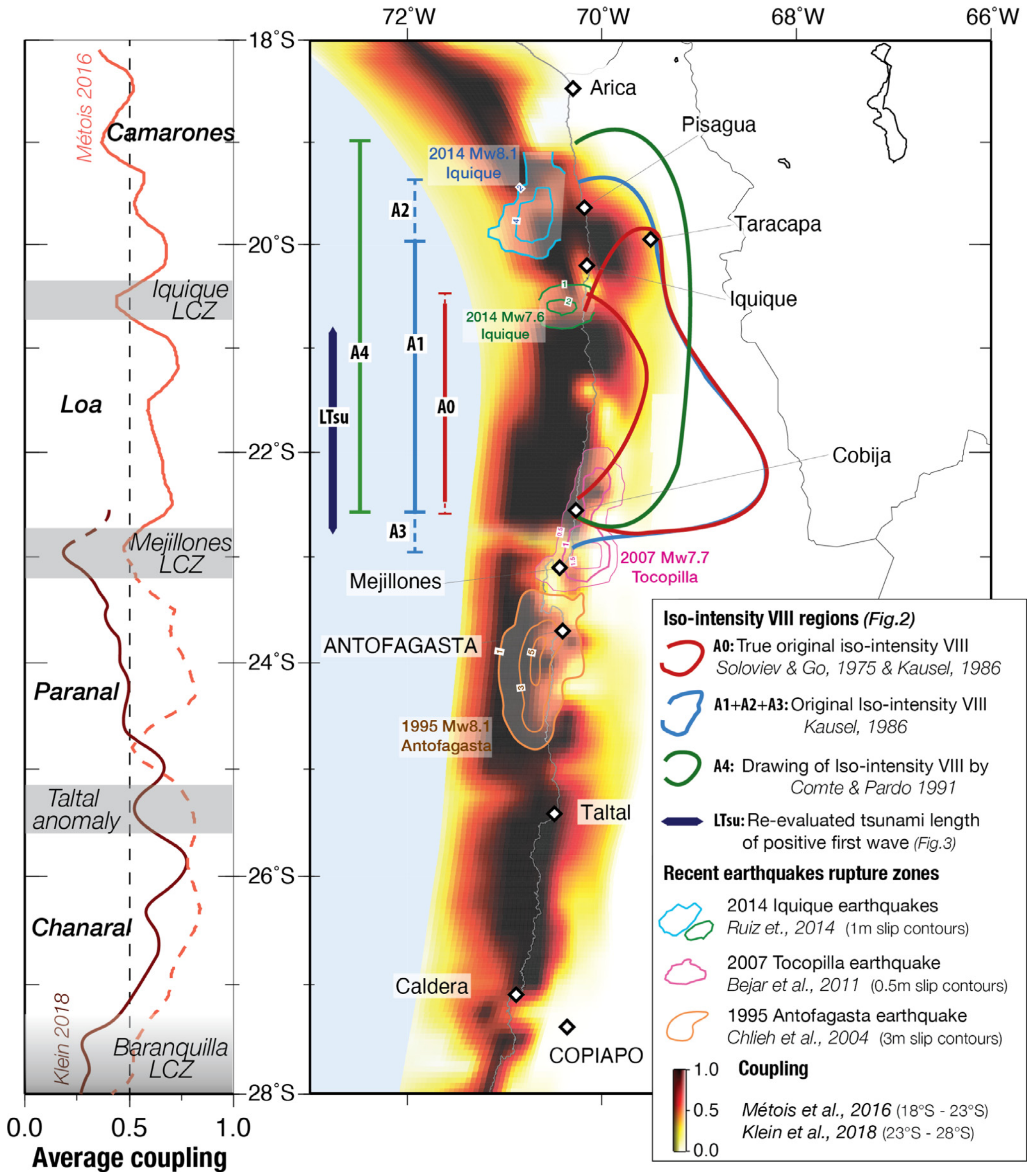

Fig. 5. Comparison of iso-intensity VIII with geodetic coupling and rupture zones of modern earthquakes. Coupling maps (right panel) and average coupling curves (left panel) are from Métois et al. (2016) in-between 18°S and 23°S and from Klein et al. (2018) in-between 23°S and 28°S. Earthquake slip models are depicted by colored contour lines. Antofagasta 1995 (Mw8.1, Chlieh et al. (2004) - orange), Tocopilla 2007 (Mw7.7, Béjar-Pizarro et al. (2013) - purple), Iquique 2014 (Mw8.1 & Mw7.8, Ruiz et al. (2014) - blue & green). Original iso-intensity VIII areas from (Soloviev and Go, 1975) and Kausel (1986) (red curves & red length A0); enlarged iso-intensity VIII by (Kausel, 1986) (blue curve & blue length A1+A2+A3) and (Comte and Pardo, 1991) (green curve & green length A4). Length LTsu (dark blue line) depicts the coastline length along which a positive first arrival was reported in (Geinitz, 1878) (Fig. 3).

work confirms it and corroborates it by providing a substantial amount of evidence. Finally, the complex segmentation and patchy coupling imaged by GPS and InSAR also supports the hypothesis that the two large historical earthquakes of 1868 (Peru) and 1877 (Chile) are likely disjointed by at least 200 km instead of having ruptured two contiguous segments of 400–500 km long. However, it is notorious that coupling is not very well constrained on the shallowest part of the interface by on-land geodetic measurements, especially when the coastline is far away from the trench. In Chile, the coastline runs quite close to the trench, except precisely around the Arica bend, north of 19°S. So coupling is less well determined there and there is a possibility that some shallow coupled surface, located precisely in between the 1868 and 1877 ruptures, escaped detection. We argue here that the 1877 rupture did not go across the Iquique LCZ and did not rupture any length of the Camarones segment, whether coupled or not, but this could have happened on other occasions.

8. Conclusion

For more than 30 years following Kausel (1986) and Comte and Pardo (1991), the 1877 North Chile earthquake has been associated to a ~500 km long rupture and a large magnitude of ~9 in the scientific literature. A careful cross-reading of the ancient articles allows to detect mistakes and exaggerations, and leads to a downward revision of these figures to lesser values. The rupture is more likely 200–250 km long only, as attested by true original iso-VIII curves by Soloviev and Go (1975) and Kausel (1986), and by the coastal impact of the real tsunami as redefined in this work. The magnitude should probably also be lowered to ~Mw 8.5 according to the comparison with the size and amplitude of the more recent Chilean tsunamis of the last 10 years.

From there, two hypotheses emerge: either 1877's magnitude is indeed revised downward to ~8.5 or it is really around 9. In the first case (lesser magnitude), the characteristic earthquake of the region would occur about every 100–150 years, as suggest by Comte and Pardo

(1991), but over a reduced length of about 200–250 kilometers and with a slip of less than 10 m. The 10 m amount corresponding to the maximum inter-seismic accumulation occurring at the velocity of plate tectonics in the region (~6 cm/year) over the longest period of 150 years. It is therefore an earthquake of magnitude "only" ~8.5. In the second case (larger magnitude), the 1877 earthquake is exceptional in that it corresponds to much more slip released over the same (small) length. It cannot be repeated before a much longer duration: ~300 years to accumulate twice as much deformation and generate a Mw~8.8, ~500 years for a Mw~9.

In all cases, the seismic hazard of the region must be completely revisited in light of these revised lesser figures and of the coupling revealed by GPS. If the Arica section (poorly coupled) and the Pisagua section (already ruptured in 2014) of the Camarones segment, do not participate in either the 1877 earthquake or its upcoming repeat, these earthquakes (past and future) correspond to a length of 200–250 km long, meaning twice shorter than believed. In 100–150 years, i.e. the return period established by Comte and Pardo (1991), at 6 cm/yr only 6–9 m of deformation are accumulated, the release of which corresponds to a Mw ~8.5 earthquake. For a larger magnitude of Mw ~8.7–8.8, with the same length, one would have to accumulate at least twice as much deformation, therefore wait at least twice as long, i.e. 200–300 years. One would have to wait even longer, i.e. ~500 years to accumulate the 30 m needed to produce a Mw ~9 earthquake, still on the same short length. The North Chile gap may very well be an other example of a place where two earthquake cycles are superimposed: a normal cycle of frequent but "smaller" earthquakes and a super-cycle of much larger giant earthquakes, but much less frequent (e.g. Sieh et al., 2008). In North Chile, that would mean one magnitude ~8.5 every 100–150 years and possibly one magnitude ~9 every 500 years. Additionally, although the ruptures of the 3 last megathrust earthquakes in Chile (Maule 2010, Iquique 2014 and Illapel 2015) matched well single highly coupled segments, it cannot be ruled out that a given rupture would propagate into an area of low coupling, enhancing the rupture length and the earthquake magnitude. Then, another contiguous segment could also break simultaneously, e.i. part or all of the Camarones segments to the North or the Paranal and/or Chanaral segments to the South. This would increase the magnitude even more. We argue here that this was not the case of the 1877 rupture but could have happened in the past (cf. Salazar et al. (2022)) and could happen in the future.

In any case, a larger recurrence is quite compatible with an important observation made by Vidal-Gormaz (1878) and echoed by Montessus de Ballore (1911) : "*[...] Towards the east of the mouth of the Loa river there were enormous artificial dams built with large rocks by the ancient inhabitants to channel the river and use its waters to irrigate the valley; but these old and colossal works disappeared completely with the earthquake of May 9th, leaving no traces of human labor, forcing the river to change its course because of the debris; which leads us to suppose that this region had not experienced a similar cataclysm in the historical epoch of South America, and that the earthquake of May 9th has been for the Loa river much greater than any it had experienced for many centuries [...]*". Therefore, the next magnitude ~9 earthquake in the region, if it ever happened and if it ever happens again, would not be for the 21st century, but rather for the 24th, or later.

CRediT authorship contribution statement

Christophe Vigny: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Emilie Klein:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation.

Data availability

Scans, transcripts and translations (if relevant) of 9 ancient articles (Geinitz, 1878; Vidal-Gormaz, 1878; Tribune, 1877; Milne, 1880; Harnecker, 1895; Harnecker, 1897; Montessus de Ballore, 1911; Soloviev and Go, 1975; Kausel, 1986) are available as electronic supplements. Further citations of this work or use of transcripts or translations should also refer to these original articles.

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 pro version of DeepL translator. We thank our three reviewers and our editor Prof. E. Contreras-Reyes for their very constructive reviews. This work was supported by CNRS and ANR grant number ANR-19-CE31-0003.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jsames.2022.103878.

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