THE EARTHQUAKES OF AUGUST 1868 AND MAY 1877 THAT AFFECTED SOUTHERN PERU AND NORTHERN CHILE

The last two major earthquakes that affected the regions of Tarapaca and Antofagasta were the earthquakes of August 13, 1868, which was felt in southern Peru and northern Chile, and that of May 9, 1877, known as the Tarapaca earthquake, which affected areas of southern Peru, Bolivia and northern Chile.

Earthquake of August 13, 1868 at 16h 45m

This earthquake is considered one of the great catastrophes of the last century in Chile and Peru. It was felt from Guayaquil to Valparaiso. According to the information of damages compiled by Montessus de Ballore (1911-1916) for diverse localities along the coast and interior towns, and the antecedents gathered by Domeyco (1868) and Von Hochstetter (1868-1869) referring to the tidal wave that accompanied it, lashing the coasts of the Pacific, it can be estimated that the epicentral region covered the coastal area approximately between 16.5° and l9° South Latitude, also affecting the towns located further inland such as Arequipa, Moquegua, Tacna and others. In this work, the epicentral region is understood as the area enclosed by the isoseismic curve VIII (Modified Mercalli scale).

According to our appreciation of the effects of the earthquake compiled by the authors indicated above, we can estimate the intensities as follows:

VIII or higher	: Arequipa, Moquegua, Locomba, Tarata, Mollendo, Ilo, Islay, Sama. Arica, llabaya, Paucarpata, Tiabaya. Characato, Quinqueño. Yarabamba, Savandia.
VII to VIII	: Tarapaca
VII	: Caraveli, Nasca, Chala, Ica, Pisagua, La Noria, Iquique, Tirana, Pachia, Calana (Peru).
VI	: Cañete (Peru), Chincha, Tocopilla. Chiu-Chiu. Calama.
V - VI	: Cobija
V	: Mejillones del Sur, Antofagasta, Coloso, Lima, Pisco.
IV	: Chañaral, Copiapo, Taltal.
III	: Caldera

Fig. 1 shows the approximate layout of the main isoseismic curves. Since most of the buildings in both Chile and Peru were made of adobe, it is not possible to estimate intensities greater than VIII from the damage.

The experience acquired in the study of other earthquakes (e.g. that of May 22, 1960) indicates that the length of the rupture zone of the fault of an earthquake in Chile is approximately equal to the major axis of the isoseismic curve that encloses intensities equal to or greater than VIII. The dimensions of the rupture zone are also intimately linked to the extension of the tsunami generating zone, to the area covered by the aftershocks, to the region where the coastline experiences permanent subsidence or uplift, etc.

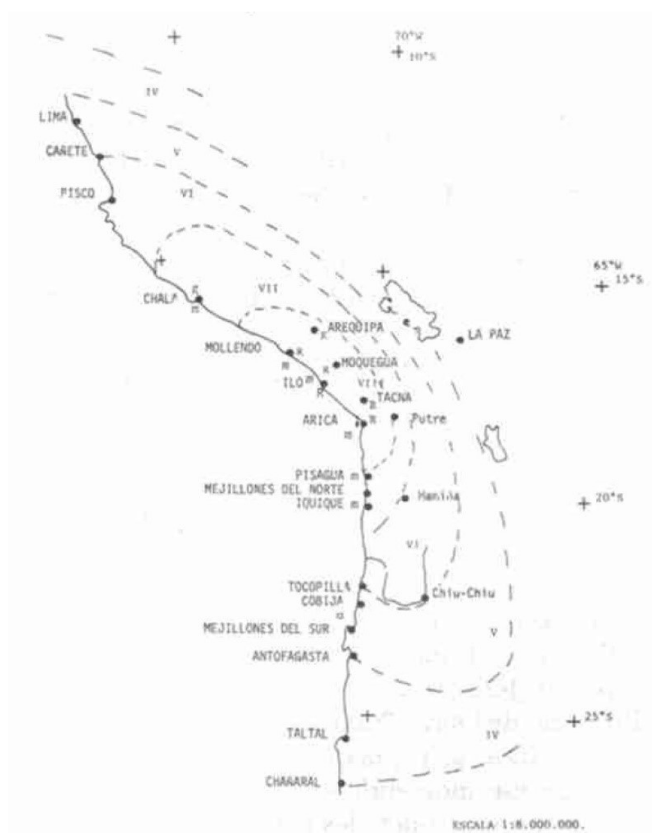

Fig.1. *Earthquake of August 12, 1868. M = 8 ½; M_t= 9; M_w = 9.1. Modified Mercalli isoseismic curves. Key: ● Locations with estimated intensity (see text). ↓ Possible coastal subsidence; R Aftershocks; m high-intensity tsunami.*

The epicentral or rupture zone was then determined by taking into account the possible limits of isoseismic VIII together with estimates of tsunami wave heights at various ports, the time elapsed between the earthquake and the tsunami, information concerning possible coastal uplift or subsidence, comparison of the number of aftershocks felt at different locations, etc.

The background described below allows us to estimate with some confidence that the area covered by the 1868 earthquake rupture extended between 16.5° and 19° south latitude.

An eyewitness account, written in Tacna a few days after the earthquake and reproduced by El Pacífico of Thursday, August 13 and Friday, August 14, 1883 (see Montessus de Ballore, 1911-1916), mentions that "the island of Alacrán that served as a prison in Arica, with the houses and prisoners that were there, was submerged". This information is useful to include Arica within the region of rupture and supports the idea that the intensity in that city equaled or exceeded grade VIII.

Wave heights at the main ports indicate that the highest tsunami intensities covered Chala, Mollendo, Islay, Arica and Pisagua. This background helps to locate the epicentral zone as it appears in Fig. 1. Considering that in Pisagua the intensity was VIII, the southern limit of isoseismic VIII should be located slightly north of that locality, judging by the intensity of the tsunami observed there.

There are some antecedents related to the frequency and intensity with which aftershocks were felt in certain localities. We have assumed that those towns in which the aftershocks were felt almost continuously during the first day after the earthquake or in which it is inferred that the aftershocks continued for days, weeks or months, are included in the epicentral zone.

The direction of approach of the tsunami is an indirect way of estimating the length of the rupture zone. For example, in a description of the earthquake by Don Juan Williamson in Lima, 1869, he states that "the sea flood, coming from the northwest, fortunately found in the island in front of Iquique an obstacle that diverted its course and restricted its violence". The NW direction in which the tsunami approached suggests that the rupture zone did not reach as far as Iquique.

The above background together with other details that emerge from a careful reading of the accounts compiled by Montessus de Ballore (1911-1916), have allowed us to trace with some confidence the northern and southern limits of isoseismic VIII, and consequently the possible length of the rupture zone, which, according to Fig. 1, we estimate to be about 480 km long.

The epicentral zone is clearly to the north of the Mejillones peninsula where we believe the intensity did not exceed grade VI on the Modified Mercalli intensity scale.

Earthquake of May 9, 1877 at 20h16 m

The epicentral zone of this great earthquake was a vast region between l9°S and 22.5° South. It was felt from Santa (Peru) to Constitución. It is interesting to note that this earthquake produced its greatest effects just south of the epicentral zone of the earthquake of 1868.

The estimation of intensities from the description of the effects of the earthquake at various locations is as follows:

VIII or higher	: Tarapaca, La Noria, Tirana, Chanabaya, Pabellon de Pica, Guatacondo, Calama, Cobija, Matilla, Chiu-Chiu.
VII - VIII	: Pica, Tocopilla, Huanillos, Mejillones del Sur, Antofagasta and Pisagua.
VII	: Tacna, Cabo Lobos, Corocoro, Desaguadero (Bolivia), Santiago de Manchaca, Iquique, Caracoles.
VI - VII	: Paposo
VI	: Taltal, Chañaral, La Paz (Bolivia)
V - VI	: Ilo
V	: Mollendo, Arequipa, Caldera, Copiapo.

Fig. 2 shows the plotting of the isoseismic curves. The epicentral zone delimited by isoseismic VIII has been determined using additional background information such as tsunami height, aftershocks, permanent topographic changes, etc., analogous to what was done for the earthquake of 1868.

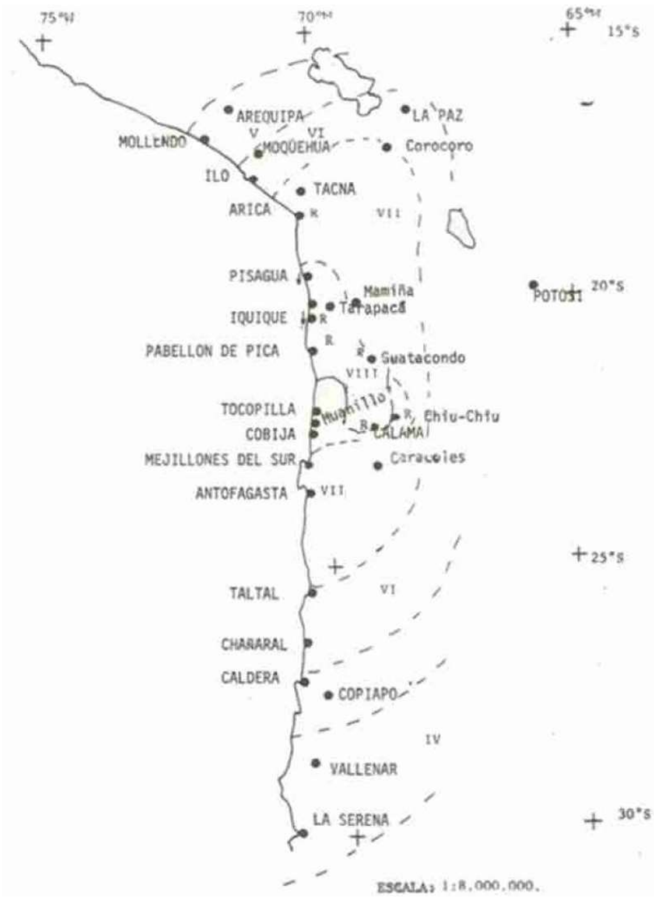

Fig. 2. *Earthquake of May 9, 1877. M = 8 ¼ ; M_t= 9; M_w = 8.9. Key equal to Fig. 1.*

According to Vidal Gómez (1884), the correspondent of El Comercio de Lima in Pisagua reported that he and others observed that "The land has lowered considerably since the earthquake of the 9; today (the sea) bathes in the high tides lands and rocks that have always been dry and with some buildings". This observation is very interesting because it allows us to suppose a sinking of the coast in Pisagua, which has made us include this point within the epicentral zone in spite of the fact that the intensity would seem not to have reached grade VIII. The same correspondent reports a "surprising physical phenomenon that has worried many and alarmed everyone". The people who witnessed this event say that in Pisagua "about 50 m from the beach, a thick column of smoke appeared in the sea, rounded at the top, which successively rose to a very considerable height, in which it dissipated shortly after without causing noise or detonation". The correspondent finally raises the possibility of a submarine volcanic eruption. Goli (1904) says that the phenomenon occurred on June 15, 1877, that is, one month after the earthquake.

Geinitz (1878) reports that the governor of the port of Iquique communicated that "the sea bottom seems to have sunk since several rocks in the bay are no longer visible, even at low tide", which confirms that Iquique is included within the rupture zone.

To the south we believe that the rupture zone reached Cobija judging by the intensity VIII that reached the earthquake in that locality and by the considerable number of aftershocks that were felt in almost continuous form, several of them "with dry blow from bottom to top". This last background suggests that the epicenter of these aftershocks was very close to Cobija.

The information compiled by Vidal Gomez (1878) indicates that between Pisagua and Cobija the tidal wave was felt between 5 and 20 minutes after the earthquake, while in Mejillones del Sur it started 30 minutes after the earthquake. This background supports our idea that the rupture zone of the earthquake did not reach much further south than Cobija. On the other hand, Lieutenant V. Cueto, officer of the armored ship Blanco Encalada stationed in Antofagasta, reported that "apparently in Antofagasta the wave penetrated around Punta Tetas" and "a current was noticed that forced the use of the engines to prevent being swept away in the direction of Caleta Chimba" (to the south of Antofagasta). Captain Castillo, 2nd commander of the vessel, reported that "there were many continuous ebbs and flows that seemed to have their origin in the North". The information of Cueto and Castillo agree in estimating that the tidal wave came from the North and therefore it is not adventurous to consider that the zone of rupture of the earthquake did not reach as far as Antofagasta.

The towns most affected by the aftershocks were Iquique, Chanabaya, Pabellón de Pica, Punta Lobos, Huanillos, Cobija, Caracoles, Chiu-Chiu and other inland towns, all located between l9°S and 22.5° South.

Reports from Antofagasta indicate that the aftershocks were quite significant. Mr. Arancibia reported that in Antofagasta "It continued to tremble from minute to minute with more or less force" (Vidal Gormaz, l884) and that "the aftershocks occurred throughout the 13, the day when people fled to the hills as a result of one of them" (Geinitz, 1878). On the other hand, the information on the tidal wave coincides in indicating that it occurred between 10 and 15 minutes after the earthquake. With these data, Antofagasta could also be included in the epicentral zone. However, we prefer to consider Cobija as the southern end of the epicentral zone due to the global background we have been able to analyze.

Milne (1880) determined the epicenter of this earthquake using information of the travel time of the seismic waves and the tsunami to different locations, locating the focus at 21 1/3°S - 71 1/4°W, that is to say in the sea about 100 km. from the coast in front of Pabellón de Pica. A similar conclusion is reached by Geinitz (1878) when locating the epicentral zone between Iquique and Pabellón de Pica. Montessus de Ballore (1911-1916) on the other hand, taking into consideration the damages occurred in towns in the interior of Iquique and Tocopilla, such as Guatacondo, Matilla, Tirana, Chiu-Chiu, Calama, and giving much importance to information from a muleteer who affirmed that "the tremor made the colossal mountain of Tacora collapse", concludes that the epicentral area extended obliquely to the mountain range from Lake Titicaca to Chiu-Chiu.

The unusual proportions of the tsunami originated by the earthquake are not compatible with an epicentral zone in the interior of the continent. On the other hand, if indeed the intensities recorded along the coast were somewhat lower than inland, this may be due to the generally better soil conditions on the coast (rock) compared to localities such as Calama and others where houses rest on soils of poorer quality.

Bruggen (1943), commenting on the 1877 earthquake, says that the subsoil of Calama is unfavorable, sand with shallow groundwater, while Chiu-Chiu is off the valley floor on a low terrace. Pica and Tarapacá were also destroyed to a large extent. The subsoil in Tarapacá "is not very bad" while that of Pica consists of loose or poorly cemented sand and is "much worse". In other towns, such as La Noria and the San Pedro saltpeter office, the subsoil is good; but the high intensity could be explained "by the vicinity of several recent transverse faults of 200 m of dip". Towns like La Tierra located in the center of the Pampa del Tamarugal are built on thicknesses of a few hundred meters of clays and sands that partly enclose underground water. Harnecker (1895) reported that the houses resisted quite well in Tocopilla because they were made of wood. However, the intensity must have been great judging by the numerous crumbling and landslides that occurred in the hills covering the road to the interior all the way down the ravine that flows into Tocopilla. Similar information for other ports, especially in relation to the fact that the constructions are made of wood and are largely supported on rock, explains the difference in the damage observed in the interior with respect to the coast. Bruggen (1943) makes an interesting comment regarding the constructions in the interior of the saltpeter zone. "They consist of walls formed by salt crust blocks that have even less resistance than adobe houses", which undoubtedly influenced the damage experienced in that area.

The above comments confirm our interpretation that the epicentral area extended between l9°S and 22 1/2°S along the coast, with a total rupture length on the order of 400 km.

Estimate of magnitude of the earthquakes of 1868 and 1877

Lomnitz (1970) makes an estimate of the Richter magnitudes (Ms) of these earthquakes, assigning them the values M = 8 ½ for the 1868 earthquake and M = 8 a 8 ½ for the 1877 earthquake. According to the extent of damage and intensity of the respective tsunamis, we agree with Lomnitz on the magnitude of the 1868 earthquake. For the 1877 earthquake, we believe that its magnitude must be greater than 8 and definitely less than 8 ½, so we dare to assign it a magnitude 8 ¼ instead of estimating only that of ½ degree proposed by Lomnitz (1970).

Recently Kanamori (1977) proposed a new scale of magnitude M_w, resulting from the combination of formulas that express the energy E with the seismic moment M_0 and of the estimation of the energy E given by Richter from the magnitude Ms. This proposition is based on the observation that the Richter magnitude saturates at the level of 8 to 8 ½, so that large earthquakes are not well represented in that scale. In the new scale Kanamori (1977) assigns a Magnitude M_w = 9.5 to the 22 May, 1960 earthquake, instead of Ms = 8.3.

The M_w scale is calibrated to match the Richter scale (M_s) for magnitudes less than 8.

Values of M_w can be calculated from M_w = 2/3 log M_0 = 10.7 (M_0 in dynes cm). M_0, in turn, can be estimated from the surface area S (km^2) of the rupture zone in the fault plane, using the formula:

$$M_0 = 1.23 \text{ x } 10^{22} S^{3/2}$$

and introducing M_0 in the expression for M_w, thus obtaining :

$$M_w = \log S + 4.03$$

Since S is difficult to determine due to the lack of data defining the fault plane for the 1868 and 1877 earthquakes, we will use a relationship proposed by Abe (l975), who estimates that on average the length L of the fault and its width W are in the ratio 2:1, i.e. L = 2W, for large earthquakes.

In this form $S = ½ L^2$

and therefore: $M_w = 2 \log L + 3.73$

Using this relationship we have estimated Kanamori magnitudes for the 1868 and 1877 earthquakes with fault lengths L of 480 Km. and 400 Km., respectively. The result is:

13 August	1868	M_w = 9,1
9 May	1877	M_w = 8,9

These results compare quite well with the magnitude M_t defined by Abe (1979) on the basis of the height of tsunami waves observed at large distances from the epicenter, i.e. far-field tsunami observations. Abe (1979) defines magnitude M_t as:

$$M_t = \log H + B$$

where H is the maximum observed height in meters and B is a constant that depends on the region where the source is located and the characteristics of the tide gauge station.

Abe (1979) has calibrated the constant B such that on average M_w and M_t coincide for earthquakes where M_w and log H could be determined independently. The results show that the Kanamori magnitude M_w is a good measure of far-field tsunamis, and conversely M_t is a good measure of M_w, i.e. the size of the epicentral zone L (km).

Since excellent data exist for the tsunamis generated by the 1868 and 1877 earthquakes, Abe (1979) was able to determine M_t using tide gauge observations from Honolulu, Ilo, California (San Francisco and San Diego), and Hakodate (Japan). The estimate of wave height at some of these stations for these earthquakes is rather crude, since it had to be calculated from inundation height (Ilo and Honolulu) rather than tide gauge height. The values of M_t obtained by Abe 1979 are:

13 August	1868	M_w = 9,0
9 May	1877	M_w = 9,0

This compares remarkably well with our estimate of M_w = and9,1 8.9. respectively, from the length of the epicentral zone.

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