Reappraisal of Great Historical Earthquakes in the Northern Chile and Southern Peru Seismic Gaps

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Abstract. A critical reappraisal of great historical interplate earthquakes in the occidental margin of South America, including southern Peru and northern Chile, is carried out.

A spacetime distribution of the earthquakes associated to the seismotectonics regions defined by the rupture zones of the greatest events (1868, $M_w = 8.8$ and 1877, $M_w = 8.5$) is obtained. Both regions are seismic gaps that are in the maturity state of their respective earthquake cycles. The region associated to the 1868 earthquake presents a notable seismic quiescence in the present century.

Key words. Northern Chile and Southern Peru seismic gaps, historical seismicity, rupture length, estimated magnitudes.

1. Introduction

The South American Pacific coastal region from latitudes 15°S to 24°S, corresponding to the southern Peru and northern Chile zone, can be considered as a seismic gap with a high potential of occurrence of a great earthquake (Kelleher, 1972; Nishenko, 1985). In this region, there are historical reports of great earthquakes with destructive-associated tsunamis in the past and the last two great events had occurred by the end of the 19th century.

For southern Peru, there are numerous historical reports which permit us to estimate magnitudes and rupture lengths of the largest events in the region from macroseismic data, but for the northern Chile region, particularly between latitudes 19°S and 24°S, the historical information is rather scarce, mainly due to late colonization. This region, part of the Atacama Desert, did not present favorable conditions for the development of populations because of the absence of water, so the majority of the native villages were located near the mountains, far away from the coast. With the saltpeter exploitation by the middle of the 19th century, the zone began to be populated. Few reports exist before that time of missions and isolated villages that describe the largest earthquakes that affected them. So, the estimation of magnitudes and rupture lengths of historical earthquakes in this region have more uncertainties than in the southern Peru region.

Due to the little available information, it is not possible to state precisely the location of the hypocenters of the historical earthquakes, nevertheless, they can be
classified as belonging or not to the two major zones defined by the great earthquakes of 1868 ($M_w = 8.8$) and 1877 ($M_w = 8.8$), which are the events with better historical descriptions. In order to give the approximate locations of the seismic events, the epicenter is estimated from the isoseismal distribution. For those events with insufficient macroseismic information, the epicenter given by the earthquake catalogs available were used when they were consistent with the reported intensities.

The intensities used in this study are evaluated based on historical reports of damage and they are related to the Modified Mercalli Scale.

2. Analysis of Historical Seismic Events

2.1. Seismic Parameters

2.1.1. Rupture Lengths. For interplate events typical of subduction zones, the major axis of the surface included in isoseismals of intensity VIII, can be considered as a good estimation of the rupture length of the corresponding seismic event (Dorbath et al., 1990).

Isoseismals for each historical earthquake are generated from the assigned intensities to the locations where enough information exists in the reports. Figures 1(a) to (e) show the isoseismal of intensity VIII of the great events in the region which took place in 1604, 1687, 1715, 1784, 1868, and 1877.

2.1.2. Magnitude. The criterion of the magnitude reappraisal used in this work for historical earthquakes is based on the determination of hypocentral distances and intensities from macroseismic data and historical descriptions. The magnitude is estimated using the relation given by Barrientos (1981)

$$MS(I) = aI + b \log(r) + c r + d,$$

where $I$ corresponds to intensity on the $MM$ scale, $r$ is the hypocentral distance and the constant parameters are $a = 0.7223$, $b = -2.6983$, $c = -0.0004$, and $d = -2.7782$.

For the events for which the rupture length $L$(km) is estimated, the magnitude $mL(L)$ is calculated using the relation given by Dorbath et al. (1990)

$$mL(L) = 1.62 \log(L) + 4.44. \tag{2}$$

Figure 2 shows a comparison between magnitudes $MS(I)$ and $mL(L)$ obtained from Equations (1) and (2). A high agreement can be observed from this figure. Due to the linearity between $mL(L)$ and $M_w$ (Dorbath et al., 1990), and the stated agreement between $mL(L)$ and $MS(I)$, it is possible to consider the magnitude $MS(I)$ as a good estimator of $M_w$.

In the case of events for which it is not possible to determine the rupture length from the isoseismals, this length is estimated using relation (2).
Fig. 1(a). 1604 earthquake.
Fig. 1(b). 1687 and 1715 earthquakes.
Fig. 1(c). 1784 earthquake.
Fig. 1(d). 1868 earthquake.
Fig. 1(e). 1877 earthquake.

Fig. 1. Isoseismal VIII MM indicating zones of the great earthquakes in the studied region. Some important locations are shown for reference.
2.2. Seismic Events Analyzed

2.2.1. 1471. This is the first event reported in the SISRA-Peru catalog (1985), with the following hypocentral coordinates: 16.3°S, 71.0°W, 25 km of focal depth and with maximum reported intensity IX in Arequipa. Giesecke and Silgado (1981) refer to ancient chronicles that indicate a great earthquake that destroyed the city of Arequipa during the epoch of the Inca Tupac Yupanqui (1471–1493). Almost all the inhabitants died. Also indicated is the eruption of the Misti volcano. The description is vague and it is not possible to state if this catastrophe was associated with seismic or volcanic activity, so this event will not be included in the analysis.

2.2.2. 1513. There is little information in the historical reports relative to this event, nevertheless, in the SISRA-Peru catalog (1985), it is located at 17.2°S, 72.3°W at
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In the SISRA-Peru catalog (1985), a 30 km depth, Giesecke and Silgado (1981) state that around 1513–1515 great earthquakes occurred which generated large landslides and, from the same time, natives from the coast mention that the ocean exceeded many time the usual coast line.

Although the antecedents for this event are scarce, it is possible to consider that an important event occurred with numerous aftershocks and with a probably associated tsunami. A lower limit of the rupture length, \( L = 100 \) km, is estimated for this event, which gives a magnitude of \( MS(I) > 7.7 \).

2.2.3. 1543. This event is described as a violent earthquake in the Tarapacá Province and was felt as far as southern Peru. Its epicenter was possibly between latitudes 19°S and 20°S (Greve, 1964). The SISRA-Chile catalog (1985) gives the epicenter as 19.0°S, 70.5°W, and \( X \) is the maximum reported intensity. There is no information about the magnitude or focal depth in the catalogs and the available information indicates that this event did not generate an important tsunami.

Based on historical discisions, a lower limit \( L > 100 \) km is estimated for the rupture length and a magnitude of \( MS(I) > 7.7 \).

2.2.4. 22 January 1582. There are several historians who mention this event. In 1899, Polo classified it as a violent earthquake in Arequipa, while Fray Diego de Mendoza indicated that it was a great earthquake which devastated that city (Montessus de Ballore, 1912). This event destroyed around 300 houses in Arequipa, with the number of victims being more than 30 (Silmado, 1981). The SISRA-Peru catalog (1985) gives the following coordinates for that event: epicenter 16.6°S, 17.6°W at a 30 km depth, no assigned magnitude, and the maximum intensity assigned is \( X \). There is no information about an associated tsunami.

Assuming the epicenter given by the SISRA-Peru catalog (1985), which agrees with the historical reports of damage, the magnitude is estimated at \( MS(I) = 7.9 \) and a rupture length \( L = 137 \) km is obtained. Silgado (1968) assigns a magnitude \( Ms = 7.9 \) to this event; Dorbath et al. (1990) estimate magnitudes of \( m_L = 7.5 \), \( ms = 7.1–8.0 \), and \( L = 80 \) km.

2.2.5. 24 November 1604. This is the first event of a sequence of great earthquakes that is well documented by Montessus de Ballore (1912), Greve (1964), Silgado (1968), and Lomnitz (1971). All of them agree that it was a great event with a destroying associated tsunami.

The SISRA-Peru catalog (1985) gives the following location to this event: 17.88°S, 70.94°W at a 80 km depth, magnitude \( M_I = 7.0 \), and maximum reported intensity \( X \). The SISRA-Chile catalog (1985) gives a different location: 18.50°S, 70.35°W without a focal depth, maximum intensity \( X \), and magnitude \( MS = 8.4 \) estimated from macroseismic data. This epicenter coincides with that of the 1868 earthquake which will be analysed later.
The effects of the earthquake are well explained by the epicenter given by the SISRA-Peru catalog (1985), but the focal depth is exaggerated, mainly because it was a coastal event with an important tsunami.

A mean magnitude of $MS(I) = 8.7$ and a rupture length $L = 415$ km is estimated for this event from the intensities distribution and earthquake location (Figure 1(a)).

Other reported data for this event are: magnitude $8\frac{1}{2}-8\frac{3}{4}$ (Lomnitz, 1971), $M = 8.4$ (Silgado, 1985), $MS = 8.5$ (Lockridge, 1985), $mL = 8.7$, $mt = 8.8-9.0$, $L = 450$ km (Dorbath et al., 1990).

### 2.2.6. 16 September 1615

This event appears in historical documents as an earthquake that greatly affected Arica and, to a lesser extent, Tacna (Montessus de Ballore, 1912; Greve, 1964; Lomnitz, 1971).

The SISRA-Peru catalog (1985) gives the following hypocentral coordinates: $18.25^\circ$S, $71.00^\circ$W, 40 km depth. A maximum intensity IX is reported and there is no information about magnitude. The epicenter given by the SISRA-Chile catalog (1985) is similar to the last one: $18.50^\circ$S, $70.35^\circ$W with no focal depth determined, but with a magnitude $Ms = 7.5$ obtained by the Department of Geophysics at the University of Chile from macroseismic data.

There is no information about a tsunami generated by this event in any of the mentioned catalogs. However, Bobillier (1933) and Heck (1947), in their reports about the 1604 earthquake, mention that 11 years after, another event occurred with an associated tsunami that generated less damages than that of 1604. Lockridge (1985), based on several reports (Beringhausen, 1962; Cox, 1967; Lomnitz, 1971), indicates that this event produced a smaller tsunami than the one generated in 1868. Lockridge also gave the epicenter as being located at $18.6^\circ$S, $71.0^\circ$W. The evidence that this event produced a tsunami is also mentioned by historical reports and is discussed by Lomnitz (1971), who recognizes it as an important event, but smaller than the 1604 and 1868 earthquakes, and gives it a magnitude of $Ms = 7.5$.

Considering that the locations given in the SISRA catalogs (1985) do not explain the intensity distributions and the size of the associated tsunami, it is estimated that the location of this event is similar to the 1877 earthquake: $19.5^\circ$S, $70.5^\circ$W with a shallow focal depth.

With this relocation and the evaluated intensity magnitude $MS(I) = 7.9$ and a rupture length $L = 137$ km are calculated. This explains the tsunami generated, the damages reported in Arica and Tacna, and the fact that there are no reports of damage to the north of Arica, considering that the Peruvian intensity catalog is quite complete. To the south of Arica, the region becomes a desert and the population density is very low, so no information is available.

### 2.2.7. 10 March 1681

This event is described by Montessus de Ballore (1912) as a violent earthquake in Arica, with no associated tsunami. There is no additional information in Greve (1964). It is not reported in the SISRA-Peru catalog (1985),
2.2.8. 23 August 1715. This event is called by Lomnitz 'The Great Earthquake of Moquegua' and, according to different sources, caused damage in Arica, Ilo, Cobija, Arequipa, Tacna, and Moquegua, with strong aftershocks that lasted for more than two months (Montessus de Ballore, 1912; Greve, 1964; Lomnitz, 1971). Lockridge (1985), indicated a small tsunami and located the epicenter at 18.5°S, 70.9°W. It is not reported in the SISRA-Chile catalog (1985). However, the SISRA-Peru catalog (1985) gives the following hypocenter: 17.30°S, 70.80°W, 80 km depth, with no information about the magnitude, and a maximum intensity VII.

Assuming the epicenter coordinates and tectonic aspects of the zone to be correct, the focal depth should be shallower. The mean magnitude $MS(I) = 7.8$ and a rupture length $L = 120$ km is obtained, with a calculated $mL = 7.8$ (Figure 1(b)). Lomnitz (1971) assigned a magnitude of $Ms = 7.5$ to this event. Dorbath et al. (1990), calculated a magnitude of $mL = 7.5$ and $L = 75$ km.

2.2.9. 8 January 1725. This event is found in reports as a strong earthquake that affected Arequipa and Lima (Montessus de Ballore, 1912; Silgado, 1968).

The SISRA-Peru catalog (1985) gives the following epicenter for this event: 16.0°S, 71.60°W, 80 km depth, without an assigned magnitude and a maximum reported intensity VII. There is no information about this event in the SISRA-Chile catalog (1985).

Based on macroseismic effects, and considering a shallower focal depth, a magnitude of $MS(I) = 7.1$ is obtained with an estimated rupture length $L = 44$ km. Dorbath et al. (1990) give $mL = 7.5$ and $L = 75$ km.

There are some references to an earthquake that affected the coast of Peru on 27 March 1725, with a small tsunami (Montessus de Ballore, 1912; Silgado, 1968; Lockridge, 1985). Nevertheless, it was a minor earthquake that affected the zone (estimated magnitude $MS(I) = 5.7$).

2.2.10. Earthquake Before 1768. This is an event mentioned by Montessus de Ballore (1912), who does not know to which of the previous earthquakes corresponds the description of the destruction of Pica church (20.48°S, 69.33°W) and the damage reported in Matilla (20.53°S, 69.38°W). These cities are at distances that it is not possible to assume that the 1746 Lima earthquake or the 1738 Arequipa
earthquake could be responsible for the destruction. On the other hand, there is no report of this event in the files of the city of Arica.

At that time, the most important populations were basically native establishments, located far from the coast because of water scarcity. The city of Iquique began to be populated from 1836 onwards with the saltpeter exploitation and in 1869 the Bolivian government officially founded the port. The city of Calama became a village in 1870 and in 1872 the Municipality of Antofagasta was founded.

If this earthquake is considered as an interplate event, the assigned latitude should be around 20.5°S with a shallow depth and a lower limit of the rupture length \( L > 100 \text{ km} \), which gives an estimated magnitude of \( MS(I) > 7.7 \).

2.2.11. 13 May 1784. This earthquake is known as the 'Great Earthquake of Arequipa' and it almost completely ruined that city and settlements located within a radius of 100 km (Montessus de Ballore, 1912; Silgado, 1968; Giesecke and Silgado, 1981).

The SISRA-Peru catalog (1985) gives the hypocenter as 16.50°S, 72.00°W, 70 km depth, with a maximum reported intensity of X and magnitude \( MI = 7.8 \). It is not reported in the SISRA-Chile catalog (1985). There is no information about a destructive tsunami associated with this event. Montessus de Ballore (1912) says that in Camana the sea came out about two or three blocks, but he also says that in Ilo, the sea retired for more than 12 hr, but did not exceed its usual limit.

Assuming a shallower focal depth and considering the macroseismic effects, an average magnitude \( MS(I) = 8.5 \) is estimated for this event. The rupture length evaluated from the isoseismal is \( L = 390 \text{ km} \) which gives \( ml = 8.6 \) (Figure 1(c)). Silgado (1985) reports \( M = 8.0 \) and Dorbath et al. (1990) gives \( ml = 8.4; mu = 8.0 - 8.4 \), and \( L = 300 \text{ km} \).

2.2.12. 10 July 1821. This event is considered as a violent event that affected Arequipa, Camana, Caraveli, Chuquibamba, Ocoña, and Valle de Majes (Montessus de Ballore, 1912; Silgado, 1968, Giesecke and Silgado 1981).

The hypocentral coordinates given by the SISRA-Peru catalog (1985) are 16.10°S, 72.96°W, 90 km depth; no magnitude reported and a maximum intensity VII is assigned. The mean magnitude \( MS(I) = 7.0 \) is estimated and a rupture length \( L = 38 \text{ km} \).

2.2.13. 9 October 1831. This event appears in historical reports dated 8 October; this difference of dates is due to the local and universal time difference. Descriptions correspond to a large earthquake that affected Arequipa, Tacna, and Arica.

An interesting discussion about the information from different sources is found in Montessus de Ballore (1912). Perrey says it was a disastrous earthquake felt in all of southern Peru and destroying a settlement located 15 leagues (about 100 km) to the south of Arica. However, there are other antecedents that indicate that the earthquake in Arica did not have the characteristics of a great event. Greve (1964)
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says that a strong shaking was felt in Arica and Silgado (1968) says that a violent earthquake was felt in Tacna and Arica, and in the interior of the Arequipa Department.

The epicenter given by the SISRA-Chile catalog (1985) is 18.50°S, 70.35°W, with no assigned depth and magnitude and a maximum intensity X. The SISRA-Peru catalog (1985) gives almost the same latitude (18.468°S) and a more eastern longitude (17.016°W), with a focal depth of 60 km, no reported magnitude, maximum intensity VII.

Macroseismic effects from historical reports agree more with the epicenter given by the SISRA-Peru catalog (1985), but with a shallower depth. A mean magnitude $MS(I) = 7.0$ and rupture length $L = 38$ km is obtained.


The SISRA-Chile catalog (1985) locates the epicenter at 18.50°S, 70.35°W, without information about the focal depth and magnitude, and maximum intensity X. The SISRA-Peru catalog (1985) gives the hypocenter at 18.25°S, 71.01°W, 60 km depth, no information about magnitude, maximum intensity VII.

If the historical information is analyzed carefully (Montessus de Ballore, 1912; Silgado, 1968), it can be inferred that despite the fact that this event caused damage in Arica and Tacna, it cannot be compared with greater previous events. The earthquake was felt hundreds of miles to the south in the Atacama desert. In this province, several settlements were ruined and one even disappeared with all its inhabitants (Montessus de Ballore, 1912). To the north, Sama and Locumba were severely damaged and Moquegua suffered serious damage but in Arequipa, the disaster was not so great. Greve (1968) says that in Arica it was felt as a violent shaking which demolished a great many houses and a church that had already been destroyed by previous earthquakes.

Considering the historical descriptions and the fact that important cities did not exist south of Arica at that time, it is interesting to consider that this event would have had its focus further south than those reported by the Chilean and Peruvian SISRA catalogs (1985), so the following epicenter is assigned: 19.0°S, 71.0°W, with a shallow focal depth. Therefore, the mean estimated magnitude $MS(I) = 7.4$ and the rupture length $L = 67$ km are obtained. Dorbath et al. (1990) give $mL = 7.2$–7.7 with a rupture length $L = 50$–100 km.

2.2.15. 3 June 1836. This earthquake mainly affected the village of Cobija, generating a small tsunami (Montessus de Ballore, 1912).

It is not reported in the SISRA catalogs (1985). Lockridge (1985) locates the epicenter at the same coordinates of Cobija: 22.55°S, 70.3°W, with a magnitude $Ms = 7.5$ and a probable associated tsunami.

The estimated magnitude is $MS(I) = 7.1$ and the rupture length is $L = 44$ km.
2.2.16. 13 August 1868. This event is very well documented and has been well studied by the national and international scientific community (Bobillier, 1933; Lomnitz, 1971; Abe, 1979; Kausel, 1986; Ramirez, 1988).

The epicenter given by the SISRA-Chile catalog (1985) is 18.50°S, 70.35°W, no depth assigned, maximum intensity XI, and a magnitude $M_s = 8.5$, indicating that a tsunami was generated. It reports a long list of MM intensities which coincide with those assigned by Kausel (1986) and used by Ramirez (1988). The SISRA-Peru catalog (1985) reports an event on the same date located at 16.4°S, 71.56°W, without depth and magnitude, maximum intensity X, and reports a second event located with similar coordinates to the great earthquake in the SISRA-Chile catalog (1985): 18.29°S, 70.59°W, no depth or magnitude determined, maximum intensity VI, indicating an associated tsunami. Lockridge (1985) located the event at 18.6°S, 71.0°W, with magnitude $M_s = 8.5$ and reports a great associated tsunami.

From the corresponding isoseisms, the epicenter is relocated at 17.7°S, 71.6°W, with a shallow depth of focus due to its geographic location and the generation of a great tsunami. With this hypocenter and the evaluated intensities from historical reports (Montessus de Ballore, 1912), a mean magnitude $MS(l) = 8.8$ is estimated for this event, with a rupture length $L = 500$ km calculated from the isoseisms (Figure 1(d)), which gives magnitude $mL = 8.8$.

Lomnitz (1971) gives magnitude $M_s = 8.5$. Abe (1979) calculated magnitude $m_t = 9.0$, based on the characteristics of the tsunami generated. Kausel (1986) gives $M_w = 9.1$. Ramirez (1988), considering that the $M_s$ magnitude scale is saturated at 8–8.5 levels, estimates that magnitude $M_s$ for this event is greater than 8.5 and estimates that $M_w = 8.5–8.8$. Durbath et al. (1990) assigns magnitude $mL = 8.8$, $m_t = 8.9$, and rupture length $L = 500$ km.

2.2.17. 24 August 1869. This earthquake affected southern Peru and northern Chile. It was felt from the north of Arequipa up to Coquimbo, but most damage occurred in Iquique and Pica. Some antecedents says that is generated a small tsunami that affected Arica, Pisagua, and Iquique (Montessus de Ballore, 1912). Lockridge (1985) confirms this hypothesis with documents of the Instituto Hidrográfico de la Armada de Chile and locates the event at 18.6°S, 70.0°W, with magnitude $M_s = 7.8$.

The epicenter given by the SISRA-Peru catalog (1985) is 17.50°S, 72.00°W, 30 km depth, maximum intensity VI, with an associated tsunami and no reports of magnitude. The SISRA-Chile catalog (1985) placed it more to the south at the coordinates 19.60°S, 70.23°W, with a magnitude $M_s = 7.4$ and a maximum intensity VIII, indicating that a tsunami was generated.

The historical descriptions agree better with the epicenter given by the SISRA-Chile catalog (1985). Montessus de Ballore (1912) mentions the report of the captain of the steamboat Payta sailing near to the mouth of the Camarones River at the coordinates 19°17′S, 70°21′W. The captain reported that the effects of the
earthquake were felt strongly, the passengers could not stand, and small water jets reaching 8 to 9 inches high were seen on the sea surface.

Based on the macroseismic effects reported, the mean magnitude estimated for this event is \( MS(I) = 7.4 \), with a rupture length \( L = 67 \text{ km} \). This event is an important aftershock of the 1868 earthquake that occurred in the southern limits of its rupture zone, which is also the northern limit of the rupture zone of the great earthquake of 1877, so the 1869 earthquake can also be considered as a foreshock occurring eight years before this event.

Lomnitz (1971), gives a magnitude \( Ms = 7 - 7.75 \).

2.2.18. 22 April 1870. This earthquake destroyed the city of Calama and was felt along the coast from Arica to Caldera.

The location from the SISRA-Chile catalog (1985) is 22.74°S, 68.93°W, no depth or magnitude assigned, maximum intensity X. These coordinates correspond to the city of Calama. With the descriptions of the effects of the earthquake, given by Montessus de Ballore (1912) and Greve (1964), the magnitude \( MS(I) = 7.5 \) is estimated. This earthquake was an intraplate event, so it will not be considered in the following analysis.

2.2.19. 5 October 1871. This earthquake generated much damage in Iquique and was felt from Lima to Copiapo. The SISRA-Chile catalog (1985) locates the event at 20.20°S, 70.17°W, no focal depth assigned, maximum intensity X and magnitude \( Ms = 7.3 \), indicating that a tsunami was generated. Lockridge (1985) confirms the occurrence of this tsunami and located this earthquake at 20.1°S, 71.3°W, with magnitude \( Ms = 7.5 \).

Montessus de Ballore (1912) and Greve (1964) describe the effects of the earthquake in several places, so it is possible to estimate a mean magnitude \( MS(I) = 7.4 \), with a rupture length \( L = 67 \text{ km} \). Lomnitz (1971) assigned a magnitude \( Ms = 7 - 7.5 \) to this event.

2.2.20. 26 October 1876. This earthquake destroyed the Toco salt peter offices and its effects were felt from Arquipa to Coibi and Caracoles.

Location of the epicenter in the SISRA-Chile catalog (1985) coincides with the Toco coordinates: 22.07°S, 69.63°W, no depth or magnitude assigned, maximum intensity VII.

From the descriptions of Montessus de Ballore (1912) and Greve (1964), the mean magnitude \( MS(I) = 7.2 \) is obtained. However, this is an intraplate event, so it will not be included in the analysis.

2.2.21. 10 May 1877. Nine years after the destructive 1868 earthquake, northern Chile was again affected by a great tsunamogenic earthquake. As with the 1868 earthquake, this event is well documented and the references are almost the same.
The epicenter coordinates of the event, given by the SISRA-Chile catalog (1985), are 19.60°S, 70.23°W, without information about depth, maximum intensity XI, magnitude $Ms = 8.3$, and reports of a great tsunami. It also gives a list of places with the MM intensities the same as the ones given by Kausel (1986) and used by Ramirez (1988). The SISRA-Peru catalog (1985) places the hypocenter at 19.6°S, 70.23°W, 40 km of focal depth, with maximum intensity VII, no reported magnitude, indicating as associated tsunami. Bobiller (1933) points out that the tsunami generated by this event is similar to the one associated with the 1868 earthquake, emphasizing that the effects of both tsunamis are the greatest observed at these latitudes since the arrival of the Spanish.

Epicenter determination, done by Milne (1880), locates the focus on 21.33°S, 71.25°W. Montessus de Ballore (1912), discusses this epicenter, saying that the latitude would be right, but with errors in the longitude because the coast of Chile has an almost meridian direction and the fact that the worldwide seismological stations used are towards the north. (This effect of mislocation of Chilean earthquakes from the worldwide network is quantized by Eisenberg et al. 1986.)

Based on the isoseismals of this earthquake (Figure 1(c)), the epicenter is relocated at 21.00°S, 70.25°W. Considering the reported damage and the tsunami generated, a shallow depth is assumed. With these antecedents, the mean magnitude $MS(1) = 8.8$ is calculated and a rupture length $L = 420$ km is estimated from the isoseismals, which gives a magnitude $mL = 8.7$.

The magnitudes assigned for this event by other authors are the following: $Ms = 8 – 8.5$ (Lomnitz, 1971), $ml = 9.0$ (Abe, 1979), $Mw = 8.9$ (Kausel, 1986), $Mw = 8.7 – 8.8$ (Ramirez, 1988).

2.2.22. 23 January 1878. This event appears in the literature together with the activity of the Isluga volcano, but it does not mean that both phenomena are linked. The effects of the earthquake are clearly identified and there is no additional information about damage associated to the volcanic activity.

Location of the epicenter given by the SISRA-Chile catalog (1985) is 19.92°S, 69.53°W, without focal depth, magnitude and intensities reported. The SISRA-Peru catalog (1985) locates it at 20.5°S, 77.0°W, 40 km focal depth (evidently there is a misprint in the longitude, being probably 71.0°W).

Lockridge (1985) presents an earthquake that occurred on the same date in continental southern Peru: 16.3°S, 71.3°W, with magnitude $Ms = 7.0$, and a small associated tsunami. It is interesting to note that the mentioned catalogs report only one event with this date and the above locations. The coordinates assigned by Lockridge (1985) are not compatible with tsunami generation.

Descriptions of the effects of the earthquake in Montessus de Ballore (1912) and Greve (1964), permit us to infer that this was an intraplate event, so it will not be included in the analysis.
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Table 1. Summary of the most important characteristics of the analyzed events

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<tr>
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<td>72.0</td>
<td></td>
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<td>7.1</td>
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</tr>
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<td>&gt;7.7</td>
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<td>&gt;100</td>
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<td>7.4</td>
<td></td>
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<td>7.4</td>
<td></td>
<td>67</td>
</tr>
<tr>
<td>1876</td>
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<td>69.6</td>
<td>7.2</td>
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<td>8.7</td>
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<td>1878</td>
<td>19.9</td>
<td>69.5</td>
<td>7.3</td>
<td></td>
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</tr>
</tbody>
</table>

2.3. Summary of Estimated Parameters

A summary of the most important characteristics of the analyzed events is presented in Table 1, indicating date, estimated epicentral location, magnitudes MS(I), mL, and rupture length L(km). The events marked with (**) are intraplate earthquakes and the one marked with (*) was obtained from Durbath et al. (1990).

3. Earthquakes in the Zone Since 1900

Due to the lack of an adequate worldwide seismological network before 1965, it has only been possible to obtain a homogeneous sample of earthquakes with magnitude Ms ≥ 7.0 since 1900. For this period, the ISC (International Seismological Centre) and NEIC (National Earthquake Information Centre) catalogs were used. The SISRA catalogs (1985) were not used in these cases, because they are mainly copies of the above catalogs or a mixture of both, and local hypocentral determination is not included. They were useful however, in the study of the historical events.
3.1. Events with Magnitudes $Ms > 7.5$

There were only two events with magnitude $Ms$ greater than 7.5 during the present century. These were the 1913 and 1933 earthquakes, for which the isoseismals have been analyzed and the magnitude $MS(I)$, calculated in the same way as in the historical earthquakes, coincides almost exactly with the reported $Ms$ magnitude.

3.1.1. 6 August 1913. This event is well documented by Silgado (1968), who describes it as an earthquake that destroyed the city of Caraveli with the principal damages in an area of 50 km around this city, being felt down as far as Iquique in Chile and La Paz in Bolivia. The SISRA-Peru catalog (1985) places the epicenter at 15.8°S, 73.5°W, no reported focal depth, with maximum intensity X and magnitude $Ms = 7.8$ (PAS). Duda (1965), considered the same location as Gutenberg–Richter: 17.0°S, 74.0°W, shallow depth, and magnitude 7.9. There are no antecedents in the local newspapers indicating that this event generated a tsunami. Lockridge (1985) gives the same hypocenter and magnitude given by Duda (1965) and agrees with the hypothesis of no associated tsunami.

Dorbath et al. (1990) suggest that this is an intraplate event, which explains the reported intensities and the isoseismal of this earthquake done by Umlauf in 1915 (Silaage, 1968). Magnitude $MS(I) = 8.0$ is estimated with a rupture length $L = 156$ km, $mL = 8.0$. For the above reasons, this event will not be considered in the statistical analysis.

3.1.2. 23 February 1933. The Bulletin of the Seismological Service of the University of Chile, indicates that this earthquake mainly affected the city of Iquique and was felt from Arica to Vallenar. Greve (1964) agrees that the principal damage was observed at Iquique.

The SISRA-Chile catalog (1985) gives the location of Gutenberg–Richter for this event: 20.0°S, 71.0°W, 40 km depth, magnitude $Ms = 7.6$ (PAS), and no intensities reported. Lockridge (1985) associated the event with a small tsunami, which is confirmed by reports in local newspapers and narrations of the inhabitants of the zone.

Based on the reported macroseismic effects, magnitude $MS(I) = 7.5$ is estimated for this event, with a corresponding rupture length $L = 77$ km.

3.2. Summary of Earthquakes Parameters Since 1900

Table II shows the parameters of events with magnitude $Ms > 7.0$ which have affected the studied zone since 1900, the event with (**) is an intraplate earthquake. Information was obtained from ISC, NEIC, and the University of Chile catalogs, besides the published works by Heck (1947), Berninghausen (1962), Cox (1963), Greve (1964), Silgado (1968), Abe (1979, 1981), Giesche and Silgado (1981), and Duda (1965).
Table II. Parameters of events with magnitude $M_s > 7.0$ since 1900

<table>
<thead>
<tr>
<th>Date (y m d)</th>
<th>O. Time (GMT)</th>
<th>Lat. ($^\circ$S)</th>
<th>Lon. ($^\circ$W)</th>
<th>H (km)</th>
<th>$M_s$</th>
<th>$MS(I)$</th>
<th>L (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1905 04 26</td>
<td>21:43</td>
<td>21.0</td>
<td>70.0</td>
<td>s</td>
<td>7.0</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>1906 08 30</td>
<td>02:38</td>
<td>21.0</td>
<td>70.0</td>
<td>s</td>
<td>7.2</td>
<td></td>
<td>51</td>
</tr>
<tr>
<td>1906 12 26</td>
<td>06:53</td>
<td>18.0</td>
<td>71.0</td>
<td>s</td>
<td>7.0</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>1911 09 15</td>
<td>13:10</td>
<td>20.0</td>
<td>72.0</td>
<td>s</td>
<td>7.3</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>1913 07 28</td>
<td>06:40</td>
<td>16.6</td>
<td>73.3</td>
<td>50</td>
<td>7.0</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>1913 08 06</td>
<td>22:14</td>
<td>15.8</td>
<td>73.5</td>
<td>7.9</td>
<td>8.0</td>
<td>156 (**)</td>
<td></td>
</tr>
<tr>
<td>1922 01 06</td>
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<td>16.5</td>
<td>73.0</td>
<td>s</td>
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<td></td>
<td>51</td>
</tr>
<tr>
<td>1928 11 20</td>
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<td>22.5</td>
<td>70.5</td>
<td>s</td>
<td>7.1</td>
<td></td>
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<tr>
<td>1933 02 23</td>
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<td>71.0</td>
<td>40</td>
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<td>7.5</td>
<td>77</td>
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<tr>
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<td>s</td>
<td>7.2</td>
<td>51</td>
<td></td>
<td></td>
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<tr>
<td>1947 07 29</td>
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<td>23.5</td>
<td>71.0</td>
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<tr>
<td>1956 01 08</td>
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<td>70.0</td>
<td>11</td>
<td>7.1</td>
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<td>44</td>
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<tr>
<td>1967 12 21</td>
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<td>21.9</td>
<td>70.1</td>
<td>20</td>
<td>7.3</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>1979 02 16</td>
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<td>16.5</td>
<td>72.6</td>
<td>41</td>
<td>7.0</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>1988 04 12</td>
<td>23:19</td>
<td>17.3</td>
<td>72.4</td>
<td>5</td>
<td>7.0</td>
<td></td>
<td>38</td>
</tr>
</tbody>
</table>

Figure 3 presents a summary of interplate earthquake activity in the studied zone with a spacetime distribution of the rupture lengths associated to each event. The information is complete for magnitude $M > 7.0$ since 1900 and for magnitude $M > 8.0$ for historical events.

4. Conclusions

Taking into account that the elastic characteristics of the interplate region in subduction zones could not accumulate stress for periods greater than 100–150 years, and the fact that the studied zone can generate great interplate earthquakes (the last two having occurred more than 120 years ago), this zone can be considered as a seismic gap with two regions associated with the 1868 and 1877 earthquakes.

4.1. The Southern Peru Region

The series of historical great events in the region associated to the rupture of the 1868 earthquake is 1604, 1784, and 1868. It is interesting to note that the rupture lengths of all them are limited to the north by a physical barrier corresponding to the Nazca Ridge, and to the south by a geometrical barrier which corresponds to the change in the direction of the South American coastline around Arica.

In order to complete this series, the 1513 event could be included, although it is poorly documented. Furthermore, the lack of great seismic activity between the 1604 and 1784 earthquakes can be filled with the 1687 and 1715 earthquake sequence, which is not quite comparable with the rupture of the great events.
GREAT HISTORICAL EARTHQUAKES

The historical information regarding the intermediate earthquakes in the region is presented in Table I and II. Information is complete for magnitude M > 3.9 and complete for magnitude M > 7.0 since 1900. The scale between latitudes 14° S and 16° S is different, corresponding to the projection of the South American coastline in the N-S direction.

ACKNOWLEDGEMENTS

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mentioned, considering the variable rupture mode of the earthquake in the region observed in Figure 3.

Considering the time between the occurrence of the 1513, 1604, 1784, and 1868 earthquakes as a random series, the return period obtained in 118 ± 44 years. If the 1687–1715 sequence is included as a single event, a notable regular return period is obtained, 89 ± 6 years; and if the 1513 event is ignored, the return period is 88 ± 6 years, confirming that this event is part of this series.

The fact that no great earthquake had occurred during the last 121 years can be physically explained by the large amount of energy dissipated by the 1868 earthquake, the greatest of the series, so the time to restore the stress accumulated in the region should be more than the expected return period of the whole series, but it is within the return period of the great events series.

Moreover, also observed in Figure 3, is the second-order seismic quiescence as defined by Scholz (1988) in the interplate seismic activity $MS > 7.0$ of this century, with a reactivation in 1979 and 1988. The above statements indicate that this region has a high potential for the occurrence of a great earthquake in the near future. This agrees well with the results obtained from studies of the regional stress field done by Lay et al. (1989) and Campos and Comte (1989), who point out that this region is a seismic gap with a substantial maturity in its earthquakes cycle.

4.2. The Northern Chile Region

The historical information in the region associated to the rupture of the 1877 earthquake is more scarce than in the southern Peru region, mainly due to the low density of population before 1800. For this reason, it is not possible to define a complete series of great earthquakes in this region. Nevertheless, considering that the error bars of the estimated magnitudes are greater than those for the southern Peru region, the 1543, 1615, 1768, and 1877 earthquakes gives a return period of 111 ± 33 years.

It is important to note that the 1868 and 1877 earthquakes were coupled in time. Both presented foreshock activity within the limits of their associated rupture lengths (Figure 3). Furthermore, after the 1868 earthquake, there was seismic activity prior to the 1877 earthquake in its northern rupture limit, indicating a migration of seismic activity to the south.

The seismic activity $MS > 7.0$, in this century does not present a clear quiescence as in the southern Peru region. It is concentrated towards the limits of the 1877 rupture zone and there has been no interplate activity $MS > 7.0$ since 1967.

The regional stress field indicate that this region is a seismic gap that is reaching the maturity of the earthquake cycle (Lay et al., 1989; Campos and Comte, 1989).

Acknowledgement

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