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ASSESSMENT OF THE SIZE OF LARGE AND GREAT HISTORICAL EARTHQUAKES IN PERU

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ABSTRACT

A critical reappraisal of great historical earthquakes in Peru is made in order to obtain quantitative estimates of rupture length, seismic moment, tsunami magnitude M_t, and moment magnitude M_w. Newly collected information concerning several historical earthquakes permits the evaluation of macroseismic zones and from the size of these zones, the estimation of length of rupture, seismic moment and magnitude M_w. It is found that local tsunami data provide good quantitative estimates of M_t, and therefore an independent way of verifying macroseismic estimates of rupture length and seismic moment. A space-time diagram of great historical earthquakes shows the existence of three zones roughly corresponding to the segmentation of the Nazca plate (Hasegawa and Sacks, 1981) subducting under Peru. The northern zone looks aseismic. The central one is very complex; it breaks either completely or in smaller segments, and it may go through long quiescence periods. The recurrence time for the southern segment, the more regular one, is of the order of one century.

INTRODUCTION

The seismic history of Peru begins with the Spanish conquest and the colonisation of the country after the victory of Pizarro over the Inca Empire from 1532 to 1535. Oral traditions evoke older earthquakes (see, for example, Inca Garcilaso de la Vega, 1609), but with great imprecisions in geographical location and timing.

The quality of historical data, and therefore the confidence we may have in the results obtained from them, depends on the distribution and the density of the population in the region under study. In the case of Peru, the estimation of earthquake intensities relies mainly on the European part of the population up until relatively recent times. The chronicles, administrative reports, testimonies, etc., are generally concerned with the inhabitants of Spanish origin and their properties (sometimes, only with important persons, "la gente que cuenta"), not taking into account but exceptionally the Indian majority. The most comprehensive accounts of the historical seismicity of Peru have been given by Silgado (1968, 1978, 1985), and we are specially indebted to him. But in many cases we have been obliged to go back to the original sources in order to settle some controversial points. The data we have gathered originates essentially from the coastal zone of Peru and the Pacific side of the Andes, because the colonization of the high Andes was not followed by large settlements of European immigrants, except in a few sites (Fig. 1).

The coastal zone of Peru is a desert where several decades may pass without any rain. It is therefore a very arid region. The population concentrates at the outlets of the Andean rivers, where irrigation networks are easily dug and maintained for agriculture (most of the ducts have been in use since the Inca Empire). Industrial activity has been developed mostly during this century. In general, we may say that our information, though concentrated around villages, is quite evenly distributed along the country except in the south-central part, between Ica and Acari, where we find only a few minor hamlets ignored by official reports. Our sources are nevertheless continuous in time, and there is no gap in the chronology. The

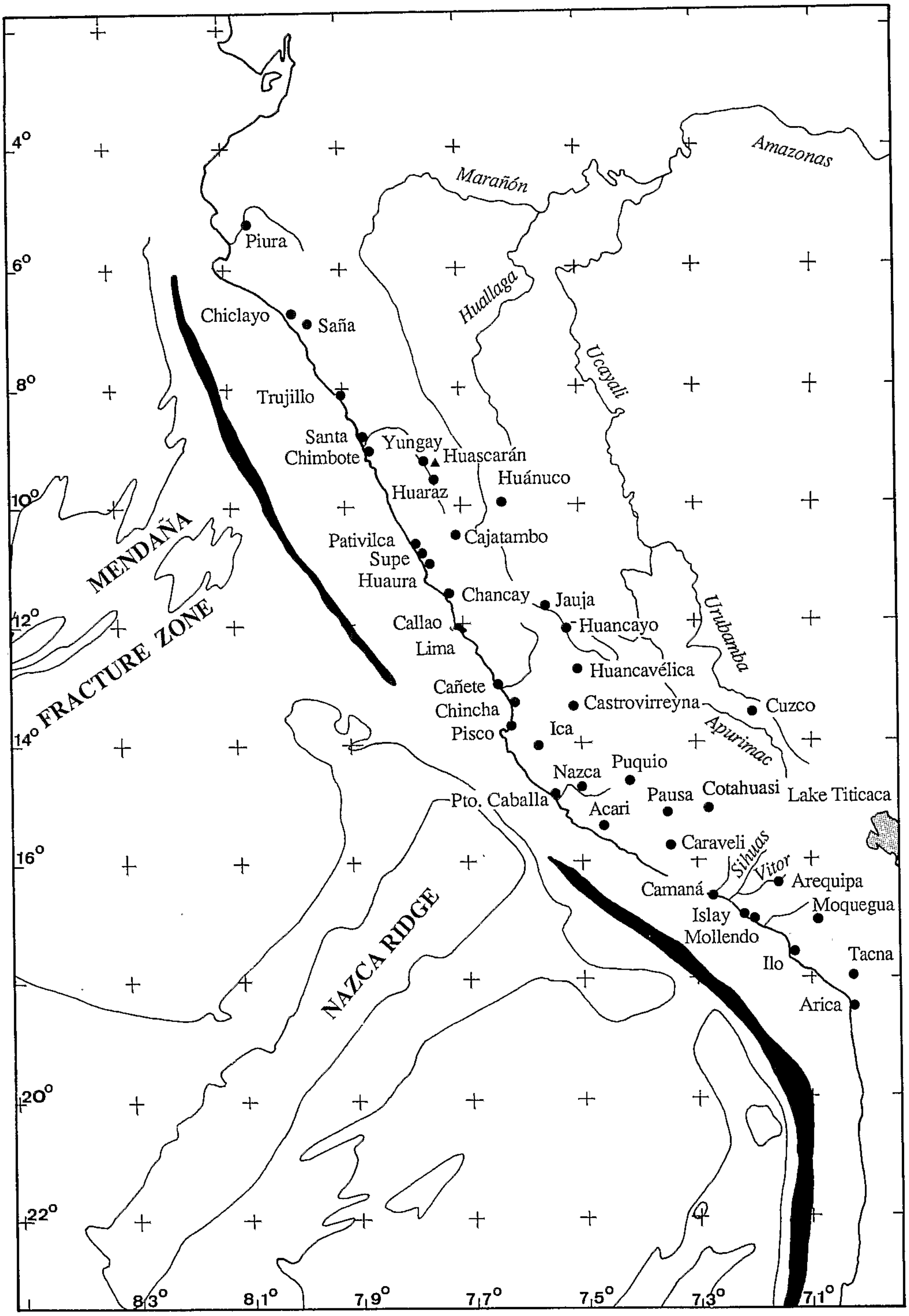

FIG. 1. Main sites referred to in the different sources of historical seismicity of Peru. Main rivers quoted in the texts are indicated. The Nevado Huascarán is shown by a solid triangle. Ocean floor topography in front of Peru, showing the presence of the Nazca Ridge and the Mendaña Fracture Zone, provides insight on the segmentation of the rupture process. The trench is shown in black.

locations, structures, methods of construction, and materials have experienced only few transformations between the conquest and the beginning of the 20th century. The description of a "quincha" house by Ulloa and Juan in 1752 is still valid in general terms. The most important change during this period was the substitution of two-stage buildings by single-stage ones as a safety precaution against earthquakes. On the other hand, the concentration of the population in towns led to the construction of a rather large variety of civil and religious buildings, thus permitting some accuracy in the estimation of macroseismic effects.

Our purpose is to estimate source parameters, such as rupture length, during great historical earthquakes in Peru by using macroseismic observations. Such a work has already been done in South America and other parts of the world, for example in Chile (Nishenko, 1985), Colombia (Kanamori and McNally, 1982) and Indonesia (Newcomb and McCann, 1987). Lomnitz (1970a) listed the major earthquakes in Chile since 1535 and estimated their magnitudes. This work was extended later on by Kelleher (1972) for 20th century earthquakes all along the South American subduction zone in order to include the more recent concepts of rupture length and seismic moment. Nevertheless, most of the studies in South America were directed towards the estimation of classical magnitudes rather than seismic moment or M_w. This point of view may bias the results because magnitude is an empirical parameter not directly connected to the physical model of the source.

Estimation of the Size of Great Historical Earthquakes

We are looking for earthquakes that ruptured a large (100 km long, or more) portion of the plate boundary. For this purpose we chose those events which satisfy two or more of the following criteria, taken from Sykes *et al.* (1981): a) extremely strong shaking, b) extensive damage at two or more separate localities, c) shaking lasting a minute or more, d) generation of a large tsunami, e) existence of surface ruptures, f) triggering of landslides, and g) aftershocks lasting weeks to months.

The selected events were examined in detail in order to quantify rupture length, and to provide an estimate of either M_w or the tsunami magnitude M_t. In the case of ancient earthquakes, it is often difficult, if not impossible, to produce a detailed isoseismal map because gaps of information are frequent, and many descriptions deal with ancillary facts, not giving the elements that might lead to an appreciation of the intensity. This is particularly true for regions that are far away from the areas where severe destruction occurred. Nevertheless, it is generally possible to determine the extension of the region of destruction, and therefore rupture length, with sufficient precision and confidence. Early studies often give the intensity values in the Rossi–Forel scale, but we carefully avoided using such values, preferring instead to go back to the original sources and assign Modified Mercalli intensities. Hence, in the following paragraphs all of the intensities are given in Modified Mercalli values with one explicit exception.

Intensity VIII Isoseismals

To estimate the size of great historical earthquakes, we have to answer to the questions of a modem macroseismic enquiry using documents which are not always pertinent and often incomplete. Previous work on this topic suggests that rupture zones are adjacent to regions of substantial destruction. In terms of isoseismal curves, the latter coincide roughly with the areas inside the curve of intensity VIII. We know the length of rupture for some Peruvian events of this century through seismological observations, like the distribution of aftershocks. Furthermore, we use descriptions of their macroseismic effects on the continent. So we are able to test whether the coincidence between the length of a rupture zone, and the length of the region of intensity VIII or more, is valid or not. For this purpose, we selected the 1942, 1966, 1970 and 1974 events (Broggi, 1946; Abe, 1972; Lomnitz, 1971; Cluff, 1971; Plafker *et al.*, 1971; Esteva *et al.*, 1967; Lomnitz *et al.*, 1970; Giesecke *et al.*, 1974; Lomnitz and Cabré, 1968; Lee and Monge, 1968; Lomnitz, 1970b; Berg and Husid, 1971; Espinosa *et al.*, 1977; Langer and Spence, 1978; Spence *et al.*, 1975; Dewey and Spence, 1979; Silgado, 1978; Gajardo, 1970). The affected areas are divided into three zones in decreasing order of strength of shaking (see Fig. 2). Zone 1 includes the areas where C-type constructions, mainly adobe, suffered from severe to complete destruction; A- and B-type masonries were damaged partly or extensively; and cracks were observed in the ground and on steep slopes. It corresponds roughly to intensities VIII or more. Zone 2 shows only minor damages (intensity = V to VII), and zone 3 corresponds to regions where the event was only felt.

One can observe that the definition of the rupture zone as the area adjacent to zone 1 gives a satisfactory estimation of the true rupture zone (as depicted by the aftershocks area), since the ratio between this estimation and the actual rupture length varies from 1 to 1.5. In the case of the 1966 event, which displays the largest ratio, it is worth noting that this high value may result from some parts of Lima (Chorillos, La Molina) where local responses to earthquake waves are known to be

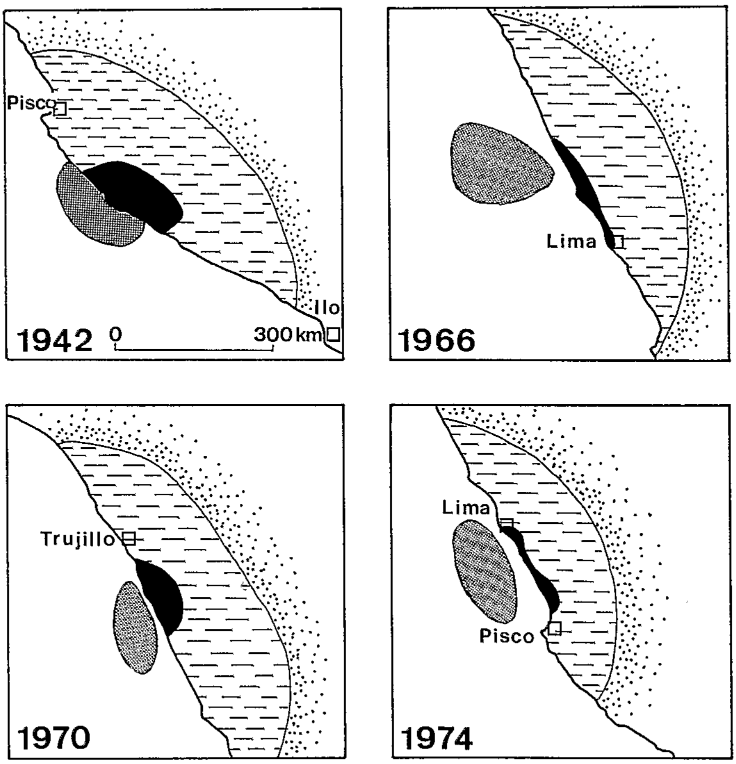

FIG. 2. Test earthquakes (1942, 1966, 1970, and 1974) for a comparison between the aftershock area (gray) and the isoseismal of intensity VIII (black) or zone 1. Horizontally hatched region is zone 2, and dotted region is zone 3.

abnormally large. This effect may have contributed to the extension of zone 1 to the south.

Figure 2 also shows a difference in the lateral extension of zone 1 into the continent between events in Central Peru and that of 1942. This is due to the peculiar shape of the shoreline which makes a shift to the east due to the subsidence of the continental margin in Central Peru (Macharé, 1987). The trench being farther away from the coast, interplate earthquakes produce extensive damages only in a narrow fringe along the coast. This effect was particularly evident during the 1974 earthquake.

Rupture Length and Magnitudes.

Estimations of magnitude for historical earthquakes by the analysis of the macroseismic effects and the extrapolation of modern data, but without a physical source model in mind, are likely to suffer from a personal bias due to the expert involved in the calculation.

A comparison of the magnitudes assigned by Lomnitz (1970a) and Silgado (1978) to South American earthquakes with their respective M_S and M_{wt} magnitudes (Kanamori, 1977) is presented in Table 1 and in Figure 3. It appears that the magnitude scales of Lomnitz and Silgado are not M_S; their values being systematically greater for large earthquakes. That may be due to the well known saturation of M_S. However the comparison with M_w exhibits a large dispersion, so that their magnitude is not M_w either.

The introduction of the rupture length will allow a more objective estimation of M_w (Table 2). For several South American earthquakes, M_w is known (Kanamori, 1977; Kanamori and McNally, 1982), and also L, the rupture length (Kelleher, 1972; Nishenko, 1985). We plotted M_w against Log L in Figure 4. A linear relationship between these quantities is observed which is better than expected. Therefore an

TABLE 1

MAGNITUDE (LOMNITZ, SILGADO) AGAINST M_S AND M_w

Date (m/d/y)	M	M_S	M_t	M_w
08/17/1906	8.6*	8.1	8.4	8.2,‡ 8.2–8.4§
08/06/1913	$7\frac{3}{4}$†	7.8		
12/04/1918	7.5*	7.6		
11/11/1922	8.4*	8.3	8.7	8.5,‡ 8.7–8.9§
12/01/1928	8.4*	8.0		7.6,‡ 7.4–7.6§
01/25/1939	8.3*	7.8		8.3§
05/24/1940	8.2†	7.9		8.2‡
08/24/1942	8.4†	8.2		8.2‡
04/06/1943	8.3*	7.9	8.2	8.2‡–8.2§
12/17/1949	7.5*	7.7		7.6–7.7§
10/17/1966	7.5†	7.8	8.2	8.1‡
05/31/1970	7.7†	7.6		7.9‡
10/03/1974	7.5†	7.6	8.1	8.1‡

* Lomnitz (1970a).
† Silgado (1985).
‡ Kanamori (1977).
§ Nishenko (1985).
M_S = Abe (1981), Abe and Noguchi (1983).
M_t = Abe (1978).

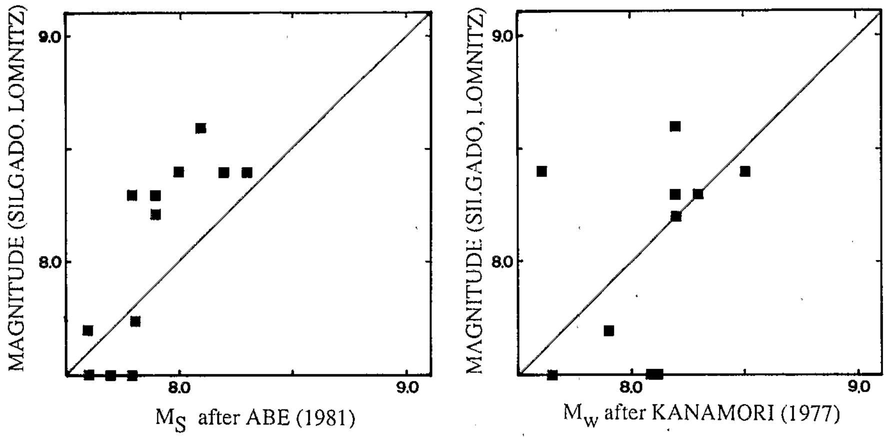

FIG. 3. A comparison between Lomnitz or Silgado magnitudes and either M_S (Abe, 1981; Abe and Noguchi, 1983) or M_w (Kanamori, 1977).

TABLE 2

LENGTH OF RUPTURE AGAINST M_w FOR 20TH CENTURY EARTHQUAKES IN SOUTH AMERICA

Date (m/d/y)	Length (km)	M_w
01/31/1906	520†	8.8*
08/17/1906	330‡	8.2,* 8.2–8.4‡
11/11/1922	330–450‡	8.5,* 8.7–8.9‡
12/01/1928	90‡	7.6,* 7.4–7.6‡
05/24/1940	220	8.2*
05/14/1942	110†	7.6§
08/24/1942	200†	8.2*
04/06/1943	150–250‡	8.2*
01/19/1958	110†	7.7§
05/22/1960	1000	9.5
10/17/1966	120	8.1*
05/31/1970	130	7.9*
10/03/1974	180	8.1*
12/12/1979	200†	8.2§

* Kanamori, 1977.
† Kelleher, 1972.
‡ Nishenko, 1985.
§ Kanamori and McNally, 1982.

estimation $[M_w]$ of M_w is possible, when L is known, through the relationship:

$$[M_w] = 1.62 \log L + 4.44 \tag{1}$$

where L is the rupture length in km.

Tsunami Magnitude

Another way to measure the size of a great earthquake is to use the tsunami data, whenever a tsunami is generated. Imamura (1939) and Iida *et al.* (1967) proposed a conventional tsunami magnitude m defined by the relationship:

$$m = \log_2 H_r \tag{2}$$

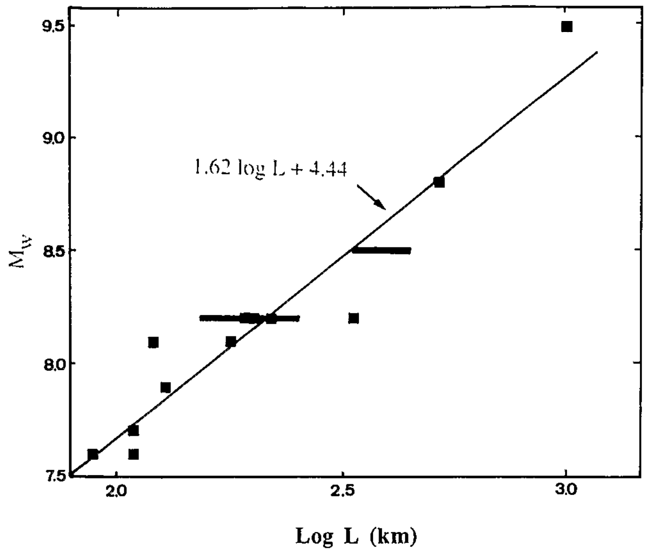

FIG. 4. M_w against Log L (rupture length in km) for several South American earthquakes of this century. Data from Kanamori (1971), Kanamori and McNally (1982), Kelleher (1972), and Nishenko (1985).

where H_r is the maximum height of the tsunami wave (in meters) measured at the coast, in the vicinity of the source region. More recently, Abe (1979) defined a new magnitude scale, M_t, by using the maximum amplitude of far-field tsunami waves, H, and adjusted the M_t scale to be M_w. In the particular case where H is measured at Hilo (Hawaii) and the source region is South America, he found:

$$M_t = \log H + 8.5 \tag{3}$$

where H is measured in meters.

A comparison between M_t and m (Abe, 1979) shows a large scatter of data. According to Abe, this result is due to the variability of m, that depends strongly on the effect of local topography over the height of the waves in the near field. However, the dispersion is strongly reduced if the South American earthquakes are considered alone, and a linear relationship between M_t and m becomes evident. In the same manner as the constant term in (3) depends on the source, the comparison between M_t and m should be made for each region separately. That means that the Iida magnitude is useful and reliable, provided that the constant term does not depend only on the path but on the source region as well.

The tsunami magnitude determined by Abe (1979) for some South American earthquakes and the local maximum height of the corresponding waves are shown in Figure 5. The scatter of data points is very low, lower than in the original figure of Abe (1979) in which m is rounded to the nearest integer. The relation between the estimate $[M_t]$ of M_t, and H_r is then given by:

$$[M_t] = 1.1 \log H_r + 7.7 \tag{4}$$

where H_r is the local height in meters.

We will take as an example the case of the 1 December 1928 earthquake in Chile. This event had a magnitude $M_w = 7.6$ according to Kanamori (1977), and 7.9

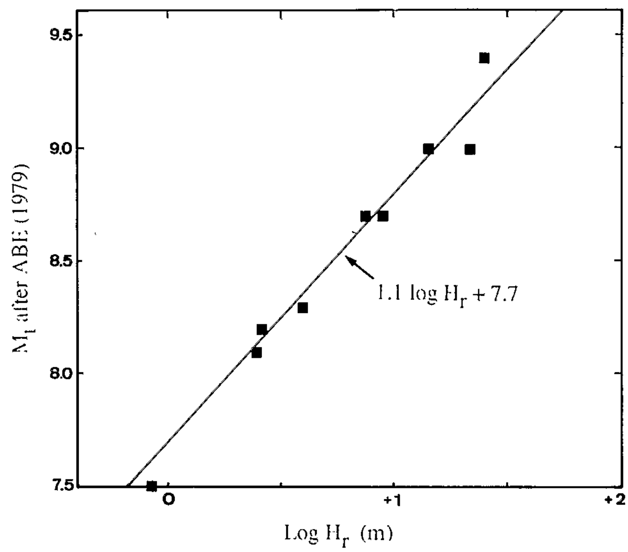

FIG. 5. Linear regression between the tsunami magnitude M_t (after Abe, 1979) and the local wave height $H_r(m)$ for South American earthquakes. The small dispersion for South America contrasts with the large scattering shown by Abe when all regions are included.

according to Nishenko (1985), while Lomnitz (1970a) gave a magnitude of 8.4. The rupture length is evaluated at 90 km by Nishenko (1985) and the local tsunami height was 1.5 m at the city of Constitucion (Lomnitz, 1970a). From (1) we find $[M_w] = 7.6$ and from (4) $[M_t] = 7.8$. Another example is given by the 22 May 1960 Chilean earthquake with magnitude $M_w = 9.4$, length of rupture 1000 km and local tsunami height of 25 m (Abe, 1979); we find here $[M_w] = 9.3$ and $[M_t] = 9.3$.

These two examples show that our estimations are quite reasonable, and that both relationships (1) and (4) may be used to evaluate, in two independent ways, the size of the great historical Peruvian earthquakes. If these two values coincide, we may say that the bias due to the personal equation played a limited role in the estimation of the size of the earthquake.

PERUVIAN HISTORICAL EARTHQUAKES

In this section, we summarize the quantification of the large and great historical earthquakes of Peru according to the results presented above. The main historical sources are listed in the references, but the Appendix contains the more pertinent detailed observations and the figures with the isoseismal areas concerning the historical earthquakes. Figure 6 illustrates a summary of our results and Table 3 contains the corresponding numerical values in addition to the estimated magnitudes $[M_w]$ and $[M_t]$.

Northern Peru

A unusual earthquake struck northern Peru in 1619 destroying Trujillo within a region that does not present an important activity since then. We obtained a not-so-well-defined rupture length of about 100 to 150 km from macroseismic data, but we did not find any reference to a tsunami.

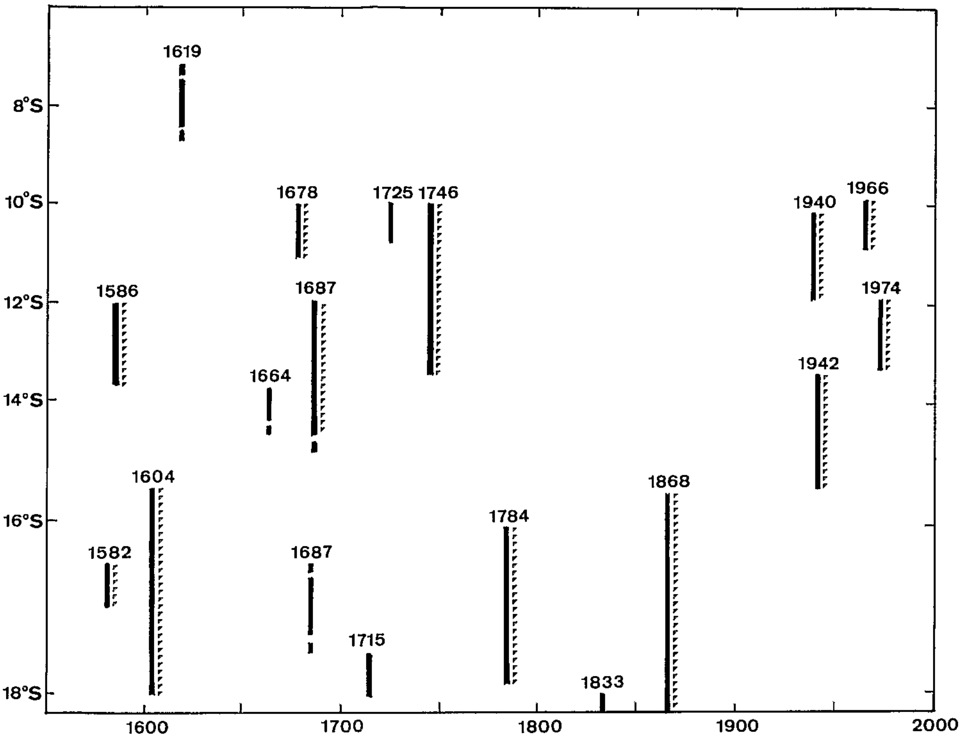

FIG. 6. Rupture zones of historical earthquakes in Peru as a function of time. The scale of latitude varies because length is measured along the trench and not along a meridian. The wavy symbols indicate tsunamogenic earthquakes. Three zones are clearly delimited in latitude.

TABLE 3

HISTORICAL EARTHQUAKES IN PERU: ESTIMATES OF MAGNITUDE

Year	L(km)	H_r (m)	$[M_w]$	$[M_t]$	M(Silgado)
1582	80	1–2	7.5	7.7–8.0	7.9
1586	175	5	8.1	8.5	8.1
1604	450	10–15	8.7	8.8–9.0	8.4
1619	100–150		7.7–8.0		7.8
1664	75		7.5		7.8
1678	100–150	5 (?)	7.7–8.0	8.5	
1687	300	5–10	8.4	8.5–8.8	8.2
1687	150 (?)		8.0		
1715	75		7.5		
1725	75		7.5		
1746	350	15–20	8.6	9.0–9.2	8.4
1784	300	2–4	8.4	8.0–8.4	8.0
1833	50–100		7.2–7.7		
1868	500	14	8.8	8.9	8.6
1940	180	3	8.1	8.2	
1942	200	3	8.2	8.2	
1966	100	2.6	7.7	8.2	
1974	140	1.6	7.9	7.9	

L = rupture length; H_r = local tsunami height; $[M_w]$ = estimate of moment derived magnitude; $[M_t]$ = estimate of tsunami magnitude.

Central Peru

Seismic activity in central Peru is rather complex due to the irregularity of rupture lengths, locations of epicentral zones and timing. The 1586 earthquake had a rupture length of the order of 175 km, and a local tsunami height of some 5 m, even though some reports give a much larger value (see the Appendix). A large earthquake struck the region to the south of Lima in 1664; its southern limit is not well defined but in any case the rupture cannot be larger than 75 km, a value that explains the absence of reports of a tsunami. The 1678 event is poorly recorded, but it looks similar to the 1966 earthquake. The year 1687 registered two large earthquakes separated by one day, giving origin to some confusion in the historical accounts. The first one, one of the strongest in central Peru, had a length of rupture of about 350 km and a local tsunami height of 5 to 10 m. We believe that the second one is a different event situated in southern Peru. Another not-so-large earthquake occurred in 1725 in north-central Peru with a length of rupture that cannot extend beyond 75 km and without an associated tsunami. The 1746 great earthquake that destroyed Lima completely, ruptured along some 350 km and produced a tsunami with local height of 15 to 20 m. A period of quiescence that lasted almost two centuries followed in central Peru after that. Large activity reassumed in 1940 with an earthquake that broke along 180 km and produced a tsunami with local height of 3 m, similar values being observed for the 1942 shock. The 1966 earthquake in north-central Peru (Esteva *et al.*, 1967; Abe, 1972) had a rupture length of 100 km and a local tsunami height of 2.6 m. The 1974 event, in front of Lima (Giesecke *et al.*, 1974; Espinosa *et al.*, 1977; Langer and Spence, 1978), broke through 140 km and had a local tsunami height of 1.6 m. The 1970 shock (Lomnitz, 1971; Abe, 1972) is not included in this list because its mechanism corresponds to a normal fault within the subducting plate rather than to the interplate area.

All of the earthquakes that occurred during this century have the advantage of being recorded by seismological observatories and hence we have access to intrumentally determined source parameters.

Southern Peru

Southern Peru presents a simpler and more regular pattern of seismicity. The 1582 earthquake, the first documented event in Peru, probably had a rupture length $L = 80$ km and no clear evidence of tsunami. The first great event in southern Peru occurred in 1604, it ruptured along some 450 km and we estimated a local tsunami height $H_r = 10$ to 15 m. The second great earthquake that occurred during 1687 in southern Peru, is obscured by the attention paid to the previous one that affected central Peru as stated above, nevertheless we were able to infer a rupture length of at least 100 to 150 km. A not-very-well-documented earthquake affected the actual boundary between Peru and Chile in 1715, with a length of rupture of some 50 to 100 km. The third great earthquake of southern Peru occurred in 1784 with a fault length of about 300 km and local tsunami height of 2 to 4 m. In 1833 an earthquake struck the actual Peru-Chile border region but with rupture length of the order of 50 to 100 km. The great 1868 earthquake, a well reported event that is linked to that of 1877 in northern Chile, had a rupture length of 450 to 500 km and a local tsunami height of 14 m. This is the fourth great earthquake in southern Peru, and we believe that a similar one is likely to occur in the near future, given the recurrence times of the previous ones.

Discussion

A synthesis of our estimation of rupture lengths is presented on Figure 6. The Peruvian coast appears to be seismically divided into three distinct zones: a) a northern zone that extends down to 10°S; b) a central zone, from 10°S to 14°S, including Lima; and c) a southern zone from 15.5°S to the Chile boundary.

On the other hand, Figure 7 represents $[M_w]$ versus $[M_t]$, the two estimates of M_w previously defined, for all Peruvian events that produced tsunamis as listed above (see Table 3). The error bars correspond to about 30 per cent error in the determination of rupture length and 50 per cent in tsunami height, respectively. Although $[M_t]$ seems to be slightly overestimated, the overall picture shows that there is a fairly good linear dependence between both sets of values. In any case, this difference is within the one standard deviation margin which is about 0.2 in magnitude, hence no major systematic bias has been introduced in our evaluation of rupture length, and we may rely on these results.

Historical seismicity at the border between the central and the southern zones is less important than that of both adjacent areas. The 1942 event is the only one that ruptured this portion of the subduction entirely. As stated previously, this part of the continent has always been almost inhabited, but we do not think that a great earthquake in this region would be unnoticed. Therefore we conclude that a large part of the convergence is taken on by aseismic slip, even in the case when the southern tip of the 1687 rupture zone went further south than we estimated. This might look quite surprising since this segment corresponds to the entrance of the Nazca ridge into the subduction zone. As a consequence, the trench is shallower (Fig. 1) and the coast is uplifted. Nevertheless, the stress field does not seem to be greatly modified (Macharé, 1987). It is worth noting that during the last centuries no great earthquake occurred in Ecuador where the Carnegie ridge enters into the subduction zone. Kelleher and McCann (1976) had already observed that the

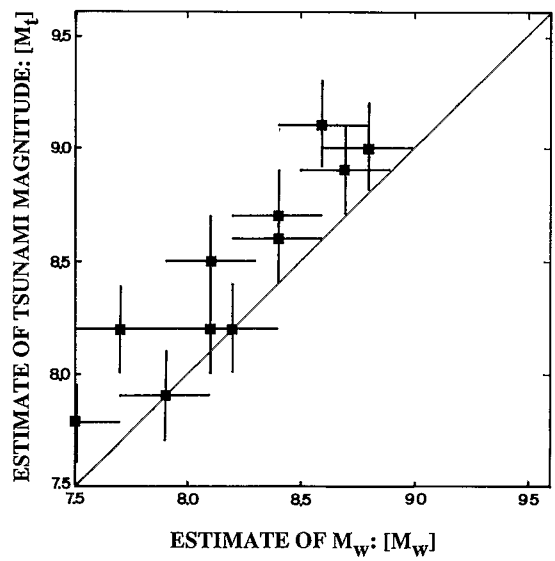

FIG. 7. A comparison between the estimates $[M_w]$ for M_w and $[M_t]$ for M_t for Peruvian historical earthquakes. The values of $[M_t]$ are somewhat higher than $[M_w]$, but the difference of 0.2 is not statistically significant. The slope is unity.

likeliness of occurence of great earthquakes lowered in presence of suboceanic ridges. Nevertheless, a counter-example is given by the Michoacán earthquake in Mexico, which is associated with the Orozco fracture zone.

The Northern Zone

Since the beginning of instrumental seismology, the only major earthquake in this zone is that of 31 May 1970 (epicenter at 9.15°S, 78.83°W, and magnitude $M_w = 8.0$) that produced more than 50,000 dead. Its mechanism corresponds to a normal fault within the Nazca plate (Abe, 1972) and not to a slip along the subduction surface. Historically, the only event recorded north of 10°S is the 1619 earthquake. We do not have arguments to assert that it was a subduction earthquake. But if it were so, the seismic slip would be by far lower than the aseismic slip and would not account for more than 20 per cent of the convergence. It is also evident that we do not have a time window large enough to make an estimation of recurrence times.

The Central Zone

The space–time distribution of great earthquakes in this area shows the most complex pattern of all the Peruvian subduction zone. To the north, all of the ruptures end at about 10°S. This point corresponds to the entrance of the Mendaña fracture zone into the subduction region (Fig. 1), a feature that seems to play the role of a very effective barrier. Another barrier appears to exist at the latitude of Lima (12°S), that was neither broken by earthquakes which occurred north of it (1678, 1940), nor south of it (1687, 1974), except during the 1746 earthquake. There is no obvious structure on the Nazca plate that explains the presence of such a barrier at this latitude.

Hence it appears that there are different modes of rupture in the Central zone: two earthquakes (1678, 1687), three earthquakes (1940, 1966, 1974), or a unique event (1746). This last one is thus the largest possible earthquake for the Lima area. Its magnitude is estimated between $M_w = 8.5$ and 9 (Table 3). This configuration looks similar to that of the Valparaiso (Chile) gap, or the Buenaventura (Colombia) gap, where the rupture was due either to a single great earthquake (1906 in both cases), or to a sequence of smaller events. Such a complex situation is not favorable to estimate recurrence times of great earthquakes. However, it is worth noting that the 1746 event was followed by two centuries of quiescence, and that the 17th century sequence preceded the 1746 earthquake by six decades, and that it followed the 1586 event by one century. Hence, we may suggest that the next great earthquake that will affect Lima will not occur before about a quarter of century.

To the south, ruptures stop at 14°S, a position that coincides clearly with the northern flank of the Nazca ridge (Fig. 1). This barrier might have been overcome during the 1687 event.

The rupture of the 1974 earthquake propagated from north to south, as inferred from the relative positions of the epicenter of the main shock and the aftershock area. The same sense can be deduced from the epicenter, the area of destruction and the propagation of the tsunami during the 1940 shock. Therefore, the obstacle in front of Lima acts as a barrier for the earthquakes to the north of the town, and as an asperity for earthquakes to the south. The sense of rupture, from north to south, is the same as the space–time order of earthquakes in a particular sequence, i.e., the northern earthquake tends to precede the southern one {?(N) $\rightarrow$ 1586; 1678(N) $\rightarrow$ 1687(S); 1940(N) $\rightarrow$ 1942(S); 1966(N) $\rightarrow$ 1974(S)}.

Using the scaling law $d = 2 * 10^{-5}L$, where d is the slip in meters and L the rupture length in meters on each individual earthquake (Scholz, 1982), we obtain an average seismic slip of about 3 to 5 cm/yr, or about 50 per cent of the total rate of convergence.

The Southern Zone

The situation looks simpler here. The region experienced four great earthquakes in 1604, 1687, 1784, and 1868. Each one of them had a rupture length corresponding roughly to the whole region. The recurrence time is of the order of one century. The time elapsed since the last 1868 event is now 120 years, a value which indicates that a great earthquake is highly probable in the very near future.

Nevertheless, differences are obvious among the different earthquakes. The 1868 and 1604 events are greater than those of 1687 or 1784. The rupture seems to have overpassed the Arica bend in 1868, while in 1784 the rupture stopped, or initiated, north of the bend. The tsunamis of 1604 and 1868 are considerably greater and count among the greatest tsunamis ever observed in the Pacific ocean. A detailed study of the propagation of the 1868 tsunami by Hochstetter (1868) clearly shows that the epicenter was located near Arica, so that we can infer that the sense of rupture propagation was from south to north.

Given the lengths of rupture (Table 3), and hence the slip on each individual event after the formula $d = 2.10^{-5}L$ (Scholz, 1982), the cumulative seismic slip during the last four centuries is about 30 m and represents almost the total amount of convergence (40 m).

Coupling

The coupling factor between two plates is high when the seismic slip rate is high (Kanamori, 1986). The classical extreme examples are the Marianas, where great subduction earthquakes are unknown (seismic slip rate ≈ 0 per cent), and southern Chile, where all the convergence is taken on during great earthquakes.

Along the Peruvian subduction zone, we observe systematic change of the seismic slip rate, from very low values in the northern zone to nearly 100 per cent in the southern zone. The interplate coupling in south Peru is thus very strong. In this region, the subduction of the Nazca plate underneath South America is quite simple since it defines a single plane dipping about 30° (Grange *et al.*, 1984). In central Peru, the interplate coupling is weaker, and becomes close to zero in the extreme north of the country. These regions correspond to a very peculiar shape of the Nazca plate: it first subducts with the same angle as in the south and then turns to quasi-horizontal at a depth of 100 km. The diminution of the coupling strength that we deduced is in contradiction with the assessment of several geologists (see Mégard, 1987, for example) who postulate that the mechanical coupling is stronger in the case of subhorizontal subduction and explain in this way the absence of large extensional stresses in central and north Peru.

CONCLUSIONS

We have done a critical reappraisal of large and great historical earthquakes in Peru with the purpose of obtaining estimates of source parameters, in particular rupture length and seismic moment. We have used two independent criteria for estimating these values: the first one is based on the determination of the isoseismal corresponding to intensity VIII in order to obtain rupture length L and, from it, the estimate $[M_w]$ of M_w. The second one starts from the local tsunami height H_r in order to obtain an estimate $[M_t]$ of M_t , and hence the seismic moment. We have shown that the local tsunami height proposed by Iida is not a bad parameter for estimating magnitude provided that it be used only on a regional basis. We have established a relationship between local tsunami height and tsunami magnitude valid for South America.

We found that the space–time distribution of Peruvian historical earthquakes define three zones along the trench: the northern one, affected by only one historical earthquake, looks rather aseismic. The central one exhibits a complex rupture sequence and breaks, either as a whole or by smaller segments, or stays for a long time without large earthquakes. The southern one has been completely ruptured several times by great earthquakes and permits the determination of an average recurrence time of the order of one century. Therefore, a great earthquake is likely in the near future. It appears that the subduction displacement in this latter zone is largely due to the occurrence of great earthquakes. These three zones correspond roughly to the segmentation defined by the geometry of the subduction.

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APPENDIX: QUANTIFICATION OF LARGE AND GREAT PERUVIAN EARTHQUAKES FROM 1550 TO 1950

Many of the articles, letters, reports, and books we used are listed among the references. But they represent only a part of the literature we consulted in connection to Peruvian earthquakes. Most other sources repeat descriptions previously published without making new contributions, and they are not included here. The basic works concerning Peruvian seismicity are the catalogs of Mallet (1854), Perrey (1857), Polo (1898, 1899), Milne (1912), and Silgado (1978). In particular, Silgado (1985) recently published an inedited collection of letters and other documents from the "Archivo General de Indias" in Sevilla. We obtained most pertinent information and references to original contributions from them. The macroseismic effects of great historical earthquakes in Peru are shown in Figure A1.

1582. 22 January (Fig. 6a)

According to testimonies, this event seems to be the first great earthquake in Peru after the Spanish conquest; in any case, it is the first one to be fairly well documented. It caused extensive damage in Arequipa where most private houses were destroyed. Several of the buildings that didn't collapse were in such a bad condition that they had to be removed later on. The churches, more carefully built, suffered only slight damage. Irrigation channels were broken in the fields, and Arequipa was flooded. The estimated number of victims varies between 30 (Polo, 1899) and 40 (Silgado, 1978).

The Sihuas, Vitor, and Majes valleys, to the north and west of Arequipa, and the coastal region, at least from Islay to Camaná, were severely affected. The church of Socobaya, for example, was destroyed down to its foundations. On the other hand, the main towns south of Arequipa (Tacna, Moquegua, and Arica) did not seem to have experienced major damage. Jesuits reported that the sea receded at Islay; hence we might infer that a tsunami occurred (Silgado, 1985). However, the consulted documents never mention any damage due to this tsunami. We estimate, after considering the intensity VIII isoseismal (Fig. 6a), that the rupture region extended from 16.5°S to 17°S, with a total length of about 80 km. Sieberg (1930, 1932) is uncertain about the date of this earthquake and hesitates between 2 January and 2 July, but in fact this second date corresponds to the eruption of the Huaraputina volcano (Silgado, 1968).

1586. 9 July (Fig. 6b)

This is the first great earthquake that Lima experienced since its foundation by Pizarro. Most of the private, public, and religious buildings suffered severe damage and some were completely destroyed. Only the San Francisco monastery was not touched. The number of dead was less than 50, low compared to the amount of destruction. The explanation is that violent foreshocks which occurred during the hour before the main shock alarmed the population that left the houses for the streets and squares (Perrey, 1857).

We have information only to the south of Lima, suggesting that destruction did not extend far to the north of the city. Landslides (such as the one in Cerro San Cristóbal, Lima), as well as cracks in the ground and channel ruptures, were observed as far as Cañete, 100 km south of Lima. Further south, Ica suffered only minor damage. The shock was felt in Trujillo to the north, Huanuco to the northeast, and Caraveli and Cuzco to the southeast. The town of Lima was shaken by aftershocks for at least 2 months. We estimate a length of rupture of 175 km.

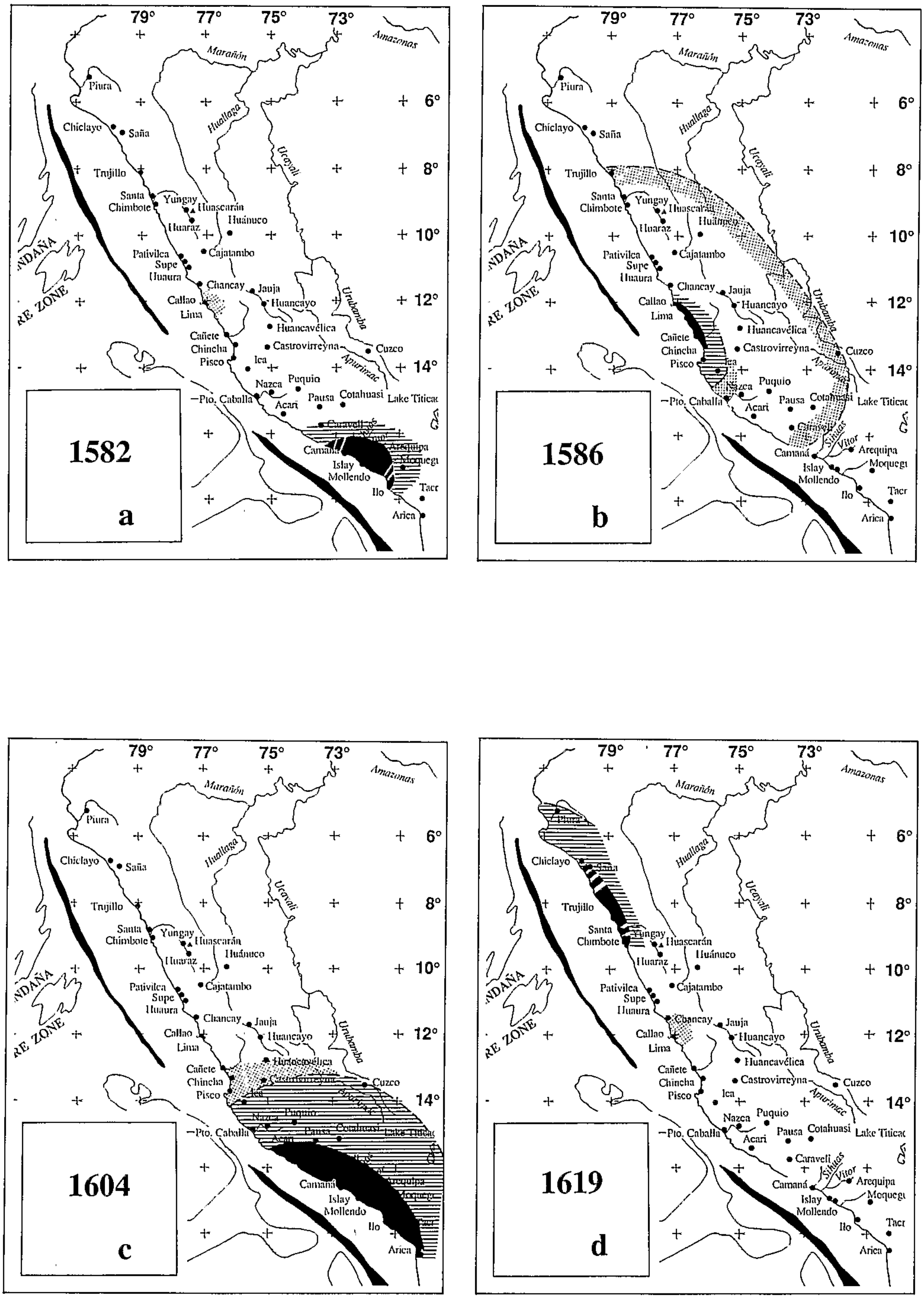

FIG. A1. Macroseismic effects of great historical earthquakes in Peru. Zone 1 (destruction corresponding to isoseismal VIII, in black); zone 2 (smaller damage, hatched); and zone 3 (felt, dotted). a) 1582; b) 1586; c) 1604; d) 1619; e) 1664; f) 1687; g) 1746; h) 1784; i) 1833; j) 1868; k) 1913 (solid isoseismals belong to the August 1913 earthquake, and hatched ones to the July 1913 event; in this case and only because we compare the isoseismal areas of both earthquakes, we kept the original figure (Umlauff, 1915) with the Rossi–Forel intensities); l) 1940.

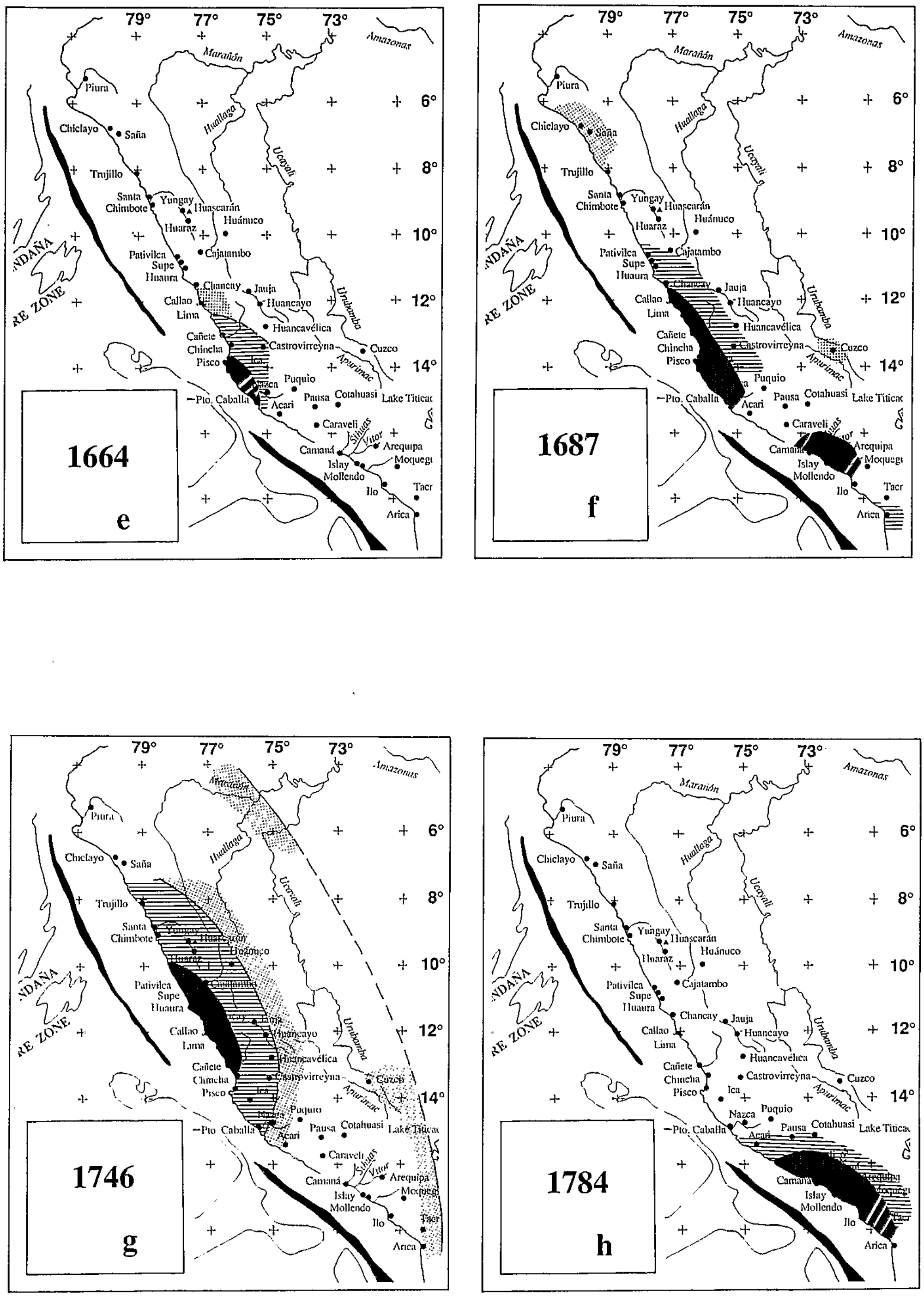

FIG. A1. (*Continued*).

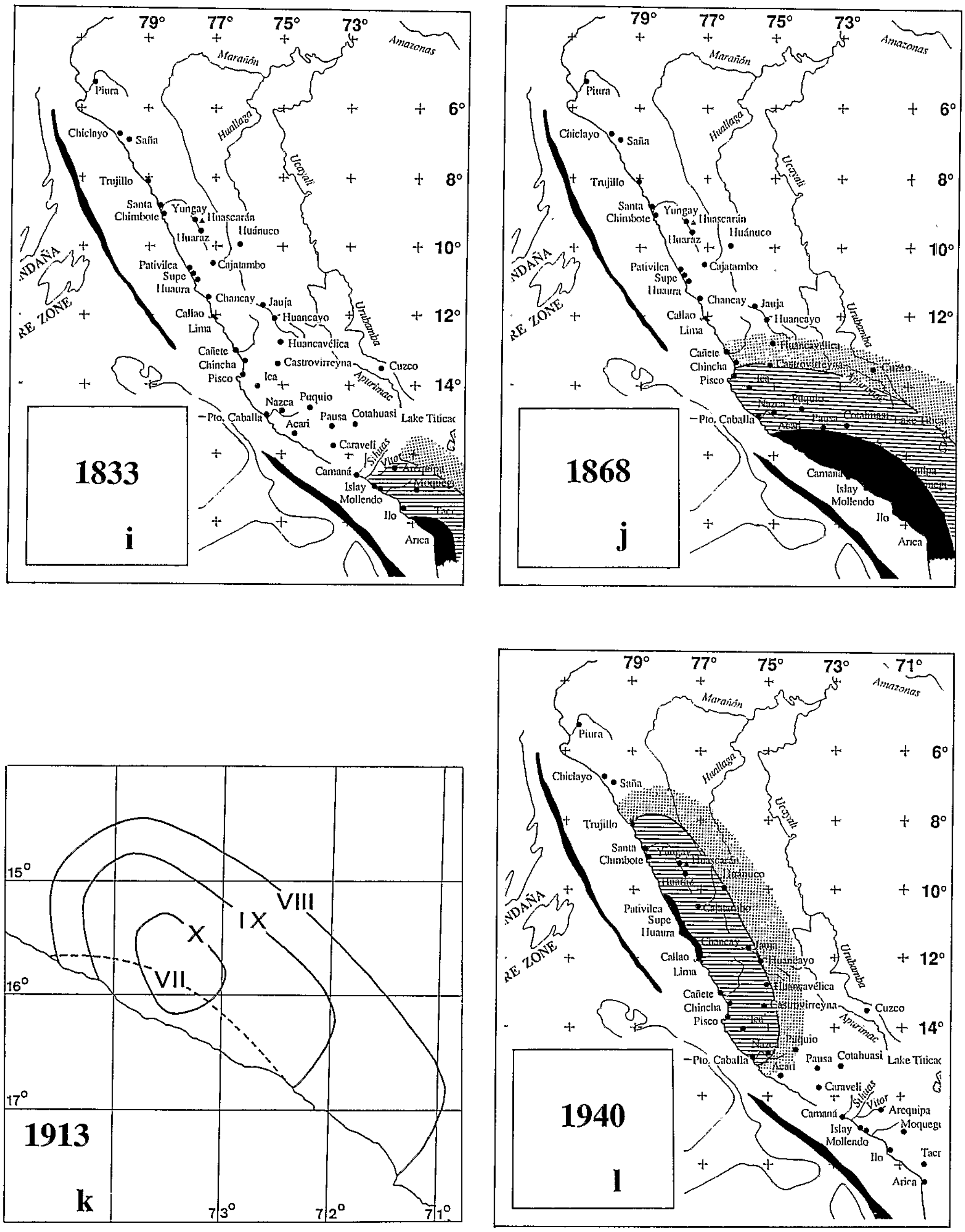

FIG. A1. (*Continued*).

A destructive tsunami followed the earthquake. The wave entered hundreds of meters inland and razed part of the port of Callao. Its height is given between 2 and 14 fathoms (3.7 to 25.6 m) according to different accounts (for instance, Perrey, 1857). This last value seems to be largely overestimated when compared with the next tsunamis of 1687 and 1746 and their respective effects. Therefore we give a value of 5 m for the local height. In Tambo de Mora, the port of Chincha, people were afraid that the stores of mercury, used to extract gold, could be destroyed. Sieberg (1930) stated that it was also destructive in Trujillo, but this is probably a misinterpretation, since a letter from Panama makes reference to a boat coming from Trujillo (Silgado, 1985). This boat brought news of the tsunami only from Lima without mentioning damage in Trujillo. This tsunami was noticed as far as Japan (Hatori, 1968). In many ways, this earthquake is comparable to the one of 1974, but it is probably slightly greater according to the level of destruction in Lima and to the importance of the tsunami, which was doubtlessly larger.

1604. 24 November (Fig. 6c)

This is one of the largest earthquakes that occurred in Peru during the last four centuries. Its magnitude is estimated at 8.25 to 8.5 by Lomnitz (1970a), at 8.4 by Silgado (1978), and we obtain $[M_w] = 8.7$ to 9.0 in this paper. It has some similarity to the 1868 earthquake which took place in the same part of the subduction zone.

The main cities of southern Peru, Camaná, Arequipa, Moquegua, Tacna, and Arica were almost completely destroyed (Frézier, 1746; Perrey, 1857; Silgado, 1985). In Arequipa, the best documented site, private buildings, churches and convents collapsed, with the exception of San Francisco convent. The area of extensive damages reached 15.5°S to the north. In Pausa, for example, 75 per cent of the houses, principally built in adobe or quincha, were razed. Great landslides occurred from this latitude down to Arica. Some of them buried villages; others blocked the rivers, forming lakes. Later on, these dams broke and the valleys were flooded. Very long cracks (several kilometers long) opened the ground, from which spouted black and nauseating water. Other phenomena, related to liquefaction, took place near springs. Their novelty may be the source of some exaggerations, such as the case of a caravan of horses and men being completely swallowed in quick sand. Slight damages are described up to Ica, outside of the zone of great destruction, and reports from Cuzco state that it was difficult to stand up, while in Lima the shock was strongly felt but no damages were indicated.

The tsunami that followed completed the destruction of Arica. The town was then built at its present location. The wave may have reached up to one and a half Spanish league (about 10 km) along the valley, and therefore we assign a local height between 10 and 15 m. All of the southern Peruvian ports were severely affected, particularly Camaná. The tsunami was observed at Callao but did not cause any damage to the wall which surrounded the town. However, the connection between Lima and its port was broken. Several authors stated that Pisco was destroyed too (for instance, Fournier in Perrey, 1857). The testimonies are not clear on this episode, many of them claiming that divine intervention saved the town, but the neighbourhoods were ravaged anyway. The rupture zone may be estimated from macroseismic data as going from 15.5°S to 18°S, namely some 450 km long.

Notice that Frézier (1746) gave the wrong date of 1605 and that Perrey (1857) and Milne (1912) repeated this error.

1619. 14 February (Fig. 6d)

This earthquake caused the complete destruction of Trujillo (Von Hoff, 1822), where some 400 victims were reported. Important destruction was observed as far as Saña (Chiclayo) to the north and Santa (Chimbote) to the south, but these reports are not reliable enough to assert that these two towns are inside zone 1 (Polo, 1898; Bachman, 1935). Large landslides, as well as cracks with spouting water, vanishing rivers, and formation of dams, were reported in the Trujillo district.

At Piura, in the extreme north of Peru, some minor damage was observed. The earthquake was felt at Lima and caused great fear. Aftershocks were felt in Trujillo for at least 2 weeks. No tsunami has been described, although the flat coast is favorable to such an observation.

The rupture did not extend beyond Chiclayo and Chimbote; its actual limits are not well constrained due to the weak density of population along this part of the coast. Silgado (1978) estimates the magnitude at 7.8 which, by comparison, corresponds to a rupture of roughly 100 km, a value that seems reasonable to us since we obtain $M_w = 7.7$ to 8.0. A question remains: is this event, that did not produce a tsunami, an interplate or an intraplate earthquake?

1664. 22 May (Fig. 6e)

Ica was almost completely destroyed during this event, and 300 dead were reported (Castelnau, 1851). The wells overflowed, trees were broken and cracks opened on the ground. Destruction was significant too at Pisco and some people died, but their number is unknown. To the south, the Nazca valley was affected to a degree similar to Ica and Pisco. Further south, the region becomes a desert and no information is available. This earthquake was felt at Lima, but no damage was reported.

The rupture could extend from Pisco to the latitude of Ica, or even further south, but probably not very far. Silgado (1978) estimates the magnitude at 7.8, and this is certainly an upper limit; on the other hand, we have calculated a value $[M_w] = 7.5$ from macroseismic observations.

1678. 16 June

There is insufficient information for this earthquake which is not listed by Silgado (1978) among the great earthquakes of Peru (however it appears in the 1985 CERESIS list of destructive earthquakes). There is no doubt that the north of Lima was the most severely shaken area. But the only useful information originates in Lima and Huaura, about 120 km to the north of Lima, where the intensity should have reach IX-according to CERESIS. Most of the buildings, even the better designed, suffered significant damage in Lima. However, there is no example of an immediate collapse. The intensity, in Lima, does not seem to have exceeded VIII. Cracks, several km long, opened near Huaura. A tsunami followed that threw little boats inland near Santa, according to the testimony of a British naval officer who went there a few years later (Parish, 1836). We did not find any references about this tsunami at Callao, but another witness confirms its occurrence at Pisco (Le Barbinais le Gentil, 1728)

This event, although poorly documented, appears to be similar to the 1966 earthquake, and we may assign to it a rupture zone going from about 10°S to 11°S after macroseismic effects. We estimated a moment related magnitude of $[M_w] = 7.7$ to 8.0.

1687. 20 October to 21 October (Fig. 6f)

At about 4 a.m., October 20th, Lima was shaken by a strong earthquake. Less than 2 hours later a second shock occurred. According to the viceroy and archbishop of Lima, Arequipa and southern Peru were also partially destroyed at the time of this second shock. He wrote: "one of the most peculiar circumstances of this earthquake is that its movement reached such an extension, as to be felt from the port of Concepción in Chile to the Villa de Saña in Peru. The movement was so intense over more than 200 leagues (1000 km) that everything flattened down from

Arequipa to Lima, according to the letters and informations I received from different sites." Montessus de Ballore (1911) followed the archbishop and described what happened this day as a single event: "the destructions of this famous earthquake of Lima extended down to Arequipa." On the other hand, the NOAA catalog of significant earthquakes lists two distinct events at the same date, both with the qualification of "severe," namely, level four out the five considered by the scale.

Polo (1898) and Silgado (1978) give 21 October between 6 a.m. and 7 a.m. for the date of the Arequipa event, because of its local appellation of "Santa Ursula" earthquake. Santa Ursula is, and was at that time, celebrated on 21 October (information given by the Diocese of Strasbourg). Given the avalaible information, it is quite difficult to assert if a multiple event occurred on 20 October causing destructions from central to southern Peru, or if two earthquakes, separated by 24 hours were active in the subduction zone. The first possibility seems unlikely and we shall follow Polo, Silgado, and the tradition in the interpretation of the southern Peruvian earthquake as a distinct event.

The first shock ruined a great part of Lima and Callao and razed Pisco. Several hundred people died. At 5 a.m. a strong aftershock was felt and at 6 a.m. the second great shock, the main one according to many people, destroyed Lima and Callao. Twenty years later a Jesuit (Nyell, 1707) wrote that one could still observe "the sorrowful effects of the ruin and the general devastation caused by the earthquake," and he added that the houses were built with only one stage after the event. Angulo (1939) published the drafts of an official investigation for the estimation of the damage, principally for the 65 churches of the town. It results that the "value of the properties went down by nearly 100 %." North of Lima, the devastation did not go beyond Chancay. Huaura, for example, suffered only weak damage. To the south, Cañete, Pisco, Ica, Otoca, Nazca, and Puerto Caballas were almost entirely destroyed. Long cracks opened between Cañete and Ica, and a witness described the soil as "powdered" near Puerto Caballas. Further inland, many buildings of Castrovirreyna were damaged, but no one collapsed. The shocks were strongly felt on a British ship, far offshore. The tsunami which followed passed over the walls of Callao, and we assign it a local height of 5 to 10 m (Feuillée, 1725; Courte de la Blanchardière, 1751). However, it seems to have been worse in Cañete, Chincha, Pisco, and Puerto Caballas. Pisco disappeared ("only a pillar that resisted indicates the past location of the town" wrote a witness), and boats were thrown inland. All along the coast, between Lima and Puerto Caballas, the reserves of mercury were destroyed. Aftershocks were felt in Lima for at least 2 months, and a very strong one occurred on 9 November.

This earthquake is the greatest one in southcentral Peru for four centuries. It largely exceeded the 1586, 1942, and 1974 events. Since everywhere the tsunami followed the second shock, the first one should be interpreted as a strong foreshock and the second one, the strongest in Lima for several witnesses, as the main event that ruptured all the subduction zone from Lima to about 15°S, namely more than 300 km long; hence we infer a magnitude $M_w = 8.4$. After this earthquake, the area did not experience a major or great earthquake until this century. The 1746 earthquake affected only the northern part of the area.

The event of the following day in southern Peru, although a major one, is in no way comparable to the 1604 and 1868 earthquakes in the same area, even if we take into account the bias introduced by the weight of Lima and its neighboring region in the Peruvian life at that time. Arequipa was destroyed at a level comparable to Lima and the whole diocese suffered important damage, particularly in the Majes, Vitor, and Sihuas valleys. According to a letter of the Duke de la Palata to the King of Spain (Silgado, 1985), Arica was destroyed, but this information does not appear in any other document and there is no mention of this earthquake in Lomnitz (1970a).

The length of the ruptured subduction zone is weakly constrained, because destruction in Lima attracted too much attention, but it was probably 100 to 150 km long, and centered around 17°S. The magnitude we obtained from macroseismic data is $[M_w] = 8.0$.

1715. 22 August

Lomnitz (1970a) listed this earthquake as a major one at the Peru–Chile boundary and estimated its magnitude at 7.5. At Arequipa, the damage was noticeable but the intensity did not reach VII. At Moquegua, Tacna, and Arica the shock was more severe (Le Barbinais le Gentil, 1728). In general, information is lacking to estimate the intensities with acceptable precision.

We shall follow Lomnitz and list this event among the major ones; the rupture was somewhere between Moquegua and Arica with a length of the order of 50 to 100 km according to the magnitude inferred by Lomnitz, which could be slightly underestimated as is generally the case in this magnitude range.

1725. 25 January

The most important damage was reported along the coast, from about 10°S to 11°S, and the intensities could have reached VIII. The mountain region from the Callejón de Huayllas (Carhuas, Huaraz) to Cajatambo was the most severely shaken according to an extensive enquiry made in the churches (Don Pedro de Moreillo, in Silgado, 1985). A glacier fell down from the Nevado Huascarán and buried Yungay, killing 1500, a tragic prefiguration of the 1970 catastrophe.

Silgado did not list this event among the great earthquakes of Peru, though we think its magnitude is probably of the order of $[M_w] = 7.5$ or slightly more. Since the destruction was more intense inland than along the coast, we estimate that this event may be an intraplate event inside the subducted Nazca plate rather than an interplate one, and similar to the 1970 earthquake.

1746. 28 October (Fig. 6g)

It is the worst earthquake Lima experienced during its history (Montandon, 1962; Davidson, 1936). After 1687, a new town had been built which was the pride of the kingdom with its geometrical, rigorous plan and its prestigious public and religious buildings, only "comparable with the Italian ones . . .". The town counted 60,000 inhabitants, 74 churches, and 14 monasteries and convents (Hales, 1752). There was only one shock, lasting less than 3 minutes, and only a very few buildings, around 25, did not collapse. The same happened in Callao. Chancay, Huaura, Supe, Pativilca, and all the towns and villages up to 10°5 were razed or badly damaged. The situation was the same to the south, at least down to Cañete. The whole region, limited to the north by Cajamarquilla, to the east by Jauja and Huancavélica and to the south by Palpa and Nazca suffered damage. The earthquake has been felt at Guayaquil (Ecuador), at the Jesuit mission located at the confluence of the Marañon and Huallaga rivers in the Amazonian basin, and at Cuzco and Tacna to the south. Almost 500 aftershocks were reported in Lima for the next 4 months.

Half an hour after the shock, a tsunami flooded Callao. The principal wave was more than 20 m high and entered more than 5 km inland. Among the 23 ships that stayed in the port, 19 sunk and 4 were thrown over the town. According to a Jesuit missionary, "Callao was a confused accumulation of sand and gravel and the previous location of this town was only marked by two large doors and a few sections of the walls that surrounded the town" (Anonymous, 1767). A permanent coastal modification was reported in Callao by Lyell (1846). The waves damaged the ports severely all along the coast. Heck (1947) and Berninghausen (1962) described a tsunami in 1724 that corresponds exactly to the one of 1746, and must be the same one. The earthquake together with the tsunami caused the death of thousands of people. In Callao 3800 persons died out of its population of 4000. Three thousand horses and mules perished in Lima. The rupture zone extends from about 10°S down to 13°S, over some 350 km, we therefore assign a magnitude $[M_w] = 8.6$, but the tsunami value is higher, $[M_t] = 9.0$ to 9.2.

1784. 13 May (Fig. 6h)

This is the third great earthquake in the south of Peru, after the 1604 and 1687 events. All of the southern coast of Peru was strongly affected, from Caraveli to Arica. Arequipa was badly destroyed and only 72 private houses, out of 2069, were safe from damage (Giesecke, 1962; Giesecke and Silgado, 1981). The cathedral and almost all the churches collapsed partially, the street pavement broke up and about 400 people died. Important destruction was reported at Sihuas, Vitor, Huchumayo, and up to Caraveli to the north. The same situation is described in the Tambo and Moquegua valleys, south of Arequipa. Montessus de Ballore (1911) extended the area of main damage to Arica, although Lomnitz (1970a) did not mention it in the list of Chilean earthquakes. Camaná appears to be the most affected city of the region. Long cracks opened and large landslides occurred choking up valleys within the area of extensive destruction. Casertano (1963) indicates that the Misti volcano gave signs of activity during 1784. The tsunami that followed was observed at Camaná, Mollendo, and Ilo, but it didn't produce any damage.

Silgado (1978) estimated the magnitude of this earthquake at 8.0, much less than the one for the 1604 (8.4) or the 1868 (8.6) events, but comparable to that of the 1582 shock (7.9). There is no doubt that this earthquake was not as strong as the 1604 and 1868 ones, as evidenced by the respective tsunamis (see Table 3). On the other hand, the extension of the destruction, particularly in the south of Arequipa (even if Arica was not damaged as infered by Montessus), leads us to consider this event as larger than the one of 1582, estimating that the rupture extended from 16°S to 18°S, with an estimated magnitude $[M_w] = 8.4$.

1833. 18 September (Fig. 6i)

This event at the Peru–Chile boundary is not listed by Lomnitz (1970a). However Arica, partly destroyed 2 years earlier by an other earthquake, suffered great damage. But the destruction reached its maximum in Tacna. Some 1000 houses collapsed or were badly damaged, out of a total of 1200. The region of destruction extended for some 50 km to the south of Arica. No tsunami was generated.

This is not one of the greatest earthquakes but it was certainly a large one, and we estimate its rupture zone to be about 50 to 100 km along the subduction zone, between 18°S and 19°S. This gives a magnitude estimation $[M_w] = 7.2$ to 7.7.

1868. 13 August (Fig. 6j)

This earthquake is widely documented and has been described in detail by several authors (Vargas, 1922; Picón, 1926; Silgado, 1968, 1978; Montessus de Ballore, 1911 to 1916; Lomnitz, 1970a). Its magnitude is estimated at 8.5 by Lomnitz, 8.6 by Silgado and a tsunami magnitude $M_t = 9$ is given by Abe (1979). All of the towns between Acari and latitude 19°S were almost entirely razed (Caraveli, Cotahuasi, Arequipa, Canamá, Moquegua, Arica, etc.). Some damage was reported at Nazca and Ica, and some minor damage at Chincha. This earthquake was felt as far as Guayaquil (Ecuador) and Concepción (Chile).

The tsunami that followed ($H_r = 14$ m) has been largely documented (Hochstetter, 1868; Fuchs, 1876; Abe, 1979). It was destructive all along the South American coast from 9°S to 37°S, and in many other places around the Pacific. Both the tsunami height and the isoseismal area are larger than those of the 1687 earthquake; on the other hand, the reported tsunami height is smaller than that of the 1746 Lima earthquake, while the corresponding isoseismal area is larger. The rupture zone may have extended from 15.5°S to 19°S; hence we obtain $[M_w] = 8.8$. This earthquake is similar to the one of 1604 in so many ways that it may be considered to be its repetition.

1913. 26 July to 6 August (Fig. 6k)

The first of these two shocks had a magnitude 7.0 (Abe and Noguchi, 1983) and thus cannot enter in the main list of Peruvian earthquakes. It is presented here only for comparison with the second one, whose magnitude is 7.8 following Abe and Noguchi (1983). Umlauff (1915) and Campbell (1914) summarized the results of large and very complete macroseismic survey. It appears very clearly that the first event, that produced a turbidity current breaking a telephone cable in the sea, was probably a subduction earthquake situated near the trench, and that the second one, having its macroseismic epicenter far inland (Fig. 6k), broke in depth away from the trench.

1940. 24 May (Fig. 6l)

The epicenter of this earthquake has been localized at 10.4°S77.2°W by the ISC, namely inland. However, the isoseismal map strongly suggests that this position is too far east and should be moved to the west by about 1°. The focal mechanism deduced from the first motions (ISC Catalog) indicates a fault plane dipping about 25°ENE, so that this event was clearly an interplate event along the contact between the Nazca and South-American plates, favoring the westerly displacement we propose for the epicenter.

Figure 6l depicts the macroseismic intensity VIII region from which we infer a rupture extending between 10.3°S and 12°S (Alcedan, 1940; Miró Quesada, 1940), and a magnitude $[M_w] = 8.1$.

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