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Southern Peru Earthquake of 23 June 2001 Reconnaissance Report

CHAPTER CONTRIBUTORS

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1 Seismicity and Tectonics

INTRODUCTION

The Southern Peru earthquake of 23 June 2001 resulted from thrust faulting on the boundary between the Nazca and South American plates. In terms of seismic moment release, the M_w (HRV) 8.4 earthquake was arguably the largest worldwide since 1965. The earthquake occurred in a 1000 km long seismic gap that previously ruptured in 1868 and 1877, and which was identified prior to 2001 as having high potential for large earthquakes. The 23 June 2001 earthquake ruptured substantially less than half of the pre-2001 gap.

Hypocenter and magnitudes of the earthquake, as reported by the U. S. Geological Survey (2001) and augmented with additional data are:

Origin time:	23 June 2001, 20:33:14.1 UTC (03:33 PM, local time)
Epicenter:	16.26°S, 73.64°W
Depth:	33 km. This is the USGS default value for shallow subduction zone earthquakes, but it is consistent with hypocenter focal depth estimates of 30 km and 32 km, given respectively by Kikuchi and Yamanaka (2001) and Tavera et al. (2002)
Magnitude:	6.7 m_b(GS); 8.2 M_S (GS); 8.4 M_W (HRV); 8.3 M_W (GS); 8.2 M_W (Kikuchi and Yamanaka, 2001); 8.1 M_e

SEISMOTECTONIC SETTING

The seismotectonics of Peru are dominated by the convergence of the Nazca plate and South American plates (Figure 1-1), at a rate of approximately 78 mm per year in southern Peru (DeMets et al. 1990). Most of the relative plate displacement is accommodated by slip on the easterly dipping thrust-fault, the interface between the subducting Nazca plate and the overriding South American plate (Leffler et al. 1997). The 23 June 2001 earthquake occurred on this interface. A number of other destructive, late 20th century Peruvian earthquakes have also occurred on this fault—such as the central Peruvian earthquakes of 17 October 1966 (Lomnitz and Cabré 1968) and 3 October 1974 (Husid et al. 1977) and the southern Peruvian earthquake of 12 November 1996 (Tavera et al. 1998). Some of the relative motion of Nazca and South American plates is accommodated by deformation of the overriding South American plate. This deformation is accompanied by destructive earthquakes, such as the Ancash, Peru earthquake of 10 November 1946 and the Pariahuanca, Peru earthquakes of 1969 (Silgado 1973). Finally, some destructive Peruvian earthquakes are generated by internal deformation of the subducting Nazca plate; an example is the catastrophic Chimbote/Yungay earthquake of 31 May 1970 (Cluff 1971).

Superimposed on the plate convergence and subduction regime of Peru are north-to-south variations in the characteristics of subduction. For example, there are broad north-to-south variations in the angle at which the Nazca plate dips beneath the South American plate, and

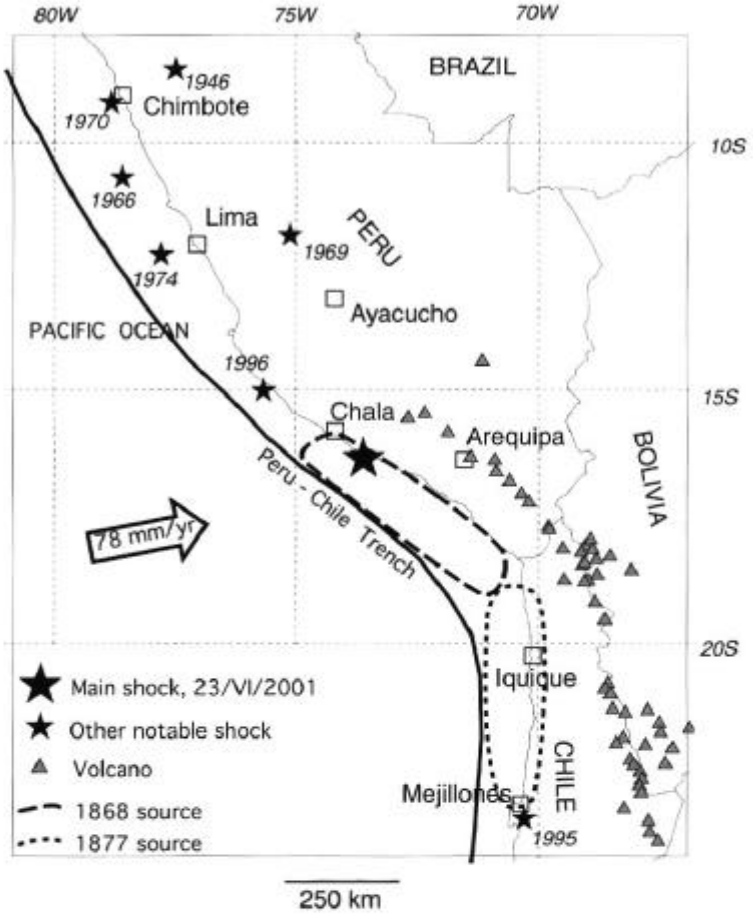

Figure 1-1. West coast of Peru and northern Chile, showing epicenter of the earthquake of 23 June 2001, source regions of the great earthquakes of 1868 and 1877, and epicenters of noteworthy 20th century earthquakes mentioned in the text. The Peru-Chile trench marks the surface trace of the east-dipping contact between the Nazca plate, west of the trench, and the South American plate, east of the trench. The broad arrow shows the direction and rate of motion of the Nazca plate with respect to the South American plate.

volcanism in the South American plate occurs only above the more steeply dipping sections of the Nazca plate (Barazangi and Isacks 1976). In Peru south of 15°S, the Nazca plate has subducted to a depth of 200 km over a horizontal distance of 350 km from the Peru-Chile trench, whereas at the latitude of Lima, it has subducted to a depth of only 150 km over a distance of 600 km. A chain of Quaternary volcanoes extends north from Chile to about 15°S (Figure 1-1). The different dips of the subducting plate, and the differences in the amounts of magma in the upper mantle beneath southern Peru and central Peru respectively, may result in different properties of lateral attenuation in these two regions.

The 23 June 2001 earthquake occurred within a long section of the western South American plate boundary that many seismologists already believed had high potential for large earthquakes in upcoming decades (e.g., Nishenko 1985; Dorbath et al. 1990). Prior to 1995, most of the plate interface thrust zone between Chala, Peru (15.9°S) and Mejillones, Chile (23°S) had been seismically quiescent since the occurrence of great earthquakes in 1868 (southern Peru) and 1877 (northern Chile). Large earthquakes on 30 July 1995 (M_W=8.0; Delouis et al. 1997) and 12 November 1996 (M_W = 7.7; Tavera et al. 1998; Spence et al. 1999) occurred on the plate interface just south and just north, respectively, of the 1868 and 1877 source regions. The source region of the 23 June 2001 earthquake lay entirely within what is inferred to have been the source region of the 1868 earthquake (Figure 1-2).

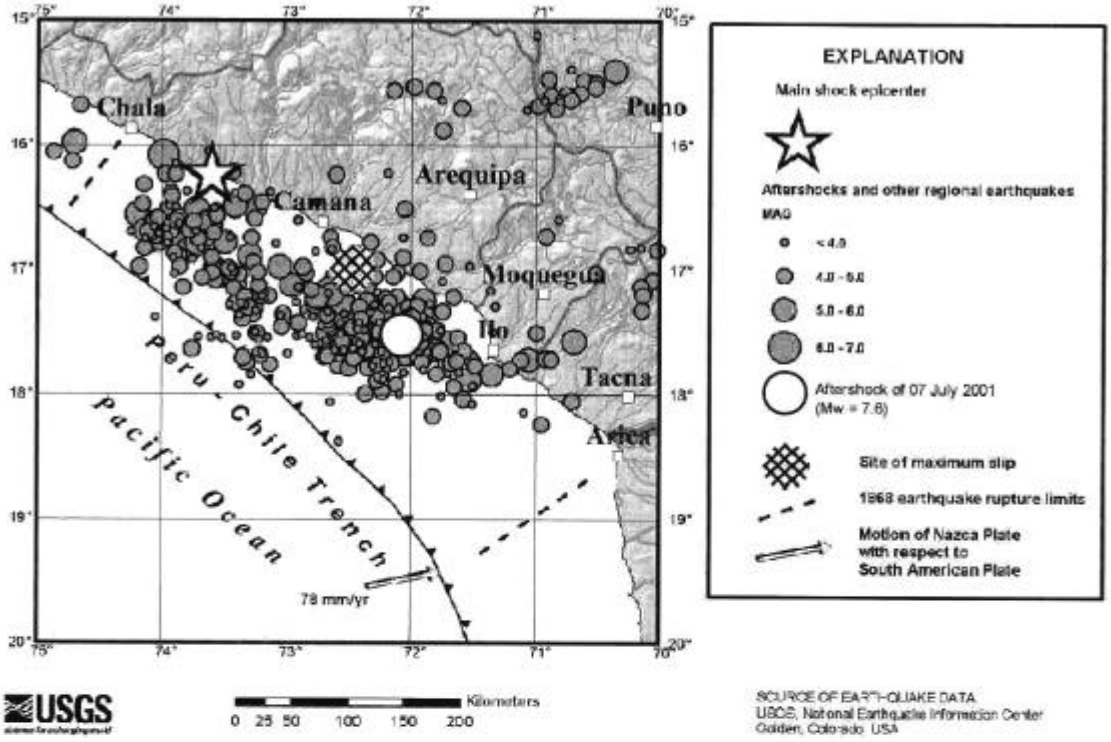

Figure 1-2. Southern Peru earthquake and associated seismicity, 23 June to 23 July 2001, as located by the USGS/National Earthquake Information Center (USGS/NEIC). The location of maximum slip corresponds to that identified by Kikuchi and Yamanaka (2001); it is positioned with respect to the final USGS/NEIC main shock epicenter. Boundaries of the 1868 rupture are as proposed by Dorbath et al. (1990).

MAIN SHOCK AND AFTERSHOCK SEQUENCE

The Peru main shock was produced by thrust-faulting on a gently northeast-dipping plane—e.g., Harvard Centroid Moment Tensor solution (USGS 2001); moment tensor inversion of Kikuchi and Yamanaka (2001); P-wave first-motion mechanism of Tavera et al. (2002). The focal mechanism of Kikuchi and Yamanaka (2001) is shown in Figure 1-3.

The earthquake occurred as a fault rupture with an along-strike length of 200-300 km, a width of about100 km, and an average displacement of several meters. From its point of nucleation at the main shock hypocenter, fault rupture propagated along-strike to the southeast and updip toward the Peru-Chile trench.

The spatial dimensions of an earthquake fault rupture may be estimated from the distribution of aftershocks under the assumption that most aftershocks, particularly those occurring soon after the main shock, occur on or near the main shock rupture (e.g., Lay and Wallace 1995). For the Peru earthquake, most aftershocks were concentrated in a zone that extends about 300 km southeast, and about 100 km toward the trench, from the main shock hypocenter (Figure 1-2). The entire length of the aftershock zone, from the epicenter to Ilo, was active in the first 24 hours after the main shock. Independently of the spatial pattern of aftershock hypocenters, finite-source models used to account for the main shock's radiation pattern also imply that large moment release occurred well southeast of the main shock hypocenter. For example, the Harvard CMT solution places the

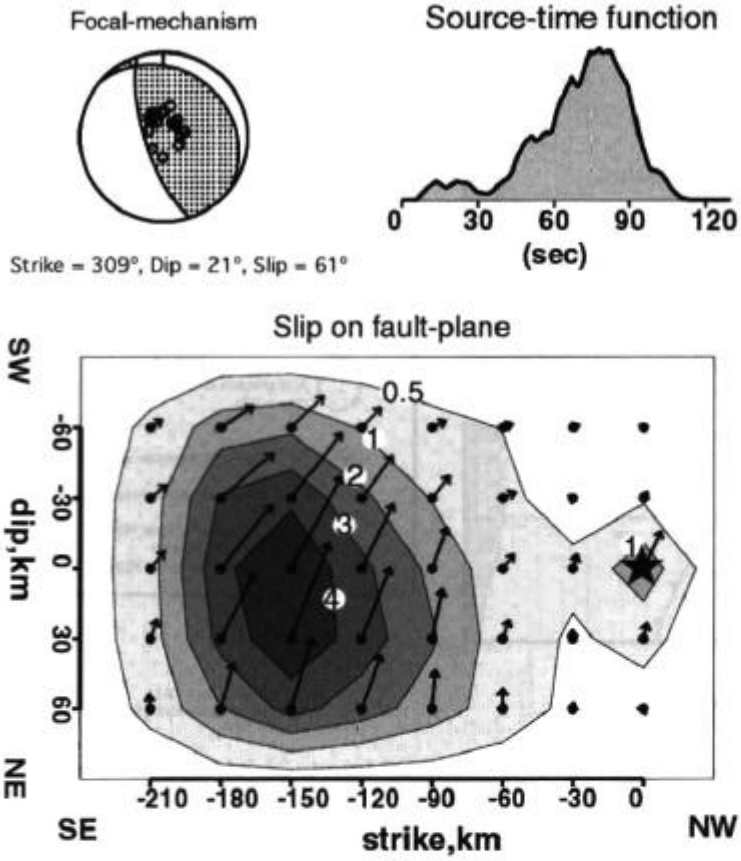

Figure 1-3. Focal mechanism, source-time function, and distribution of slip on the fault plane, as determined by Kikuchi and Yamanaka (2001) from inversion of teleseismic waveforms. This figure is their Figure 1, with minor additional labeling by the present authors. In the diagram of slip on the fault plane, the fault plane is viewed from above and the northeast. The star marks the earthquake's hypocenter. Distances are measured positive northwest along-strike and positive downdip from the hypocenter. Contours are given in meters. The longest slip arrow corresponds to a slip of 4.5 m. Slip arrows show the motion of the hanging wall of the fault with respect to the footwall.

centroid of moment release for the whole earthquake at a location approximately 130 km southeast of the earthquake hypocenter, and Kikuchi and Yamanaka (2001) inferred that the largest moment release occurred about 150 km southeast of the earthquake hypocenter (Figure 1-3). The model of Kikuchi and Yamanaka (2001), however, implies that appreciable moment release did not occur in the southeasternmost 100 km of the aftershock zone; Kikuchi and Yamanaka estimate a rupture length of 200 km.

The average displacement, D, is seismologically estimated from the relationship (e.g., Lay and Wallace 1995):

$$M_0 = \mu DS$$

where M_0 = seismic moment, μ = rigidity of the faulted medium, S = surface area of the fault. A seismic moment of 4.9×10^{21} *N*m (Harvard CMT and USGS 2001), a typical mid-crustal rigidity of about 3×10^{10} N/m^2, and a fault area of about 3×10^{10} m^2 would have an average displacement of about 5.5 m. Ruegg et al. (2001) show that such a displacement on the causative fault is consistent with a 0.5 m coseismic displacement of the earth's crust observed at a GPS site in Arequipa, about 150 km from the fault.

Other estimates of seismic moment and fault area, coupled with different physically plausible assumptions on rigidity, yield slightly different estimates of average displacement. Kikuchi and Yamanaka (2001), for example, estimate an average displacement of 2.8 m, using their seismic

moment estimate of 2.2 x 10^{21} *N*m, rigidity of 4 x 10^{10} *N*/m^2, and fault area of 2 x 10^{10} m^2. The displacement across any specific sub-area of the overall fault surface would be substantially different than the several meters of average displacement. Inversion of the teleseismic waveforms of the earthquake implies a spatially and temporally heterogeneous faulting process (Figure 1-3).

The Southern Peru earthquake was arguably the largest globally in terms of seismic-moment since the Aleutian Islands earthquake of 4 February 1965, for which some estimates of seismic moment imply $M_W = 8.7$. The M_W (HRV) = 8.4 value assigned to the 23 June 2001 Southern Peru earthquake is based on the Harvard CMT seismic moment. There have been no larger values of seismic moment computed by the Harvard CMT method, which has been systematically applied to large earthquakes occurring since 1977.[1] Nor have there been larger values of seismic moment for earthquakes occurring after the 1965 Aleutian Islands earthquake in the catalog of Pacheco and Sykes (1992), which summarizes seismic moments estimated by a number of different procedures. Other estimates of seismic moment for the 23 June 2001 earthquake, however, differ slightly from the Harvard CMT moment, due to differences in data used to obtain the moment and differences in procedures used to process the data. Thus, Kikuchi and Yamanaka (2001) estimated a seismic moment of 2.2 x 10^{21} *N*m, corresponding to $M_W = 8.2$, which would place the Peru earthquake among the largest seven earthquakes since 1965, as measured by seismic moment.

Seismic moment is only one measure of the size of an earthquake, and it reflects predominantly the behavior of the seismic source at very long periods. An example of an alternative measure of earthquake size is the USGS M_e (energy magnitude), based on radiated energy estimated according to the methodology of Choy and Boatwright (1995), which strongly reflects the behavior of the seismic source at short periods. For the 23 June 2001 main shock, $M_e = 8.1$ (USGS 2001). Since 1987, when the USGS began systematically estimating radiated energy for large earthquakes, there have been eight shocks with higher radiated energy than the June 2001 Peruvian earthquake.[2]

The 23 June 2001 main shock was followed by 60 aftershocks of magnitude 5.0 and larger in the 30 days following the earthquake. The largest of these (07 July, $M_W = 7.6$), in the southeastern part of the 23 June 2001 aftershock zone (Figure 1-2), caused damage and one death. Most of the larger aftershocks had focal mechanisms similar to that of the main shock. These represent slippages on the main shock fault system or related faults of the plate interface. The fact that the southeastern part of the 23 June 2001 aftershock zone retained sufficient stored elastic strain to produce the $M_W = 7.6$ aftershock of 07 July is consistent with Kikuchi and Yamanaka's (2001) inference that appreciable moment release did not occur during the 23 June 2001 main shock in the southeasternmost 100 km of the aftershock zone. In addition to aftershocks caused by slip on the plate interface, several of the larger aftershocks had focal mechanisms that imply that they resulted from internal deformation of the Nazca or South American plate, rather than slip on the plate interface.

1 The Harvard CMT catalog can be searched at http://www.seismology.harvard.edu/CMTsearch.html.

2 USGS estimates of radiated energy can be obtained at http://neic.usgs.gov/neis/sopar/.

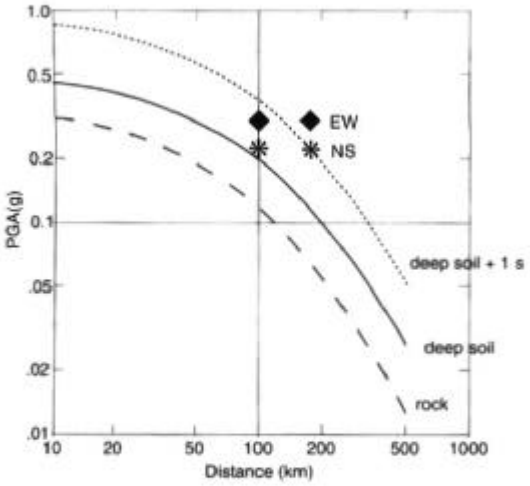

Figure 1-4a. PGA attenuation curves (Youngs et al. 1997) for an M_w = 8.4 interface-thrust subduction zone earthquake, with H_f = 30 km. Plotted are the curves for rock and deep soil sites, and the deep soil plus one standard error curve. The observed values recorded on 23 June 2001 by the NS and EW components of the Moquegua seismograph are plotted twice—at 100 km, corresponding to the distance between Moquegua and the main aftershock zone, and at 175 km, corresponding to the distance between Moquegua and the location of maximum slip identified by Kikuchi and Yamanaka (2001).

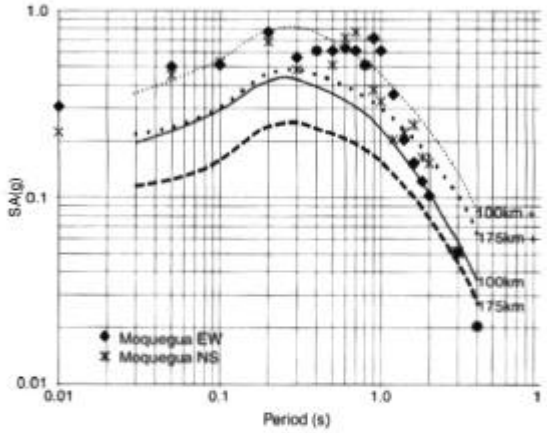

Figure 1-4b. Moquegua response spectral accelerations (5 percent damping) compared with theoretical response spectra, from the equations of Youngs et al. (1997) for a deep soil site, for source-station distances of 100 km and 175 km. Also plotted are curves corresponding to the predicted mean plus one standard error values.

STRONG GROUND MOTION AND REGIONAL INTENSITY DISTRIBUTION

One set of strong motion records was obtained at Moquegua by the Universidad Nacional de Ingenieria and the Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID). The Moquegua strong motion site is approximately 175 km from the source of maximum slip identified by Kikuchi and Yamanaka (2001) and 100 km from the nearest part of the main shock fault plane, offshore of the town of Ilo, that is suggested by the earthquake's aftershock distribution (Figure 1-2).

The accelerograms and corresponding response spectra are shown in Chapter 2, Ground Motion and Site Response. As noted in that chapter, the recording instruments are located in an effectively free-field environment and are thought to be underlain by alluvial gravel deposits. The peak horizontal ground accelerations (PGA) are 0.30g on the EW component and 0.22g on the NS component.

The recorded PGA is somewhat high with respect to values predicted by the equations of Youngs et al. (1997) for both rock and deep soil sites, for source distances of both 100 km and 175 km (Figure 1-4). Acceleration response spectra are high with respect to predictions of Youngs et al. (1997) for periods of 1 s and less for both deep soil sites (predictions shown in Figure 1-4b)

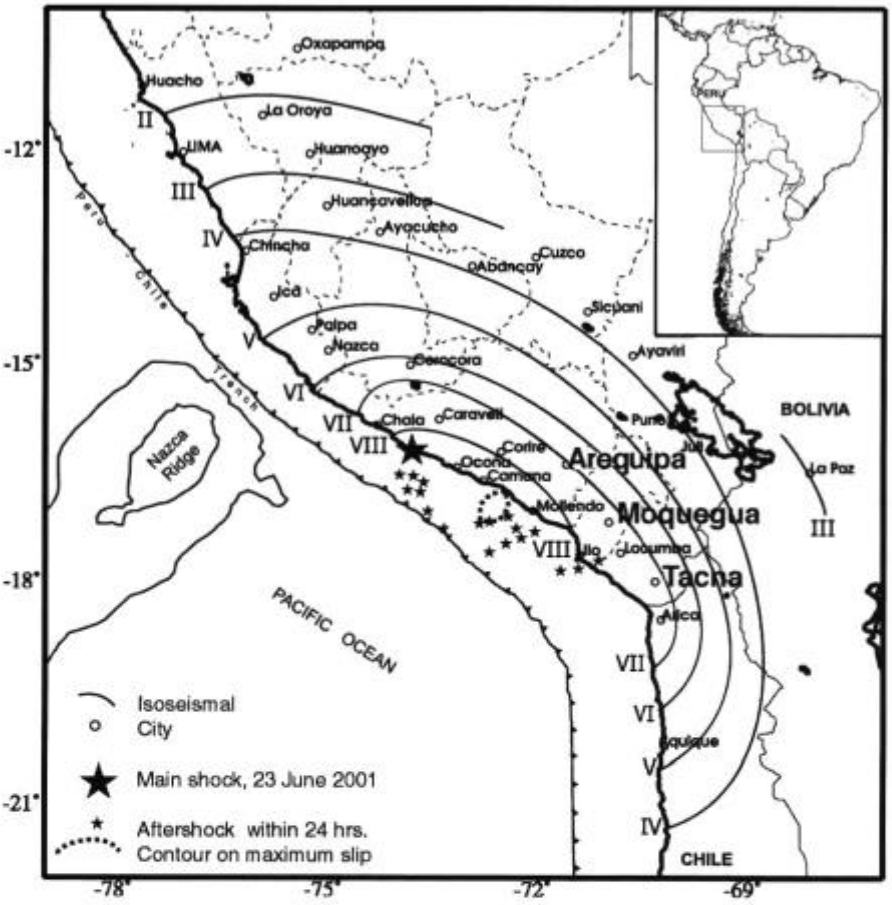

Figure 1-5. Intensity map of the 23 June 2001 earthquake, prepared by the Instituto Geofísico del Perú (Tavera et al. 2002).

and rock sites (predicted to be less than for deep soil sites). The contribution of local site amplification to the relatively high amplitude of the Moquegua accelerogram is considered in Chapter 2, Ground Motion and Site Response. The relatively high ground motions at Moquegua may also be attributable in part to source directivity resulting from the southeastward propagation of the earthquake fault rupture from the hypocenter toward Moquegua (Figure 1-2), although it is not clear why directivity effects would be most conspicuous at short periods. Additionally, it is possible that lateral attenuation of seismic waves from Peruvian subduction zone earthquakes to sites on land is intrinsically lower than in the subduction zones that contributed most of the data used by Youngs et al. (1997) to derive their equation.

The earthquake produced moderate or greater damage (MMI VII and greater) over approximately 60,000 km^2 of southern Peru and northernmost Chile (Figure 1-5). On a regional scale, the strongest shaking, corresponding to intensity VIII, is inferred to have occurred along the coast among cities that were closest to the earthquake source. As with most earthquakes, however, damage patterns were highly variable in detail. Specific sites well inland from the regional intensity VIII isoseismal received shaking that was comparable to, if not greater than, that generally

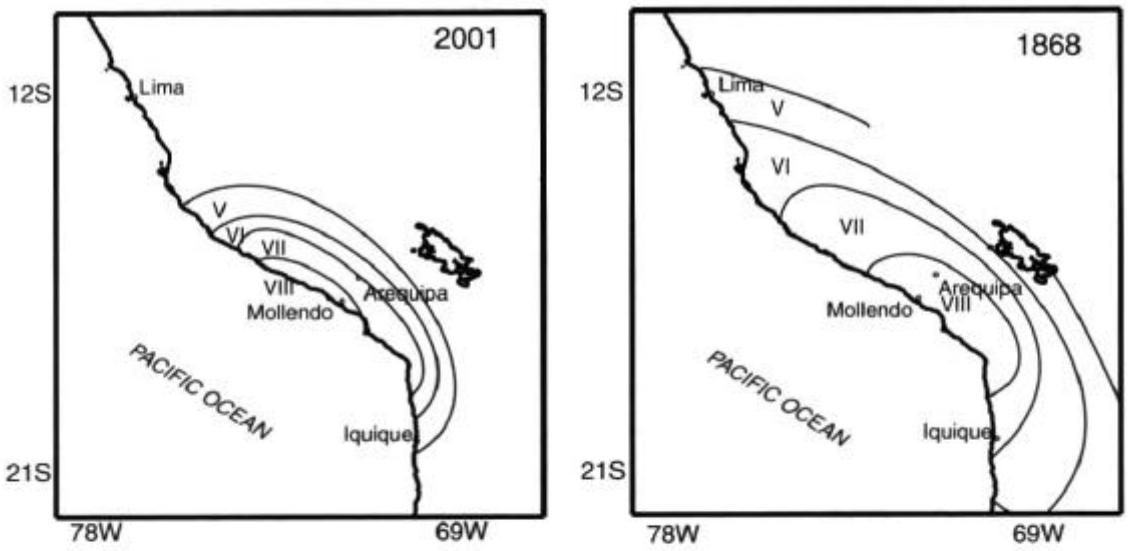

Figure 1-6. *Left* Intensity map of the 2001 earthquake. *Right* Compare with that of the 13 August 1868 earthquake (after Kausel 1986).

observed along the coast. For example, some parts of the towns of Moquegua and Tacna (locations in Figure 1-5) reported heavy damage. The high shaking in these districts has been attributed to site effects (Chapter 2, Ground Motion and Site Response).

A comparison of the isoseismal map of the 23 June 2001 earthquake with the southern Peru earthquake of 13 August 1868 (Figure 1-6) makes clear that the 1868 event was the larger of the two. This may also be inferred by comparing the sizes of the tsunamis generated by the two earthquakes (see Chapter 7, Tsunami). On the basis of both tsunami size and macroseismic observations, the 1868 earthquake has traditionally been considered to have involved rupture of the plate interface from approximately 16°S to 19°S (Figure 1-3), implying a rupture length over 1.5 times as large as the 2001 earthquake. Dorbath et al. (1990) estimated that the 1868 earthquake had an M_W of 8.8. We do not see evidence in the macroseismic data of the 2001 earthquake that would cause us to reassess the pre-2001 view of the source of the 1868 earthquake. The 23 June 2001 earthquake, while perhaps the largest worldwide in the past third of a century, is not the largest earthquake this section of coastal Peru has experienced or may experience in the future.

POTENTIAL FOR FUTURE PLATE INTERFACE EARTHQUAKES

The 23 June 2001 earthquake and its aftershocks should have substantially reduced elastic strain in a 300-km-long segment of the plate interface in Peru, but much of the remaining 700 km of the plate interface that has been quiescent since the great earthquakes of 1868 and 1877 has been accumulating elastic strain since the late nineteenth century. A seismic gap capable of producing a large earthquake probably still remains along the plate interface to the northwest of the 23 June 2001 earthquake, between the 2001 source region and that of the earthquake of November 12, 1996 (Tavera et al. 2002). South of the 23 June source region, a seismic gap remains in Peru and Chile that includes all the source region of the 1877 earthquake and the southernmost part of the source region of the 1868 earthquake, a length of over 600 km. This section of the plate interface therefore still retains the potential to produce great earthquakes in upcoming decades.

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