The June 23, 2001 Peru earthquake and the southern Peru subduction zone

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[1] The plate boundary between the South American and Nazca plate along the south-central Peru coast has been the site of large destructive earthquakes for many centuries, including the June 23, 2001 ($M_W = 8.4$) event. This underthrusting event has a fault area of 320 km by 100 km based on relocated aftershocks during the first three weeks following the mainshock. Modeling of the teleseismic broadband P waves of the 2001 Peru earthquake indicates two pulses of moment release with the larger second pulse located 130 km southeast of the mainshock initiation, indicating a unilateral rupture to the southeast. Based on intensity and tsunami reports, previous earthquakes in 1868 and 1604 were larger than the 2001 earthquake, while an event in 1784 was smaller. This provides further evidence that the size of earthquakes along the Peru coast has changed between successive earthquake cycles. INDEX TERMS: 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics. Citation: Giovanni, M. K., S. L. Beck, and L. Wagner, The June 23, 2001 Peru earthquake and the southern Peru subduction zone, Geophys. Res. Lett., 29(21), 2018, doi:10.1029/2002GL015774, 2002.

1. Introduction

[2] The southern Peru subduction zone has been the site of four large, damaging earthquakes in the past century. The recent June 23, 2001 ($M_W = 8.4$) earthquake was the largest earthquake to occur worldwide in the past 25 years. This segment of the Peru trench last ruptured in an earthquake in 1868 and was identified as a seismic gap by McCann et al. [1979]. Nishenko [1985] estimated a very high but uncertain seismic potential for the segment. In addition to the great 2001 event, earthquakes occurred along the southern Peru trench on 24 August 1942, 3 October 1974, and 12 November 1996. As shown in Figure 1, the focal mechanisms indicate that all four earthquakes were underthrusting events [Swenson and Beck, 1999; Dziewonski et al., 2002]. In all cases, the fault plane is shallowly dipping to the eastnortheast and represents the subduction of the Nazca plate under the South American plate. In this study, we have analyzed the mainshock and aftershocks of the June 23, 2001 earthquake sequence.

2. Aftershock Relocations

[3] We relocated 75 aftershocks using a relative relocation method based on a master event [Pavlis and Booker, 1983].

The aftershocks ranged in magnitude from 4.1-7.6 and occurred between 23 June 2001 and 13 July 2001. We used arrival times from U.S. Geological Survey preliminary locations and a master event on 24 June 2001 (M_W = 6.6). We used identifiable depth phases at teleseismic stations SACV, SJG, DRLN, PAS, TUC, HKT, CCM, SSPA, BINY, and HRV to determine a depth of 20 km for the master event and then fixed the depth for the relative relocations. The aftershocks show two clusters: one in the northwestern third of the fault area and one in the southeastern third of the fault area, leaving a central gap with fewer aftershocks. The aftershocks define a region approximately 320 km by 100 km.

3. Mainshock and Largest Aftershock Rupture

[4] We have analyzed the P waveforms from the mainshock for the temporal and spatial moment release. We used Pwave displacement traces for the mainshock from 14 Global Seismic Network stations that are azimuthally distributed (Figure 2). The data are filtered between 1 and 100 s, and the displacement traces are inverted for a source-time function and a spatial moment release on the fault. We assumed a simple Earth model with a 4-km water layer, a crustal thickness of 30 km at the source, and a 35-km crustal layer at the receiver. We have assumed the fault plane to be dipping 14° east-northeast. We used a pulse-stripping method based on Kikuchi and Kanamori [1982] with a wavelet-unit trapezoid that has duration of 16 s. We tested trapezoid half-widths from 6-12 s and found the best fit at 8 s. The source-time function shows two pulses of moment release, with a smaller, first pulse that occurred between 5 and 30 s followed by the second, larger pulse that occurred between 70 and 100 s (Figure 2). The second pulse contained more than two-thirds of the total moment release from the body waves. We cannot rule out any moment release between the pulses, but it must be relatively small. This spatial moment release indicates a unilateral rupture to the southeast, where the first pulse occurred within 50 km of the rupture initiation and the second pulse occurred approximately 130 km southeast of the rupture initiation (Figure 2). We are unable to fit the first motions at stations HOPE, SPA, PAS and HKT with the longperiod focal mechanism determined by the Harvard CMT, suggesting a slight change in mechanism in the first few seconds of the rupture (Figure 2). We obtain a total seismic moment of 24.16×10^{20} N m, which gives a moment magnitude M_W of 8.2. This is less than the moment magnitude $(M_{\rm W} = 8.4)$ determined by the Harvard CMT Project using the long-period phases. The largest asperity is located between the two main clusters of aftershocks.

[5] Using the same modeling approach, we analyzed the largest aftershock, which had a $M_W = 7.6$ [Dziewonski et al., 2002]. We used 20 P wave displacement traces to determine

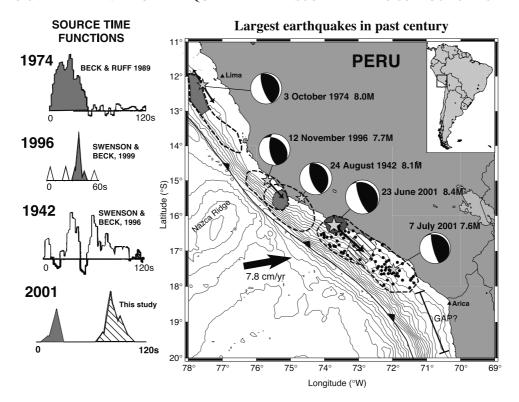


Figure 1. The largest earthquakes to occur along the south-central Peru trench in the past century, their focal mechanisms, directions of rupture, and fault areas as defined by aftershock locations are shown. Focal mechanisms for the 1996 and 2001 mainshock and largest aftershock are from the Harvard CMT Catalog [Dziewonski et al., 2002]. The focal mechanism for the 1974 and 1942 earthquakes are from Beck and Ruff [1989] and Swenson and Beck [1996], respectively. The aftershock area for the 1974 earthquake is from Dewey and Spence [1979], and the aftershock area for the 1942 is estimated and not well constrained. The shaded and hatched regions in the aftershock areas are the regions of highest moment release (asperities) and correspond to the shaded regions in the source-time functions shown on the left. The first peak on the 2001 earthquake source-time function corresponds to the smaller asperity located underneath the star; the second, larger peak corresponds to the larger asperity located southeast of the rupture inititation. There is a seismic gap southeast of the 2001 fault area where the subduction zone last ruptured in 1868.

the temporal and spatial moment release (Figure 3). We used the nodal plane that dips 14° east-northeast as the fault plane [Dziewonski et al., 2002]. The source-time function shows the total duration of rupture to be $\sim\!25$ s, occurring in two pulses (Figure 3). The spatial distribution showed very little directivity, indicating the moment release occurred very near the hypocenter. We obtained a seismic moment of 2.0×10^{20} N m for this large aftershock.

[6] We summarize our results in map view in Figure 1. For the mainshock we have interpreted the two pulses on the source-time function to be patches of moment release or asperities, a smaller one close to the hypocenter and a larger one 130 km to the southeast. We do not have a good constraint along the dip dimension for the asperity; therefore we have shown the second, larger patch to have a down-dip dimension along the entire fault area as deter-

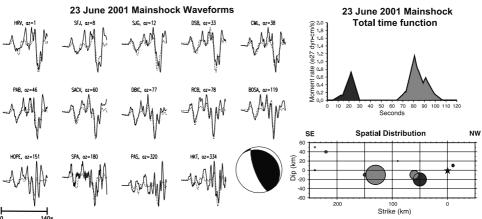


Figure 2. Mainshock *P* wave displacement waveforms, focal mechanism [*Dziewonski et al.*, 2002], source-time function, and spatial moment release distribution. *P* wave displacement traces are solid lines; synthetic waveforms are dotted lines.

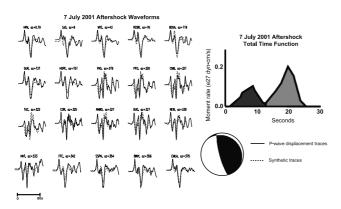


Figure 3. *P* wave displacement waveforms (solid lines), focal mechanism [*Dziewonski et al.*, 2002], and source-time function for the largest aftershock. Synthetic waveforms (dotted traces) are also shown for a model with no directivity.

mined by the aftershock relocations. We realize that this may be an overestimate, which will therefore cause any calculation of the coseismic slip to be an underestimate.

[7] Using the area of the largest asperity and the body wave moment from that area, we estimate the slip to be approximately 11 m in that region using

$$M_0 = \mu DA$$

where M_0 is the moment release, μ is the rigidity, D is the displacement, and A is the fault area. In contrast, if a uniform slip is assumed over the entire aftershock area, then the average slip is approximately 5 m.

4. Earthquakes Along the South-Central Peru Trench

[8] We compare our results for the 2001 event with information about previous earthquakes along the southern

Peru Trench. Figure 1 shows a comparison of the sourcetime functions for the events of the past century. The sourcetime functions for the 1974 ($M_0 = 8.0$), 1996 ($M_W = 7.7$), and 1942 ($M_W = 7.9 - 8.2$) earthquakes are from previous studies [Beck and Ruff, 1989; Swenson and Beck, 1999, 1996]. All four of the source-time functions have been normalized to the same amplitude and plotted at the same time scale (Figure 1). The 1974, 1996, and 1942 earthquakes have source durations of 60, 45, and 75 s respectively. On the map the shaded regions correspond to the regions of highest moment release, shown as shaded areas on the source-time functions. The 1974, 1996, and 2001 earthquakes all show unilateral rupture to the south-southeast, with the largest pulse of moment release occurring at least 100 km from the mainshock initiation. The maximum intensities observed for the 1942 earthquake also suggest a possible southeast rupture. There is some overlap along strike in the aftershock areas of these four events, but there seems to be no overlap in the rupture of the largest asperities associated with each event. The most striking observation about these earthquakes is that the regions of highest moment release are small compared to the entire fault area as defined by the aftershocks. It does not appear that any earthquakes in the past century have ruptured the same fault area as the 2001 event. To see when the 2001 segment of the plate boundary last ruptured, we look to more historical events.

5. Historical Earthquakes

[9] We compare modified Mercalli intensities of 8 and higher of past earthquakes that may have ruptured the same fault segment as the 2001 event (Figure 4a). On all of the maps in Figure 4, the star shows the 2001 epicenter, and the black bar approximates the length of the fault area as defined by the aftershocks. Looking first at the 1868 event (Figure 4b), it is clear that the intensities were much higher

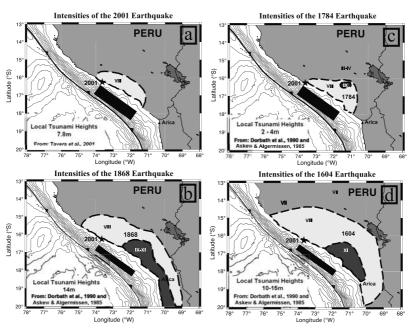


Figure 4. Star indicates hypocenter of 2001 event, and black bar approximates length of 2001 fault area. (a) Region that experienced modified Mercalli intensities of 8+ from 2001 earthquake. (b) Regions that experienced intensities of 8+ from 1868 earthquake. (c) Regions that experienced 8+ intensities from 1784 earthquake. (d) Regions that experienced 8+ intensities from 1604 earthquake.

[Dorbath et al., 1990; Askew and Algermissen, 1985] and covered a much larger region than the 2001 event. This implies that the 1868 earthquake was a much larger event than the 2001 earthquake. The 8+ intensities for 2001 overlap with 8+ intensities for 1868, suggesting that the 2001 event ruptured part of the same fault that failed in 1868. The 1868 earthquake was assigned a $M_t = 9.0$ [Abe, 1979] based on the devastating tsunami that was generated. This tsunami magnitude corresponds to a seismic moment of $350-400 \times 10^{20}$ N m. The intensity maps in Figure 4 suggest that the region to the south of the 2001 event has not ruptured since 1868; hence there is still a seismic gap that could be at least 200 km along strike.

- [10] Using a convergence rate of 7.8 cm/yr [DeMets et al., 1990] and a period of 133 years since the region slipped in 1868 gives a calculated estimate of 10.4 m of accumulated tectonic slip. This suggests that the major asperity has been locked since the last great earthquake in 1868.
- [11] Looking further back in time, the 1784 event (Figure 4c) has similar intensities [Dorbath et al., 1990; Askew and Algermissen, 1985] to the 2001 event in terms of distribution along the coast, suggesting that the same fault segment was ruptured by the 1784 and 2001 events. The intensities from the 1604 event [Dorbath et al., 1990; Askew and Algermissen, 1985] cover a much larger region than those from 2001, again suggesting a much larger earthquake in 1604 (Figure 4d). The overlap also suggests that the 2001 event ruptured only part of the 1604 fault. This limited data set suggests a possible bimodal rupture mode alternating between the truly great events in 1604 and 1868 and the smaller events in 1784 and 2001. It is also interesting to note that the time interval before the next earthquake following the large events (1604 and 1868) is longer than the interval following the smaller event (1784). This behavior is reminiscent of the timepredictable model for earthquake rupture where each earthquake occurs at a critical stress level [Shimazaki and Nakata, 1980]. One of the best-documented examples of a change in rupture mode along a subduction zone is the Colombia-Ecuador trench [Kanamori and McNally, 1982]. The bimodal behavior of southern Peru is different from the Colombia-Ecuador subduction zone, where a great earthquake occurred in 1906 (M_W = 8.8) that ruptured a 500-km segment of the plate boundary. Subsequent smaller events in 1942 $(M_W = 7.9)$, 1958 $(M_W = 7.7)$ and 1979 $(M_W = 8.2)$ appeared to have reruptured the same portion of the plate boundary [Kanamori and McNally, 1982; Swenson and Beck, 1996]. Along the southern Peru subduction zone we do not see two or more smaller events filling in the entire rupture area of the larger events in 1604 and 1868, although it is possible that the historic earthquake record is incomplete.

6. Conclusions

[12] The June 23, 2001 mainshock had an aftershock area of 320 km by 100 km and a unilateral rupture to the southeast, with the largest asperity located approximately 130 km southeast of the hypocenter. The south-central Peru segment ($12^{\circ}-19^{\circ}S$) of the subduction zone has ruptured in underthrusting earthquakes this century, from north to south, in 1974 ($M_W = 8.0$), 1996 ($M_W = 7.7$), 1942 ($M_W = 7.9-8.2$) and 2001 ($M_W = 8.4$). The 1974, 1996, 1942, and

2001 earthquakes have source durations of 60, 45, 75, and 100 s respectively, and all initiated with a small pulse of moment release followed by a larger pulse of moment release delayed in time. The 1974, 1996, and 2001 earthquakes all show unilateral rupture to the south-southeast, with the largest pulse of moment release occurring at least 100 km from the mainshock initiation. There is some overlap along strike in the aftershock areas of these four events, but there seems to be no overlap in the rupture of the largest asperities associated with each event.

[13] The 2001 fault segment ruptured by earthquakes in 1868, 1784, and 1604. A comparison of the intensities between the 2001 and 1868 earthquakes suggests that there is still a significant seismic gap southeast of the 2001 fault segment where the subduction zone has not failed since 1868. The historical record suggests that there has not been a characteristic earthquake along the southern Peru subduction zone.

[14] **Acknowledgments.** We used IRIS GSN data for our analysis of these earthquakes. We thank Anne Paquette for her help with the aftershock relocations.

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