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VARIATIONS IN THE MODE OF GREAT EARTHQUAKE RUPTURE ALONG THE CENTRAL PERU SUBDUCTION ZONE

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Abstract. The historic record for the central Peru subduction zone suggests significant variations in the earthquake size during the last 400 years. During this century there have been four great underthrusting earthquakes along the central Peru seismic zone. From north to south these are the 17 October 1966 (M_w=8.1), 24 May 1940 (M~8), 3 October 1974 (M_w=8.1), and 24 August 1942 (M~8.2) earthquakes. Modified Mercalli intensity data and tsunami observations for the earthquakes in this century are compared with the 29 October 1746 and 20 October 1687 earthquakes. The 1746 earthquake had maximum intensity values between 9° and 13°S while the 1687 event had maximum values between 12° and 14°S suggesting that the two events failed different segments of the subduction zone. We find that the 1746 event occurred along the segment that includes both 1940 and 1966 earthquakes. The size of the 1746 event is estimated to be M_w ~8.8 based on the ratio of near-field tsunami heights for the 1746 and 1966 earthquakes. The 1687 earthquake probably ruptured the 1974 segment as well as the adjacent segment to the south where there is at present a gap between the 1942 and 1974 rupture zones. The size of the 1687 event is estimated to be M_w~8.7 based on both far-field and near-field tsunami height ratios of the 1687 and 1974 events. Both 1746 and 1687 earthquakes appear to be much larger than the events of this century. In contrast to the simple, single asperity nature of the 20th century earthquakes, these older and larger events may represent multiple-asperity ruptures along the Peru subduction zone. Hence, variations in the mode of earthquake rupture from cycle to cycle along the central Peru seismic zone may explain the significant difference in earthquake size during the last 400 years.

Introduction

Studies of recent "gap filling" earthquakes along convergent plate margins have shed new light on the variability of the subduction process from cycle to cycle, in addition to demonstrating the heterogenity associated with individual earthquake ruptures. Evidence that the magnitudes and rupture dimensions of "gap filling" earthquakes vary significantly from cycle to cycle along any given segment of a subduction zone is becoming more common. Examples of variations in the earthquake cycle have been documented along the Colombia-Ecuador, Chile, Aleutians, and southwest Japan subduction zones [Kanamori and McNally, 1982; Comte et al., 1985; Davies et al., 1981; Ando, 1975; Thatcher, 1990].

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The historic record for central Peru also suggests significant variations in earthquake size during the last 400 years. During this century there were four great underthrusting earthquakes in 1940, 1942, 1966 and 1974, along the central Peru seismic zone between the Mendana fracture zone (10°S) and the Nazca ridge (15-16°S). Although our understanding of these events has improved due to recent studies [Dewey and Spence, 1979: Beck and Ruff, 1989], we still lack a quantitative appreciation of how these 20th century events compare with earlier great earthquakes in the region. The historic earthquake record along the coast of Peru dates back to the 16th century [Silgado, 1985]. Descriptions of earthquake damage and tsunamis suggest that many earlier events were, in fact, larger than the great earthquakes which occurred during this century. By comparing tsunami and felt intensity reports for events in 1586, 1687, and 1746 with the 20th century events, we attempt to quantify the apparent differences in size, and propose a mechanism by which these differences may arise.

20th Century Earthquakes

The great earthquakes of 17 October 1966 (M_w=8.1), 24 May 1940 (M~8), 3 October 1974 (M_w=8.1) and 24 August 1942 (M~8.2) ruptured adjacent segments between 10°S and 16°S along the Peru trench. Figure 1 shows the asperity distribution determined by Beck and Ruff [1989] from long-period P-waves for three of the four underthrusting events. These inferred asperities are the locations of concentrated seismic moment release relative to the epicenter. The 1966 earthquake has a source duration of 45 sec with most of the moment release near the epicenter. The 1940 earthquake is smaller than the 1966 and 1974 events and has a duration of ~30 sec with the seismic moment release near the epicenter. The 1974 earthquake has two pulses of moment release with a duration of 50 sec. These two pulses of moment release occurred on the northern half of the aftershock area. The 1974 earthquake ruptured the segment immediately to the north of the Nazca Ridge. The southern flank of the Nazca Ridge was last ruptured in the 24 August 1942 earthquake (Figure 1). We do not know the details of the spatial moment release for the 1942 event. A comparison of the P-wave seismograms of the 1940 and 1942 earthquakes indicates that the 1942 event is approximately twice the size of the 1940

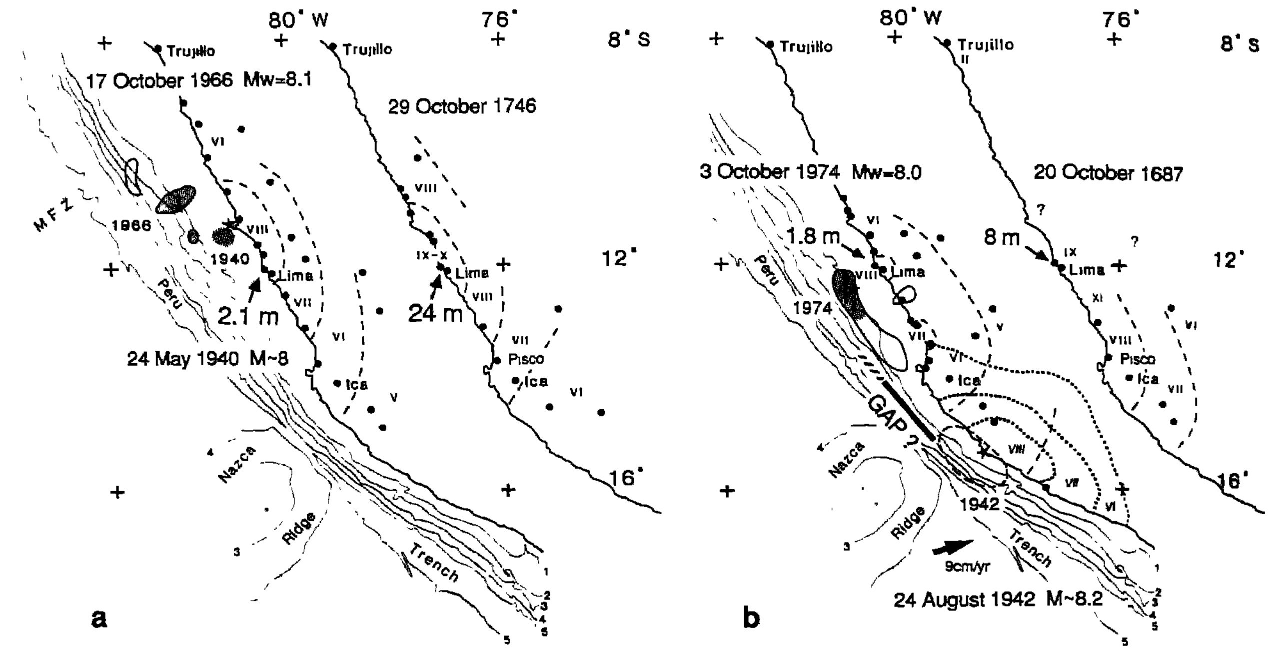

Fig. 1. A comparison of the Modified Mercalli (MM) intensity values and tsunami heights for (a) the 1746 and 1966-1940 earthquakes and (b) the 1687 and 1974-1942 earthquakes [Espinosa et al., 1975, 1977; Silgado, 1985; Askew and Algermissen, 1985]. The asperity locations for the 1966 and 1974 earthquakes (stippled areas) are based on inversions of WWSSN long-period P-waves, while the location of the asperity for the 1940 earthquake (hachured area) is estimated from the duration of the pulse of seismic moment release [Beck and Ruff, 1989]. The aftershock areas for the 1966 and 1974 earthquakes are from Dewey and Spence [1979]. The location of the 1940 and 1942 mainshocks are from J. Dewey [personal communication, 1985]. The 1942 aftershock area is from Kelleher [1972]. MFZ is the Mendana fracture zone. (a) MM intensities for the 1940 and 1966 earthquakes are similar for identical locations along the coast, hence, only one set of values are shown. (b) The dashed and dotted lines show the intensity contours for the 1974 and 1942 earthquakes respectively. The 1687 earthquake has maximum intensities near Lima but also has high intensities much further south near Ica. The 1687 earthquake may have ruptured the region that is presently a seismic gap between the 1942 and 1974 rupture areas.

earthquake and similar in size to the 1966 and 1974 events [Beck and Ruff, 1986]. With the exception of the 80-100 km gap between the 1974 and 1942 rupture zones, the entire segment (10°S-16°S) has failed in Magnitude 8 earthquakes this century.

Historic Earthquakes

The historic earthquake record for Peru extends back to the 16th century and contains many detailed descriptions of damage and tsunamis along the Peru coast. Figure 1 shows the relationship of the inferred asperities to the isoseismal patterns for the 1940, 1966 and 1974 earthquakes. Note that the area of Modified Mercalli (MM) VIII+ damage is located onshore in the immediate vicinity of these asperities. Although there are problems with interpreting historic accounts of earthquake damage (i.e. under- or overestimating damage, completeness of reporting, changes in the quality and type of construction, etc.) we can make a qualitative comparison. This spatial association suggests that areas of high intensity or strong ground motion may be used to map the relative location of patches of high seismic moment release. Kelleher [1972] used MM VIII-IX intensity contours to estimate the rupture zones of large and great South American earthquakes, noting that areas of substantial damage are usually within or adjacent to the rupture zone.

In addition to comparing isoseismal distributions, we also compare tsunami run-up heights for the above earthquakes. Published tsunami heights for historic events are based on the run-up distance at local sites along the coast [Lockridge, 1985]. For recent earthquakes, tsunami heights are based on tide gauge recordings; hence, the overall precision of these observations has varied over the last few hundred years. In addition to being dependent on fault dip, fault length and focal depth [Yamashita and Sato, 1974], near-field tsunami heights are also very dependent on local coastal conditions. For a given tsunami, factor of two variations in run-up are not unusual along the same coastline [see compilation of heights in Lockridge, 1985].

Abe [1979] defined a tsunami magnitude scale, M_t, based on observations of the far-field tsunami height, $M_t = log\ H + B$, where H is the wave height and B is a scaling constant. This relationship has extended the study of great historic earthquakes and has facilitated the quantitative comparison of recent and historic events. Unfortunately, far-field observations of pre-20th century events are often lacking and the only quantitative descriptions come from the near-field (i.e. near the epicenter or rupture zone).

Comer [1980] examined the theoretical relationships between seismic moment, M_o, the seismic moment-magnitude scale M_w, and M_t or log H, and found that the Abe [1979] relationship between seismic moment, M_o and log H, or $M_o \sim H^{3/2}$, is bracketed by two theoretical extremes that include the effects of dispersion on tsunami waveform and amplitude. For non-dispersive cases, $M_o \sim H^2$, and highly dispersive cases, $M_o \sim H$. The non-dispersive case is of particular interest for this study in that it may be a good physical approximation to the case where the observations are close to the epicenter or the tsunami generating area (i.e. the near-field). Hence, while the quality of observations has varied over the years, we can make use of the range of seismic moment-run-up relationships for an order of magnitude comparison of recent and historic events. Similar comparisons have been made for Chilean earthquakes [Nishenko, 1985] by multiplying the ratio of tsunami heights with the seismic moment of a recent event. Figure 1(a and b) shows a comparison of the felt intensity patterns and tsunami heights for the 1746 and 1940-1966, and the 1687 and 1974-1942 earthquakes respectively. We can draw important qualitative conclusions about the relative location of historic ruptures by comparing these reports with modern reference earthquakes.

1746 Earthquake

The largest, well documented pre-instrumental earthquake along this segment of the Peru trench occurred on 28 October 1746, and is estimated to have had an intensity-magnitude, M_I, of 9.2 [Ocola, 1984]. As seen in Figure 1, comparison of the highest felt intensities for the 1746, 1940, 1966, and 1974 earthquakes indicate that while the shaking and damage in 1746 is one to two Modified Mercalli values higher than in 1940, 1966 or 1974, the maximum intensities occur along the same coastal area, between 9°S and 13°S. This coincidence suggests that the rupture zone of the 1746 event is in the same relative location as the 1940 and 1966 earthquakes and may include the 1974 asperity region.

The maximum local tsunami height reported for the 1746 event is 24 m at Callao, Peru [Lockridge, 1985]. The only far-field report for the 1746 tsunami is from Acapulco, Mexico but no heights are mentioned. For comparison, the maximum run up height at Callao for the 1966 earthquake is 2.1 m [Lockridge, 1985]. We would expect an observable far-field tsunami along the coast of Japan for the 1746 event but there is no mention of one [Watanabe, 1983]. The 1966 event produced a 15-20 cm tsunami along the coast of Japan [Hatori, 1981]. For the 1940 earthquake, there is a poorly documented report of a small (2 m) near-field tsunami, and no report of a far-field observation. The ratio of near-field run ups for the 1746 and 1966 events at Callao, Peru (24 to 2.1 m), and the seismic moment of the 1966 earthquake (2 X 10^{21} N-m) indicate a seismic moment of 2-26 X 10^{22} N-m, or a M_w of 8.8 to 9.5 for the 1746 event. While we cannot verify this moment estimate with far-field data, the M_w estimate is comparable with the M_I estimate of Ocola [1984].

Both the intensity and tsunami data indicate that the 1746 earthquake ruptured the same segment of the central Peru seismic zone but was significantly larger than either the individual 1940 and 1966 (and 1974?) events or the two (or three) of them together (~3 (4.5) X 10^{21} N-m). The source time functions for the 1940 and 1966 earthquakes are relatively simple events that ruptured discrete asperities northwest of Lima [Beck and Ruff, 1989]. To account for the difference in size, we suggest that the 1746 event represents a multiple asperity rupture. Although the data to identify the asperities that ruptured in 1746 are equivocal at this point, possible candidates include the 1940, 1966 and 1974 asperities.

Another great earthquake occurred on 9 July 1586, and produced a 26 m run up near Callao, and intensity XII damage near Lima. Watanabe [1983] reports that the 1586 event caused serious damage in Japan and vicinity and assigned a tsunami magnitude of 3-4, however, there is no mention of the wave height in Japan. Although we know very little about the 1586 event, it also appears to have been larger than the 20th century reference earthquakes and may have also been a multiple asperity event.

1687 Earthquake

The largest known earthquake between Lima and Pisco along the Peru trench was the 20 October 1687 event. This event was preceeded by a smaller shock approximately two hours earlier. These two events caused widespread shaking and tsunami damage from Lima to Ica [Silgado, 1985]. The combined effect of the two 1687 events resulted in maximum intensities of XI near 13°S and VIII-IX near Lima, as well as a much larger distribution of MM VIII-IX intensities to the south than were associated with the 1974 earthquake (Figure 1b). The 1974 earthquake produced high intensities near Lima, [Espinosa et al., 1975, 1977] in close proximity to the asperity location shown in Figure 1b. However, in contrast to 1687, intensities near Pisco and Ica in 1974 are one to two MM values lower. The maximum intensity values for the 1687 earthquake are generally further south than for the 1746 earthquake suggesting the 1687 event ruptured further south than the 1746 event. We cannot determine if these two events (1) failed adjacent segments with no overlap along strike, or (2) had overlapping rupture areas and both failed the 1974 rupture area. We will assume that the 1687 earthquake failed the 1974 zone and use that as the reference event to compare with the 1687 event.

The local tsunami height for the 1687 event is estimated to be 8 m based on interpretation of tsunami intensity data [Lockridge, 1989, personal communication]. For comparison, the near-field wave height in 1974 was 1.8 m [Lockridge, 1985]. Far-field observations near Sendai, Japan, indicate tsunami heights of 50 cm for the 1687 event [Watanabe, 1983] and 4 to 10 cm for the 1974 event [Hatori, 1981]. The far-field ratio of heights, 50 to 10 cm, and the seismic moment of the 1974 event (1.5 X 10^{21} N-m), indicate a seismic moment of 1-2 X 10^{22} N-m or a M_w of 8.6 to 8.7. This estimate agrees with the ratio of near-field heights based on the estimated run-up for the 1687 event, but is less than the M_I estimate of 9.0 [Ocola, 1984].

The historic data suggests the 1687 event was much larger than the 1974 earthquake. We suggest that the 1687 earthquake broke the region of the 1974 rupture and an area further south, near Pisco and Ica. The area near Pisco is currently part of the present seismic gap between the 1942 and 1974 ruptures (Figure 1b). These observations suggest that the intersection of the Nazca ridge with the Peru trench is not a permanent barrier to earthquake rupture as the events this century might suggest. The maximum intensity values (VIII) for the 1942 earthquake are near 15-16°S, slightly south of the maximum values for the 1687 earthquake.

Discussion and Conclusion

The age of the subducting plate and the convergence rate at a subduction zone are correlated with the seismic coupling and hence, the maximum size earthquake [Ruff and Kanamori, 1980]. The age of the subducting sea floor along the Peru coast is 45 m.y. and the convergence rate is 9 cm/yr. These parameters indicate relatively strong coupling and predict a maximum size event of M_w~8.8 [Ruff and Kanamori, 1980]. In contrast, the maximum size earthquake along the Peru coast this century is only M_w=8.2. While poorly constrained, the comparisons of tsunami run up heights suggests that events in 1687 and 1746 were of M_w 8.5 to 9 and are in agreement with the regional predictions made by Ruff and Kanamori [1980].

The 1746, 1687 and possibly the 1586 events appear to have been significantly larger than the great earthquakes (1940, 1942, 1966, and 1974) that have occurred this century. We suggest that these differences in earthquake size stem primarily from a change in the mode of earthquake rupture from cycle to cycle. In contrast to the simple, single asperity nature of the 20th century events, the older and larger events may represent multiple asperity ruptures. We suggest that the 1687 earthquake failed the present seismic gap between the 1942 and 1974 rupture areas.

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