VARIATIONS IN THE RUPTURE MODE OF LARGE EARTHQUAKES ALONG THE SOUTH AMERICAN SUBDUCTION ZONE

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RESUMEN: Hemos analizado ondas telesísmicas P y S para la mayoría de los terremotos de gran magnitud en la zona de subducción Sudamericana, y hemos encontrado grandes variaciones, tanto espaciales como temporales, en la liberación de momento sísmico. En regiones con una o varias asperezas, la mayor parte de los terremotos se inician en o cerca de la aspereza dominante. El tipo de segmentación definida por los terremotos en el presente siglo, parece ser inconsistente con la secuencia anterior dada por los eventos en las fronteras de las placas a lo largo de la zone de subducción Sudamericana.

Key Words: South American subduction earthquakes, source parameters

INTRODUCTION

During the last decade our understanding of the rupture process of large subduction zone earthquakes has improved dramatically. Recently, many studies have identified temporal and spatial heterogeneity associated with the rupture process of underthrusting subduction zone events using teleseismic body waves. These studies have shown that the seismic moment release is not uniformly distributed but is concentrated in small regions or patches on the fault area. These patches of relatively high moment release and hence high slip are interpreted as asperities (Lay et al., 1982). Detailed waveform studies of earthquakes that occurred since 1963 provide us with a first-order asperity map for part of the South American subduction zone. In order to expand our understanding of the earthquake occurrence along this subduction zone, we have extended our study to include the largest historic earthquakes.

Although plate boundary segments fail repeatedly in large earthquakes, the seismic moment and recurrence interval for these major plate boundary events often vary dramatically. Study of different earthquakes over a long time interval is essential for a thorough understanding of the earthquake phenomenon. Restricting our analysis to recent earthquakes (events in the last 30 years) can lead to erroneous or misleading results for some regions. Thus, detailed analyses of earlier historic earthquakes are critical. For nearly 80 years a large number of seismographs have been recording at stations around the world. Analyzing data from historic earthquakes can yield valuable information about the earthquake occurrence. For events between 1920 and 1963 we have collected and analyzed teleseismic waveform data to determine source parameters. In addition, we have compiled information about tsunamis and intensities for events extending back approximately 400 years (Silgado, 1985; Hatori, 1968, 1981). The historic earthquake record for the South American subduction zone clearly indicates that characteristic earthquakes do not occur, but rather we see large variations in the earthquake rupture mode and segmentation between successive earthquake sequences.

COLOMBIA-ECUADOR SUBDUCTION ZONE

Two different modes of rupture have occurred along the subduction zone segment off the coast of Colombia-Ecuador (Kanamori and McNally, 1982). In 1906 a great earthquake (M_w=8.8) ruptured a 500 km segment of the plate boundary. This same segment subsequently ruptured in three smaller earthquakes, from south to north, in 1942 (M_s = 7.9), 1958 (M_w = 7.7), and 1979 (M_w = 8.2). It has been 50 years since the 1942 earthquake, longer than the 36-year interval between 1906 and 1942; hence, it is important to evaluate the 1942 earthquake. We analyzed long-period teleseismic *P* and *PP* phases to determine the size, source duration and rupture complexity for the May 14, 1942, Ecuador earthquake. The *P*-wave first motions and body wave modeling of the 1942 earthquake indicate an underthrusting mechanism consistent with the focal mechanism determined for the 1979 Colombia earthquake. The source time function deconvolved from body waves indicate a simple pulse of moment release with a duration of ~25 sec and a depth extent of 0-30 km. The 1942 earthquake failed as a single-asperity event with the moment release concentrated near the epicenter. Estimating the spatial extent of the main moment release using the source duration and a rupture velocity of 2-2.5 km/sec suggests that most of the moment release occurred on a small part of the fault area and in a region with very few aftershocks. The 1942 event is larger than the adjacent 1958 event, although both earthquakes initiated rupture at the dominant asperity and had similar numbers of aftershocks with m_b > 5.5 (Mendoza and Dewey, 1984). In contrast, the 1979 earthquake had a much longer source duration, initiated rupture ~60 km from the dominant asperity and had few aftershocks with m_b > 5.5 (Beck and Ruff, 1984). The historic earthquake record suggests that a large tsunami-generating event has not occurred prior to 1906 for at least 300 years. Large variations occur in the rupture characteristics of the individual earthquakes (1942, 1958, and 1979) as well as between successive earthquake cycles along the Colombia-Ecuador subduction zone.

CENTRAL PERU SUBDUCTION ZONE

The great earthquakes of Oct. 17, 1966 (M_w=8.1), May 24, 1940 (M_w=7.9), Oct. 3, 1974 (M_w=8.1) and August 24, 1942 (M_s~8.2) ruptured adjacent segments along the Peru trench. With the exception of a 80-100 km gap between 1974 and 1942 rupture zones, where the Nazca ridge intersects the trench, the entire segment between 10°S and 16°S has failed in magnitude 8 earthquakes this century. The 1966 and 1940 earthquakes failed as single asperity earthquakes with the dominant asperity near the hypocenter (Beck and Ruff, 1989). In contrast, the 1974 event had a bilateral rupture and failed with two asperities, the largest occurring 80 km south of the hypocenter (Beck and Ruff, 1989). The asperities are concentrated on a small part of the aftershock area (Dewey and Spence, 1979). The 1942 earthquake failed with 2 to 3 pulses of moment release, but we cannot spatially locate the moment release. The historic earthquake record suggests significant variations in the earthquake size during the last 400 years. Previous events in 1687 and 1746 were much larger than the earthquakes this century (Beck and Nishenko, 1990). The intensity and tsunami data indicate that the 1687 event ruptured not only the 1974 segment but the gap between the 1974 and 1942 events. The 1746 earthquake appears to have ruptured both the 1966 and 1940 segments.

CENTRAL CHILE SUBDUCTION ZONE

Four large historic earthquakes have occurred along the central Chilean subduction zone. From north to south, these events occurred on November 11, 1922 (M_s~8.3), April 6, 1943 (M_s~7.9), December 1, 1928 (M_s~8.0) and January 25, 1939 (M_s~8). We have evaluated source parameters for these events using long-period *P* and *SH* waveforms, *P*-wave first motions, intensities, and tsunami heights. We find that the 1922, 1928 and 1943 events are consistent with underthrusting of the Nazca Plate beneath the South American plate. All four events were well recorded in Europe at station DBN. A comparison of the source time functions determined using the *P* waves recorded at DBN indicates that the 1922 event was approximately 4 times larger than the 1943 event and approximately 6 times larger than the 1928 event. The 1922 and 1943 events produced tsunamis in Japan of 65 and 10 cm, respectively. In contrast, no far-field tsunami was reported in Japan for the 1928 event.

A moment tensor inversion using long-period *P* and *SH* waveforms for the 1928 earthquake yields a range in acceptable focal mechanisms, all of which are predominantly thrust events. The source time function for the 1928 earthquake has one main pulse of moment release with a duration of approximately 24 sec. The reported location of the maximum intensities and aftershocks for the 1928 earthquake are south of the main shock epicenter, suggesting a rupture to the south. The source duration suggests that most of the moment release occurred between the epicenter and approximately 80 km to the south. The 1943 earthquake also has a simple source time function with a duration of 24 sec; however, the rupture direction is unclear. In contrast, the *P*-wave for the 1922 earthquake recorded at DBN indicates that this earthquake has a complex source time function with three pulses of seismic moment release and a total duration of at least 70 sec. The complexity of the 1922 earthquake suggests it failed in a multiple-asperity rupture, indicating that this segment could rupture in several smaller adjacent events rather than one 1922-type earthquake.

The most damaging earthquake along the coast of southern Chile this century occurred on January 25, 1939. The 1939 earthquake caused 28,000 deaths and did extensive damage to the city of Chillan (Campos and Kausel, 1990). The 1939 event occurred just to the south of the 1928 earthquake. Although similar in size, the 1939 earthquake was much more damaging than the 1928 earthquake. Analysis of both these large subduction zone earthquakes indicates that they have different focal mechanisms.

We analyzed *P* and *S* waveforms to determine the type of faulting and source parameters for the 1939 earthquake. A comparison of waveforms recorded at the same station for the 1939 earthquake and underthrusting earthquakes in 1928 and 1943 along the Chile subduction zone confirms that the 1939 earthquake is not an underthrusting event. The *P*, *SV* and *SH* first motions, the amplitude ratio of the *SH* to *SV*, and modelling of *P* waveforms indicate an oblique normal focal mechanism. The high intensities, lack of a tsunami, and inland location associated with the 1939 event are all consistent with an intraplate event within the down-going slab. Thus, large, intermediate-depth, intraplate earthquakes represent a significant seismic hazard along the coast of Chile.

The 1928 earthquake ruptured southward with most of the seismic moment release occurring 60-80 km south of the 1928 epicenter but still north of the 1939 region. In light of this information the underthrusting plate interface segment (updip of the 1939 event) between 36°S and 37.5°S needs to be re-evaluated. This segment failed in 1835, 1751, and 1657 with large tsunami-generating earthquakes. Although we know very little about these previous events, the large tsunamis and intensity patterns suggest that they were underthrusting earthquakes and not intraplate earthquakes similar to the 1939 event. If the 1939 event is indeed not an underthrusting earthquake, then this segment has not failed for 157 years and may be a "seismic gap".

CONCLUSIONS

Much of the South American subduction zone has failed in magnitude 8 or larger earthquakes this century. The rupture characteristics of these individual earthquakes have varied greatly. The regions of high moment release and hence large displacement are concentrated on small patches of the fault area as defined by the aftershock area. Both single- and multiple-asperity ruptures occur and most earthquakes initiated at or near the dominant asperity. We do not understand what these seismically determined asperities represent physically because, in general, they do not correspond to any observable geometric features associated with the subduction zone. The South American subduction zone does not fail in characteristic earthquakes. The segmentation defined by the earthquakes this century appears inconsistent with the previous sequence of plate boundary events. Along segments of the Colombia-Ecuador, central Peru, and Chile subduction zones, the earthquake rupture mode varies between successive earthquake sequences.

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