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Invited review paper: Seismicity along the South American subduction zone: Review of large earthquakes, tsunamis, and subduction zone complexity

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ABSTRACT

Earthquakes along the shallow South American subduction zone exhibit heterogeneous rupture characteristics, going back several centuries of the earthquake record in this area. This heterogeneity is manifest in several ways, such as changes in rupture mode from magnitude >8 events during one century followed by smaller ones in other time periods, as well as unusual tsunami events. There is also an apparent interaction between earthquake rupture and subducting plate complexity in this region. Significant complexity exists on the subducting Nazca plate, including fracture zones and ridges such as the large Nazca Ridge. Several large magnitude earthquakes have occurred in the region of ridge subduction, but no earthquake rupture has ruptured through these features into adjacent regions, suggesting that these subducting features act to segment the margin. Other features, such as fracture zones and variable sediment thickness on the Nazca Plate, appear to influence earthquake behavior over a wide range of magnitude scales. Upper plate features such as crustal faults also lead to heterogeneous earthquake behavior. Here I provide an overview of seismicity along the margin since 1850 in the context of the subduction zone structures. This includes great earthquakes such as the 1906 Ecuador and 1960 Chile events. I also present results showing increased rupture complexity in moderate magnitude earthquakes that can also be linked to certain Nazca Plate features.

1. Introduction

Along the South America margin, the Nazca Plate subducts beneath the South American Plate, causing volcanism, deformation, and shallow seismicity (e.g. Pilger, 1984; Cahill and Isacks, 1992). This latter product of subduction is the topic of this review. Many earthquakes with magnitude >7.5 have occurred at the interface between the subducting Nazca and overriding South American plates during the 20th and 21st centuries (Fig. 1). Historical records back to the 1500s suggest additional great ($M>8$) earthquakes along this margin. In fact, much of the margin has broken in great earthquakes with the largest earthquake on record to date, the 1960 moment magnitude (M_w) 9.5 rupture zone, anchoring the southern portion of the margin. In addition, there are cases of fairly rare events along the Peru margin, namely the 1960 and 1996 tsunami earthquakes. Tsunami earthquakes, seen in a few other subduction zones as well, are characterized by slow rupture and tsunami larger than expected for the earthquake size (Kanamori, 1972) and may be related to rupture in weak sedimentary materials in the shallow portion of the subduction zone (e.g. Kanamori and Kikuchi, 1993; Satake and Tanioka, 1999). Other slow velocity earthquake processes are been noted along the margin, including significant afterslip following the 1995 M_w 8.1 Antofagasta earthquake (Pritchard and Simons, 2006).

Clearly there is evidence of heterogeneity with the earthquakes themselves. There is also complexity inherent in the geologic structure of the Nazca and South American plates. Features such as seamounts, ridges, fracture zones, and variable sediment supply enter the trench. In addition, there are various upper plate features such as transverse faults and forearc basins observed along the South American Plate. These types of features are observed in subduction zones around the globe, and there are many suggestions that these features affect large earthquake occurrence (e.g. Ryan and Scholl, 1993; Scholz and Small, 1997; Spence et al., 1999; Kodaira et al., 2000; Husen et al., 2002; Bilek et al., 2003; Song and Simons, 2003; Wells et al., 2003). In the case of South America, many large earthquakes occur in the regions where these large Nazca Plate features, such as the Nazca Ridge, enter the trench.

Not only do the earthquake locations correlate with the presence of large subducting features, these bathymetric features, once in the seismogenic portion of the megathrust zone, may influence details of seismic moment release and slip during individual earthquakes. The linkages between these features and earthquakes include concentration of slip in the areas of where subducting features have been imaged or inferred at depth, thus acting as asperities, or concentration of slip away from these features, thus acting as barriers to rupture. These can be manifested in the patterns of slip distribution on the fault

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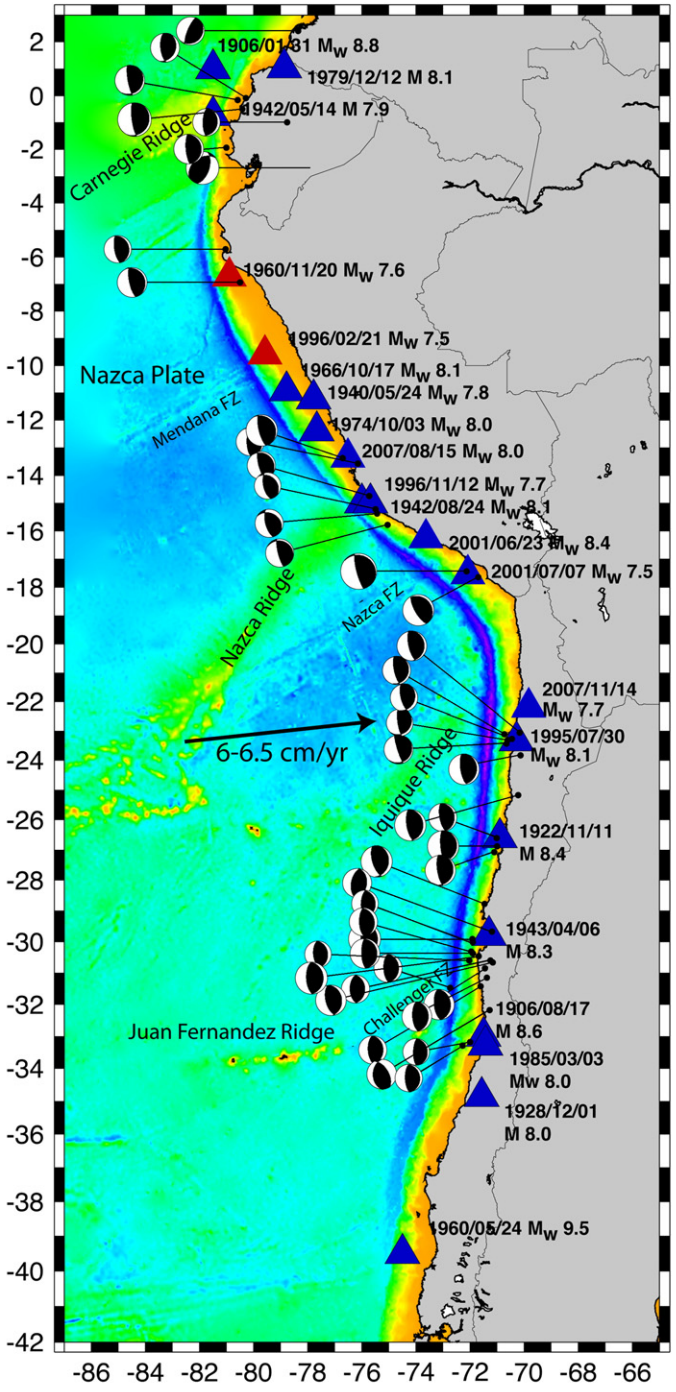

Fig. 1. Overview map of South American subduction zone with significant earthquakes from the 20th and 21st centuries. Earthquake locations (triangles) and magnitudes are based on sources within the text. Red triangles show locations of the 2 tsunami earthquakes that occurred off of the Peru coast. Bathymetry from Smith and Sandwell (1997) and convergence rate from Kendrick et al. (2003). Also included are earthquake locations (black circles) and focal mechanisms (gCMT) for the moderate magnitude earthquakes analyzed in this study.

plane and complexity in the moment release history throughout an individual rupture. These features may also act to limit rupture areas for individual events. In addition, presence or absence of weak, low velocity trench sediment can also affect earthquake rupture, resulting in slower rupture velocities or even aseismic slip. This connection is described for several subduction zones around the world (e.g. Cloos, 1992; Scholz and Small, 1997; Kodaira et al., 2000; Husen et al., 2002; Bilek et al., 2003), and South America is no exception. The 2001 M_w 8.4 Peru earthquake provides one example of a subducting fracture zone influencing the earthquake rupture, acting as a barrier early in the rupture but breaking later (within 100 s) in a high slip event (Robinson et al., 2006). In this case, the subducted feature acts as both a barrier and an asperity during a single event.

An important question is how other subducting and upper plate features influence earthquakes along South America to produce seismic heterogeneity and segmentation. This review article addresses this question by presenting a description of significant and notable events along the margin in the context of the heterogeneous margin architecture. As an overview to past large earthquake characteristics, I present a north to south review of significant earthquakes along the margin. This overview is followed by new analysis of rupture complexity in moderate magnitude events along South America as compared to subducting features as well as a review of various conditions and processes that might link together the heterogeneous structure and seismicity.

2. Significant earthquakes

Almost the entire length of the South American margin has ruptured several times in the past few centuries, as detailed in historical accounts that date back to the 1500s. Several authors have already provided rupture descriptions and historical accounts for events pre-1900s (e.g. Lomnitz, 1970; Kelleher, 1972; Beck and Nishenko, 1990; Comte and Pardo, 1991; Lomnitz, 2004). Here I review the significant earthquakes along the margin from 1850 to 2007, beginning in the north with the 1906 M 8.8 event in Ecuador and extending to the 1960 $M_w = 9.5$ Chile earthquake in the south (Fig. 1). More details about the ruptures are also provided throughout the text and figures (Figs. 2–4), most of which are derived from literature estimates based on a variety of datasets (primarily waveform inversion, aftershock patterns, and intensity reports).

Along the northern extent of this margin (3°N to 10°S), few earthquakes greater than M 8 are present in catalogs. Two areas of note are in northern Ecuador and northern Peru (Fig. 2). Along northern Ecuador and Colombia, the largest subduction zone earthquake occurred in 1906 (January 31, $M_w \sim 8.8$). This event ruptured a section of ~500 km with significant directivity to the northeast (Kanamori and McNally, 1982). The epicenter is north of the subducting Carnegie Ridge, and estimates of the rupture extent suggest most of the slip occurred away from this ridge (Kanamori and McNally, 1982). Since 1906, this segment of the margin continues to be active, although earthquakes in the 20th century were smaller magnitude and ruptured smaller areas than seen during 1906. For instance, the 1942 $M_w = 7.8$ earthquake ruptured the southern portion of the 1906 zone (Fig. 2) and the central and northern portions ruptured during earthquakes in 1958 and 1979 (Kelleher, 1972; Kanamori and McNally, 1982). This change in rupture mode, from dominantly big earthquakes to smaller magnitude events that ruptured only portions of previously ruptured areas, is not unique to Ecuador, as it is also noted in central Peru and in other subduction zones around the world such as Nankai, Southwest Japan (e.g. Ando, 1975; Cummins et al., 2002).

The northern Peru margin is also host to fairly rare events, specifically two tsunami earthquakes, that are different from the seismicity along other parts of South America. Tsunami earthquakes fall into a class of earthquakes that generate large tsunami for the size of the earthquake and typically have long rupture durations (e.g. Kanamori, 1972). The 1960/11/20 earthquake occurred in the northern Peru segment between the Carnegie Ridge to the north and the Mendaña Fracture Zone to the south (Figs. 1, 2) where few great earthquakes have occurred in the past. Pelayo and Wiens (1990) determine the rupture history and seismic moment of this event and compute an M_w of 7.6, significantly higher than the M_s value of 6.75 estimated previously. This event is also notable for the very long