

Control of seafloor roughness on earthquake rupture behavior

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ABSTRACT

Earthquake rupture complexity is described for three recent large underthrusting earthquakes along the Costa Rican subduction zone, the 1983 Osa, 1990 Nicoya Gulf, and 1999 Quepos events. These earthquakes occurred in regions characterized by distinctly different morphologic features on the subducting plate. The 1990 and 1999 events occurred along linear projections of subducting seamount chains and had fairly simple earthquake rupture histories. Both events are interpreted as failure of the basal contact of closely spaced isolated seamounts acting as asperities. In contrast, the 1983 event occurred along the subducting Cocos Ridge and had a complex rupture history. Comparison of rupture characteristics of these large underthrusting earthquakes with size and location of subducting features provides evidence that seamounts can be subducted to seismogenic depths and that variations in seafloor bathymetry of the subducting plate strongly influence the earthquake rupture process.

Keywords: earthquakes, subduction, Costa Rica, seamounts, asperities

INTRODUCTION

The Middle America Trench off the western margin of Central America is the site of Cocos plate subduction beneath the Caribbean plate at a rate of ~ 8.5 cm/yr (DeMets, 2001). The Cocos plate offshore Costa Rica can be divided into several domains based on morphologic features, as seen in detailed bathymetry data from von Huene et al. (2000) (Fig. 1). Near the Nicoya Peninsula, the oceanic crust is smooth with a 500-m-thick sediment blanket covering the plate (von Huene et al., 1995). Offshore central Costa Rica, between the Nicoya and Osa Peninsulas, the seafloor is disrupted by many seamounts. Roughly 40% of the oceanic crust offshore central Costa Rica is covered by seamounts that range in size between 1 and 2.5 km high and between 10 and 20 km wide (Ranero and von Huene, 2000). Continuing to the southeast along the Middle America Trench, the Cocos Ridge enters the trench offshore the Osa Peninsula. The ~ 200 – 300 -km-wide Cocos Ridge, an area of thickened oceanic crust, variable sediment thickness up to 1 km, and elevated seafloor (Walther et al., 2000; von Huene et al., 2000; Kolarsky et

al., 1995), is likely a trace of the Galápagos hotspot as the Cocos plate passed over the hotspot during the Miocene (Barckhausen et al., 2001).

The variety of seafloor features entering the subduction zone creates corresponding diversity in the overriding plate deformation. von Huene et al. (2000) provided descriptions of the continental slope corresponding to various topographic domains on the subducting plate. The observed small local relief opposite subduction of the smooth Cocos plate region and the highly irregular topography, such as furrows and scarps, opposite the seamount domain are consistent with features produced in sandbox models of seamount subduction in a trench system (Dominquez et al., 1998). Increased rates of forearc uplift and rotation along the Nicoya Peninsula and continental-slope uplift along the Osa Peninsula can be attributed to subduction of individual seafloor features (Gardner et al., 1992; von Huene et al., 1995; Fisher et al., 1998).

In addition, Protti et al. (1995a) correlated seismic coupling, a measure of the ability to generate large earthquakes, with characteristics of the subducted seafloor. They noted that the largest underthrusting earthquakes (magnitudes >7.5) have historically occurred only along the Nicoya Peninsula, suggesting strong seismic coupling. Intermediate-magnitude thrust events (M_s up to 7.4) occur in southeastern Costa Rica where subduction of the buoyant Cocos Ridge creates moderate plate coupling. Earthquakes with maximum magnitude of 7.0 characterize the central Costa Rica region, where isolated seamounts subduct and may reduce plate coupling. Shallow, smaller-magnitude seismicity is more common in regions of seamount subduction than in the smoother region subducting off northern Costa Rica (Fig. 1), suggesting that subduction of topographic highs localizes seismicity. As there is no evidence for sheared off seamounts along the slope region, von Huene et al. (2000) proposed that the seamounts associated with the Fisher Seamount Chain near Nicoya enter the seismogenic zone and act as asperities for large ($M_s = 6.4\text{--}7.0$) earthquakes.

Three large ($M_w \geq 6.9$) earthquakes that occurred within the past 20 yr offshore Costa Rica provide an opportunity to examine the influence of variable seafloor topography on earthquake rupture size and behavior by using high-quality seismic data. A $M_w = 6.9$ underthrusting earthquake on 20 August 1999 occurred to the northwest of the Osa Peninsula in the area of seamount and Quepos Plateau subduction (Fig. 1). We determine the rupture characteristics of this event to investigate its relationship to seamount subduction. The other events occurred in the vicinity of subduction of the Fisher Seamount Chain (1990 $M_w = 7.0$) and near the Osa Peninsula (1983 $M_w = 7.4$). Details of the rupture processes of these events determined by others are compared with details of the 1999 event and with seafloor characteristics. Comparison of the rupture histories of these three events suggests a connection between subducting-plate structure and earthquake rupture that has important implications for seismic hazard and earthquake potential along the Costa Rican margin.

1999 QUEPOS EARTHQUAKE RUPTURE PROCESS

Several techniques are used to determine the rupture history for the 1999 earthquake. Simple point-source deconvolution of P -wave data suggests an optimal depth for the earthquake of 21 ± 4 km and a very simple moment-release history with most moment released within the first 10 s of rupture. Empirical Green's function (EGF) deconvolution of surface and body waves provides approximate spatial constraints on the

rupture process (e.g., Ammon et al., 1993). We use an EGF earthquake located near the main shock with a focal mechanism and depth similar to the main shock (Table 1). Analysis of the earthquake using this technique suggests a rupture length of ~16–20 km, with minor southeast rupture at an azimuth of 120°–130° from the epicenter.

As the EGF method can only provide gross attributes of the rupture, a body-wave inversion technique is used to provide information on the full spatial extent of rupture (Kikuchi and Kanamori, 1986). A fixed focal mechanism and a trapezoidal time function are used, with timing, moment release, and location of rupture subevents determined and stripped from the observed waveforms. Several iterations of the inversion—using variable trapezoid rise times and durations, focal mechanisms, number of subevents, and grid spacing—are performed to determine the source parameters that produce synthetic seismograms that best fit the observed data. Figure 2 shows the inversion results and location of major moment release using the best inversion parameters (Table 1). The time function overall is very simple, with two significant pulses of moment release in the first 10 s. Moment was concentrated spatially with rupture likely propagating to the southeast with a direction of ~100°, consistent with the EGF analysis.

AFTERSHOCK LOCATIONS

A temporary seismic network was deployed by University of California, Santa Cruz, San Diego, OVSICORI, University of Miami, and GEOMAR shortly after the 1999 event and recorded seismicity between September and November of 1999. This network consisted of 11 ocean-bottom seismometers, positioned above many of the subsequent aftershocks, and six land stations. Locations of the largest 197 events recorded by this network are presented in Figure 2 (DeShon et al., 2001). The aftershock locations show a fairly scattered pattern, mainly updip of the area of main moment release. The total area encompassed by aftershock activity and subevent moment release is ~400 km².

SEAMOUNTS AS ASPERITIES

Detailed bathymetric surveys offshore central Costa Rica allow us to compare bathymetric feature size with rupture areas of the large earthquakes (Fig. 3). Projecting the disrupted Quepos Plateau section of subducting crust along the plate-motion vector intersects the location of the 1999 earthquake, suggesting that its occurrence represents the rupture of specific seamount contact zones with the overriding plate. This scenario would help explain the concentrated and simple nature of moment release for this earthquake. Figure 3B shows two cross sections through the Quepos Plateau area (QP1 and QP2). Several of the subducting features opposite the northwestern Osa segment have dimensions of 12–25 km along the dip direction and comparable dimensions in the strike direction (150–400 km² in area), including several high patches of the Quepos Plateau and large seamounts to the northwest of the Quepos Plateau. The aftershock region does not extend beyond the along-strike width of the Quepos Plateau, and incoming seamounts and patches of moment release are of similar size, suggesting that topographic highs in the Quepos Plateau region served as rupture asperities.

The 1990 $M_w = 7.0$ Nicoya Gulf earthquake had a slightly more complex rupture history compared to the 1999 Quepos earthquake. Protti et al. (1995b) described two large subevents of moment release between 18 and 24 km depth (Fig. 3A). The early

aftershock pattern suggests an initial rupture area of $<600 \text{ km}^2$ (Protti et al., 1995b). This earthquake occurred in the region of Fisher Seamount Chain subduction and likely represents the rupture of seamount contacts with the overriding plate (Protti et al., 1995b; Husen et al., 2002). Evidence for seamounts reaching seismogenic depths in this region comes from the measurements of forearc uplift (the uplifted tip of the peninsula forms an $\sim 400 \text{ km}^2$ area) based on radiocarbon dating of terraces and rotation in southeastern Nicoya (e.g. Gardner et al., 2001), as well as seismic tomography (Husen et al., 2002). Individual seamounts within the chain can reach $\sim 300\text{--}400 \text{ km}^2$ (von Huene et al., 2000). Rupture of more than one seamount within the seamount chain could produce the separate subevents of moment release determined for the 1990 Nicoya Gulf event; seamount size or spatial separation is possibly responsible for the small differences between it and the 1999 Quepos earthquake.

The 1983 Osa earthquake ($M_w = 7.4$) was one of the largest underthrusting earthquakes to occur in the Osa Peninsula region (Tajima and Kikuchi, 1995). Studies of the 1983 earthquake consistently show a more complicated rupture process than the 1990 and 1999 events. The 1983 earthquake had a longer source duration and possible mechanism variations along strike (Adamek et al., 1987; Tajima and Kikuchi, 1995). The complex 1983 earthquake occurred to the southeast near the highly disturbed crust containing the Cocos Ridge. Comparing moment release locations obtained by Tajima and Kikuchi (1995) with the limited regional bathymetry suggests this earthquake ruptured both of the elevated features (between CR1 and CR2) on the high area of the Cocos Ridge along with additional rupture propagation to the southeast. The high subducted relief and rock variability in the area of the 1983 rupture led to the more complicated rupture behavior of this event.

Comparisons of source durations scaled for event moment (following the procedure of Bilek and Lay [1999]) also suggest variations between the earthquakes. The normalized source durations for these events are 6.7 s (1983), 3.7 s (1990), and 3.5 s (1999), clearly distinguishing the 1983 Osa earthquake from the 1990 and 1999 events. The longer duration of the 1983 earthquake may be related to either a slower rupture velocity or a lower stress drop for this earthquake than for the 1990 or 1999 events.

DISCUSSION

Several models describing seamount subduction have been proposed to increase local coupling in regions where these features are subducted (e.g., Cloos, 1992; Scholz and Small, 1997). This study demonstrates that the size of subducted seamounts or topographic highs influences the size of maximum slip regions or asperities of large earthquakes. Seamounts can limit the size and therefore establish characteristic earthquakes for subduction zone segments. Protti et al. (1995a) segmented the margin on the basis of magnitudes of previous earthquakes and inferred seismic coupling. The 1999 earthquake is an example of the typical central segment event, whereas the more complicated 1983 earthquake is a typical Osa segment event. Earthquakes in the Quepos segment are likely related to the number and size of incoming subducting plate features, whereas the Nicoya and Osa segments undergo more frequent large earthquakes because of smooth plate subduction (Nicoya) or continued subduction of the Cocos Ridge (Osa). The difference in earthquake source duration may also be related to this variable seismic coupling. It is possible that stronger coupling in the Cocos Ridge segment plus the

interaction of continued rupture through low strength sediment trapped within the ridge basins may have led to slower rupture velocity for the 1983 earthquake.

Recent work on seamount subduction in other subduction zones suggests that seamounts can act as either asperities or barriers to earthquake rupture. Kodaira et al. (2000) combined detailed seismic refraction data in the Nankai Trough and seismic/geodetic data for the 1946 Nankaido earthquake to describe a subducted seamount acting as a rupture barrier. Abercrombie et al. (2001) suggested that a subducted seamount served as an asperity for the 1994 Java earthquake, finding most slip near a bathymetric high interpreted as a previously subducted seamount. It appears that seamounts also acted as asperities for the 1990 and 1999 Costa Rica earthquakes. The frictional behavior of seamounts is clearly influenced by heterogeneous seafloor morphology, material properties, temperature, and fluid pressure, allowing the role of seamounts to change over a seismic cycle. Further identification of subducted seamounts and determination of their roles in regional seismicity are needed to address this question.

CONCLUSIONS

Variable rupture processes have been observed for several earthquakes along the Costa Rica margin. A comparison of the rupture characteristics of these earthquakes allows us to investigate the influence of subducting-plate topography on the earthquake-rupture process. Simple rupture histories for the 1990 and 1999 earthquakes suggest the rupture of one or multiple closely spaced asperities abundant in the seamount and Quepos Plateau domain along central Costa Rica. Areas adjacent to Cocos Ridge subduction are subject to earthquakes with more complicated rupture histories, similar to the 1983 earthquake. These Costa Rican earthquakes, combined with available high-quality bathymetry data, provide additional information on the influence of subducting plate topography on large earthquake ruptures.

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FIGURE CAPTIONS

Figure 1. Map of Costa Rica and subducting Cocos plate. Bathymetry from von Huene et al. (2000) shows locations of high topographic features such as Cocos Ridge (CR), Quepos Plateau (QP), and Fisher Seamount (FS). Triangles indicate locations of land and ocean-bottom seismometers deployed following 1999 earthquake. Yellow circles show locations of shallow seismicity (<70 km) from 1973 to 2002 with M_w of >5.0 (NEIC, 2002). Stars show locations of three large earthquakes that have occurred in region since 1983. Gray ellipses denote rupture areas for these large earthquakes. Transect lines indicate locations for bathymetry profiles for Figure 3.

Figure 2. Analysis results for 1999 Quepos earthquake. A: Seismograms (black) and synthetic seismograms (red) from best inversion parameters. Station name and azimuth are listed for each record. B: Moment release history determined from body-wave deconvolution. Large circles indicate locations of major moment release during first 10 s of rupture, with some rupture propagation to southeast (from 1 to 2). Dashed ellipse encompasses rupture area. Inset shows source time function for this event. Harvard centroid-moment-tensor focal-mechanism solution is also shown. Blue circles show

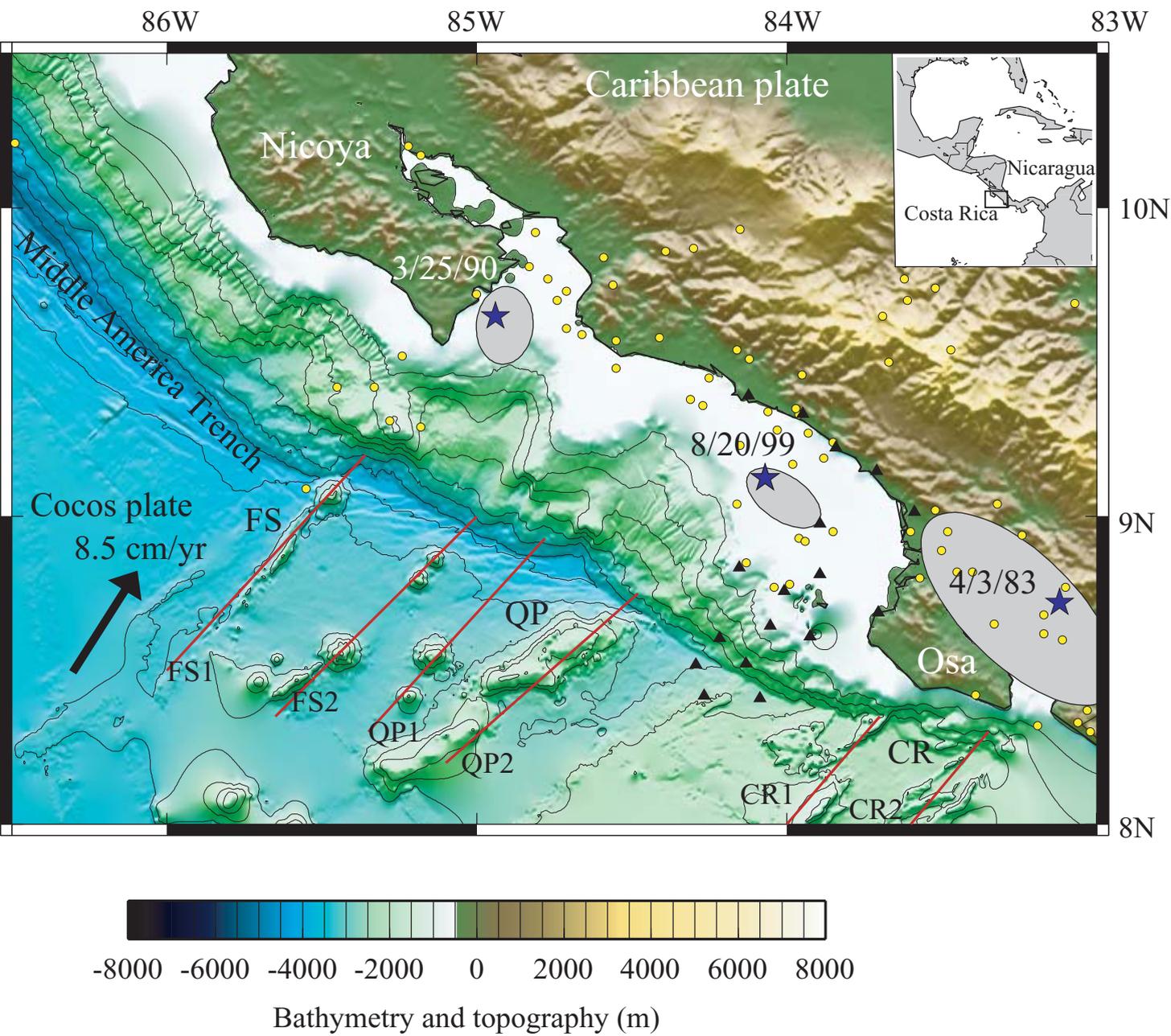
locations of 197 aftershocks (magnitude 1.6–4.3) recorded by temporary seismic network (small triangles). Maximum location errors are ~3 km. Red circles are earthquakes within one month after main earthquake (NEIC, 2002), which do not fill in the gap downdip of the main moment release.

Figure 3. Comparison of source time functions for three earthquakes along with cross sections of bathymetry of transects shown in Figure 1. A: 1990 event information from Protti et al. (1995b). B: 1999 event time function from this study. C: 1983 earthquake from Tajima and Kikuchi (1995). The 1999 Osa event is simplest; 1990 and 1983 events increase in complexity of source time function. This complexity may be related to variations in subducting plate entering Middle America Trench.

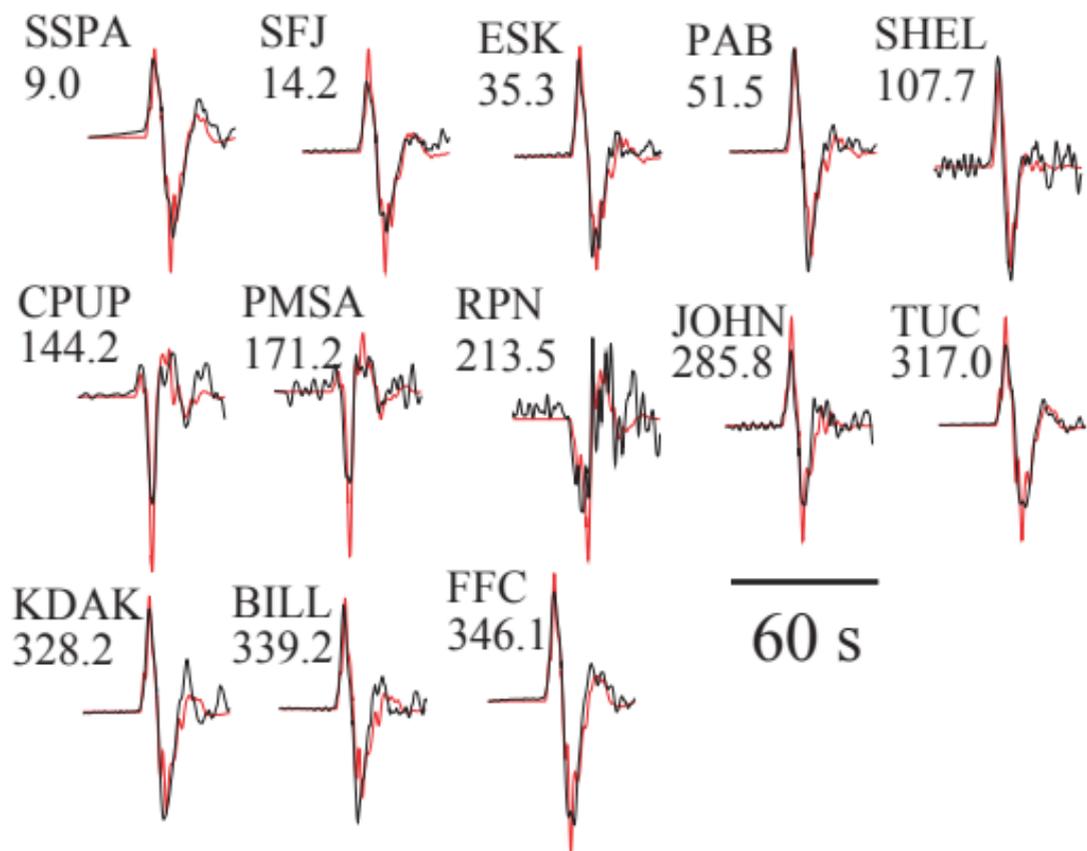
Table 1. 1999 EARTHQUAKE ANALYSIS PARAMETERS

EGF analysis						
Event	Date	Origin time	M _w	Lat	Long	Mechanism (strike, dip, rake)
Mainshock	Aug.20, 1999	10:02:31.0	6.9	9.28N	84.10W	306, 27, 102
EGF	Sept. 4, 1996	19:06:55.6	6.2	9.37N	84.36W	301, 21, 102

Body wave inversion parameters						
Mechanism	Duration (s)	No. Subevents	Grid Spacing (km)	Depth (km)	Moment (N·m)	Convergence
306, 27, 102	3	6	3	21	4.15 x 10 ¹⁹	0.2208



A



B

