Tomographic evidence for a subducted seamount beneath the Gulf of Nicoya, Costa Rica: The cause of the 1990 Mw = 7.0 Gulf of Nicoya earthquake

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[1] Tomographic images constrain the existence of a subducted seamount beneath the Gulf of Nicoya, Costa Rica. The subducted seamount is found at a depth of 30 km within the rupture area of the March 25, 1990, Mw = 7.0 Gulf of Nicoya earthquake. The Gulf of Nicoya earthquake was a typical thrust-type subduction earthquake and occurred on a shallow dipping thrust fault parallel or along the boundary between the subducting Cocos plate and the overriding plate. Precise relocation of the mainshock and its aftershocks in a 3-D P-wave velocity model shows that the area of the mainshock rupture is coincident with the imaged subducted seamount. Most of the aftershocks are relocated within or close to the inferred subducted seamount above the subducting oceanic plate. We interpret the subducted seamount as an asperity whose rupture caused the 1990 Gulf of Nicoya earthquake. *INDEX TERMS:* 1734 History of Geophysics: Seismology; 6982 Radio Science: Tomography and imaging; 7209 Seismology: Earthquake dynamics and mechanics; 7230 Seismology: Seismicity and seismotectonics

1. Introduction

[2] Along subduction zones, most of the largest earthquakes nucleate within a zone—generally called the seismogenic zone—where coupling between the subducting and overriding plates takes place. It has been speculated that subduction of seamounts has a profound impact on the coupling along the seismogenic zone either enhancing large subduction earthquakes or inhibiting them [*Kelleher and McCann*, 1976; *Cloos*, 1992; *Ruff*, 1992; *Scholz and Small*, 1997]. Subducted seamounts may act as asperities that rupture by stick slip faulting, thus generating large subduction earthquakes. The size of the seamount would determine the magnitude of the subduction earthquake [*Cloos*, 1992]. In addition, the excess mass and buoyancy of a subducted seamount will increase normal stress across the seismogenic zone, enhancing seismic coupling [*Scholz and Small*, 1997]. In the case of strong coupling along the seismogenic zone, the increased normal stress will result in an increase in magnitude and in the recurrence time of large subduction earthquakes. In the case of low coupling, the subduction of a large seamount would lead to local coupling decreasing the recurrence time of large subduction earthquakes.

[3] On March 25, 1990, a Mw = 7.0 earthquake occurred at the entrance of the Gulf of Nicoya, central Costa Rica (Figure 1). Mainshock and aftershock series were recorded by local networks and the earthquake produced considerable damage throughout central Costa Rica [*Protti et al.*, 1995]. Analysis of the source-time function revealed that the rupture process of the 1990 Gulf of Nicoya earthquake was dominated by two sources: The first was impulsive, whereas the second was emergent; suggesting that two subevents resulted from rupture of an asperity followed by rupture towards a weaker zone [*Protti et al.*, 1995]. The existence of several seamounts offshore Costa Rica [*von Huene et al.*, 1995] and the pattern of the source-time function of the mainshock suggested that the 1990 Gulf of Nicoya earthquake was caused by the rupture of a subducted seamount [*Protti et al.*, 1995]. *McIntosh et al.* [2000] imaged the Gulf of Nicoya area by a 3-D refraction and reflection experiment but clear evidence for the presence of a subducted seamount in the Gulf of Nicoya area was not found owing to high noise content in the data and lack of reflected seismic phases. Hence, evidence for the location of a subducted seamount at the site of the 1990 Gulf of Nicoya earthquake is still missing.

[4] Imaging subducted seamounts seismically within the seismogenic zone is hampered by the fact that in most subduction zones the seismogenic zone is below the offshore-onshore transition zone. A subducted seamount has been imaged in the rupture zone of 1946 Nankaido earthquake by a high-resolution seismic refraction study. However, this seamount did not cause the 1946 Nankaido earthquake but changed seismic rupture from seismo-tsunamic brittle to tsunamigenic slow slip [*Kodaira et al.*, 2000]. Our tomographic results presented in this paper confirm the existence of a subducted seamount beneath the Gulf of Nicoya. Relocated aftershocks restrict mainshock rupture of the Gulf of Nicoya earthquake to a region within or close to the inferred subducted seamount. Therefore, we infer that the subducted seamount act as an asperity whose rupture caused the 1990 Gulf of Nicoya earthquake.

2. Tomographic Study and Results

[5] The Cocos plate subducts beneath Costa Rica along the Middle America trench with a convergence rate of 9 cm/year [*De Mets et al.*, 1990]. Seismicity associated with the subduction of the Cocos plate is high in central Costa Rica and low in northern and southern Costa Rica [*Protti et al.*, 1994] (Figure 1). Two seismograph networks operated independently by the Universidad Nacional de Costa Rica (OVSICORI) and by the Red Sismologica National (RSN) have recorded seismicity in Costa Rica since 1984. Both datasets were merged [*Quintero and Kissling*, 2001], taking special care to reduce large and systematic errors in hypocenter and station locations. Out of the merged dataset we selected 3790 well-locatable earthquakes showing at least 8 P-wave observations and a GAP

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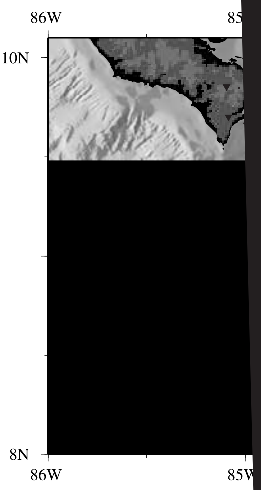

(greatest angle without [redacted] the simulps code [[redacted] extended by *Haslinger and* [redacted] to invert simultaneously for [redacted] structure. The method [redacted] velocity problem by a [redacted] iteration the velocity [redacted] relocated using the updated [redacted] inversion scheme with [redacted] initial reference model [[redacted] a coarse 3-D velocity model, [redacted] in areas of high seismicity [redacted] spacing was 10 by 10 km [redacted] 10 km in depth.

correspond to an average rupture area reflecting the size of the seamount [*Cloos*, 1992]. As it can be inferred from anomaly A in our tomographic results, the size of the subducted seamount ruptured by the mainshock would be approximately 300 km^2 or 20 km in diameter (Figure 3) assuming a circular shape of the subducted seamount. This corresponds to a thrust-type subduction earthquake with a moment magnitude of Mw = 7.4, assuming rupture of the entire seamount. A moment magnitude of Mw = 7.0 would correspond to a seamount area of approximately 145 km^2 or 14 km in diameter. However, the size of the smallest resolvable feature in our tomographic image is limited by our gridnode spacing of 10 km in both horizontal- and vertical-directions (Figure 3). Therefore, we cannot distinguish from our tomographic images a seamount of 14 km from a seamount of 20 km in diameter. The inferred seamount height of 10 km may also be exaggerated by a factor of two due to our vertical gridnode spacing and inherent vertical velocity smearing. An extensive chain of seamounts facing the trench off Nicoya Gulf and leaded by Fisher Seamount (Figure 1) show an average diameter of 20 km and an average height of two to four kilometers [*von Huene et al.*, 1995; *von Huene et al.*, 2000]. This suggests that the imaged subducted seamount could be part of the same chain.

[10] We obtained precise hypocenter locations of the mainshock of the Gulf of Nicoya earthquake and of its aftershocks occurring within the first 30 days by relocating them in our three-dimensional P-wave velocity model (Figure 3). Location accuracy of aftershocks located inside the network is ±2 km, whereas aftershocks located just outside the network are less well constrained leading to a location accuracy of ±5 km. According to the epicentral distribution of aftershocks (Figure 1), the rupture of the mainshock propagated mainly to the southeast and ended offshore Punta Judas. Focal depths of aftershocks are limited to a region above the subducted Cocos plate; most of the aftershocks occured within or close to the inferred subducted seamount (Figure 3). Seamounts are thought to subduct with the oceanic plate at the speed of subduction until they may become jammed against the base of the overlying plate [*Cloos*, 1992]. The observation that some subducted seamounts retain their normal magnetization suggests that seamounts are possibly not mechanically detached or destroyed at an early stage of subduction [*Barckhausen et al.*, 1998]. As inferred from the centroid moment tensor solution [*Dziewonski et al.*, 1991], the 1990 Gulf of Nicoya earthquake occurred on a shallow dipping thrust fault parallel to or along the plate interface (Figure 3). Relocated hypocenter locations of the aftershocks restrict the mainshock rupture to a region within or close to the inferred subducted seamount. This is consistent with our interpretation that a subducted seamount acts as an asperity whose rupture produced the mainshock.

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We believe that these two historic events, as well as the 1990 Gulf of Nicoya earthquake, were caused by rupture within the same subducted seamount beneath the Gulf of Nicoya. The fact that seamounts seem to persist through time causing frequent earthquake rupture at the same site may suggest that much of the topographic feature remains attached to the subducting slab to those depths. Little is scalped off the oceanic plate and added to the overriding plate.

[12] On August 20, 1999, a Mw = 6.9 subduction earthquake occurred offshore the city of Quepos at the southeastern end of the seamount-dominated segment (Figure 1). Gravity and magnetic data suggest the presence of a subducted seamount in this area [*Barckhausen et al.*, 1998] and the continuation of a large oceanic guyot (Quepos Plateau, Figure 1) can be observed in the continental slope and outer shelf [*von Huene et al.*, 2000]. Resolution of our tomographic results in this area is poor; however, the similarities in magnitude and focal mechanism of the Gulf of Nicoya event and the Quepos event, in addition to the above findings, suggest that the 1999 Quepos subduction earthquake was caused by a subducted seamount similar to the one beneath the Gulf of Nicoya. The 1990 Gulf of Nicoya and the 1999 Quepos event left a small area that did not ruptured during both events. The presence of subducted seamounts in this area suggests that the next possible large subduction earthquake could rupture this area.

4. Conclusions

[13] We have presented tomographic evidence for the existence of a subducted seamount beneath the Gulf of Nicoya. Precise relocation of aftershocks restrict the rupture of the Mw = 7.0, 1990 Gulf of Nicoya earthquake within or close to the inferred seamount. This is consistent with our interpretation that the inferred subducted seamount acts as an asperity whose rupture produced the Gulf of Nicoya earthquake.

[14] Our tomographic image of the subducted seamount shows striking similarities with the image of a subducted seamount in the rupture zone of the 1946 Nankaido Earthquake, Japan [*Kodaira et al.*, 2000]. This seamount is thought to have acted as a barrier changing the rupture process from seismo-tsunamic brittle rupture to tsunamic slow slip because of locally strong coupling at the subducted seamount [*Kodaira et al.*, 2000]. This process is different from what we observe, where subducted seamounts act as asperities whose ruptures causes large subduction earthquakes. In both cases, however, subduction of seamounts shows a profound impact on the coupling along the seismogenic zone with different effects depending on the original stress condition (decoupled versus coupled) of the seismogenic zone.

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