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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Received 6 September 2001; revised 14 November 2001; accepted 14 November 2001; published 26 April 2002.

[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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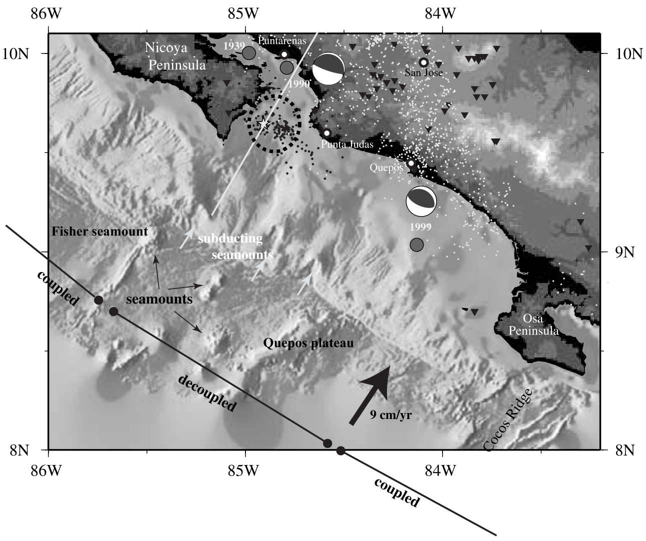

Figure 1. Bathymetry of the Cocos plate offshore Costa Rica and seismicity associated with subduction. Bathymetry was obtained by multibeam hydrosweep measurements [*von Huene et al.*, 2000]. White dots are relocated epicenter locations of a merged earthquake catalog for Costa Rica [*Quintero and Kissling*, 2001]. Earthquakes were relocated using the 3-D P-wave model obtained in this study. Only well locatable events showing at least 8 P-wave observations and a GAP (greatest angle without P-wave observation) less than 180° associated with the subduction of the Cocos plate (deeper than 30 km) are shown. Black dots are relocated aftershocks of the 1990 Gulf of Nicoya earthquake. White star denotes relocated epicenter location of the mainshock using the 3-D velocity model of this study. Large grey dots indicate NEIC locations of large (Mw > 7.0) earthquakes associated with seamount subduction. Centroid moment tensor solutions of the 1990 [*Dziewonski et al.*, 1991] and 1999 [*Dziewonski et al.*, 1999] earthquakes are shown at the corresponding epicenter location in lower hemispheric projection. Inverted, filled triangles indicate seismic stations operating in Costa Rica. Offshore central Costa Rica seafloor of the Cocos plate is 40% covered by seamounts (indicated by black arrows). Furrows in the continental slope (indicated by white arrows) are interpreted as caused by subduction of seamounts [*Ranero and von Huene*, 2000]. White line marks vertical depth section through the three-dimensional P-wave velocity model shown in Figure 3. Dashed circle marks location of subducted seamount detected by this study. Extent of the circle is based on the size of anomaly As shown in Figure 3. The absence of very large earthquakes (Mw > 7.5) and the high rate of small earthquakes define the central part of the Cocos plate off Costa Rica as seismically decoupled [*Protti et al.*, 1994]. To the northwest and to the southeast the plate interface is coupled.

(greatest angle without observation) of less than 180°. We used the simulps code [*Thurber*, 1983; *Eberhart-Phillips*, 1990], extended by *Haslinger and Kissling* [2001] for 3-D ray shooting, to invert simultaneously for hypocenter locations and 3-D velocity structure. The method solves the non-linear, coupled hypocenter-velocity problem by a linearized, iterative scheme. After each iteration the velocity model is updated and earthquakes are relocated using the updated velocity model. We used a gradual inversion scheme with increasing complexity starting with a 1-D initial reference model [*Quintero and Kissling*, 2001], inverting for a coarse 3-D velocity model, followed by a fine gridded inversion in areas of high seismicity and high station density. Final gridnode spacing was 10 by 10 km horizontally and varying between 5 and 10 km in depth.

[6] High number of stations and a high seismicity (Figure 1) suggest good resolution in the Gulf of Nicoya area. We assess solution quality by investigating resolution estimates such as hit count and the diagonal element of the resolution matrix and performing a test with synthetic data (Figure 2). Tests with synthetic data provide important information about model parameterization, resolution capability of the actual data set and damping [*Kissling et al.*, 2001]. We follow the approach of using a characteristic model [*Haslinger et al.*, 1999; *Husen et al.*, 2000] to construct a synthetic input model. A synthetic characteristic model is based on the results obtained with real data but has different sign and geometry of the observed anomaly. Synthetic travel times are computed through this model using the same station and event distribution of the real data set. Gaussian noise is added to the synthetic travel times according to the observational weight. Comparing the output model obtained by the inversion of synthetic travel times to the synthetic input model allows identification of well-resolved, i.e. well-recovered, areas. At 10 km and 30 km depth, good recovery of the shape and amplitude of the synthetic input model indicates good resolution in the Gulf of Nicoya area (Figure 2). At 20 km depth, the presence of small artifacts indicates a certain amount of vertical velocity smearing.

[7] Tomographic images in the Gulf of Nicoya area show low velocities in the Gulf of Nicoya area at 30 km depth (Anomaly A in Figure 3). Adjacent areas show higher velocities interpreted as subducted oceanic crust of the Cocos plate (Anomalies B in Figure 3). Along a vertical cross section (Figure 3b), the low velocity anomaly is overlain by an area of higher velocities. Seismic refraction studies [*Hildebrand et al.*, 1989; *Peirce and Barton*, 1991; *Weigel and Grevemeyer*, 1999] across seamounts show a region of high P-wave velocities (6–6.5 km/s) beneath seamount summits interpreted to represent a cooled central conduit or a plutonic suite. On the other hand, oceanic crust beneath seamounts shows lowered P-wave velocities (Anomaly A in Figure 3) due to crustal thickening. We interpret the higher velocities representing the seamount summit and the lower velocities representing the root of the seamount. Absolute velocities (Figure 3b) show an up bending of the 6.5 km/s contour line and a down bending of the 7.0 km/s contour line yielding an apparent thickening of the oceanic crust at the site of the seamount. *Kodaira et al.* [2000] interpreted an identical velocity pattern as a subducted seamount in the Nankai trough.

3. Discussion

[8] There are a number of geological and geophysical evidences for subduction of seamounts beneath central Costa Rica. Detailed swathmapping offshore central Costa Rica [*von Huene et al.*, 2000] provided a high-resolution Quaternary tectonic map. Several seamounts are detected on the oceanic plate in front of the Middle America Trench (Figure 1). Large furrows and rounded uplifts or domes in the lower and middle part of the continental slope (Figure 1) suggest the presence of seamounts in the early stage of subduction [*Ranero and von Huene*, 2000; *von Huene et al.*, 2000]. The presence of subducted seamounts at the head of large furrows was further supported by modeling gravity and magnetic data [*Barckhausen et al.*, 1998]. Local free-air gravity highs and small-scale magnetic anomalies may be explained as subducted seamounts of considerable size. Geological mapping of Holocene marine terraces showed that the southeastern tip of the Peninsula de Nicoya is uplifted and rotated in response to seamount subduction beneath the Gulf of Nicoya [*Gardner et al.*, 2001]. This seamount, however, is located further to the trench than the one imaged in this study.

[9] If the 1990 Gulf of Nicoya earthquake was caused by the rupture of a seamount asperity then its moment magnitude should

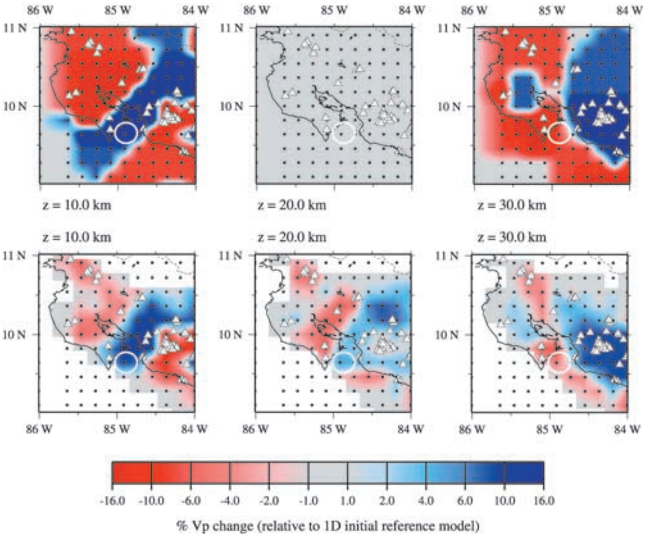

Figure 2. Solution quality of tomographic results shown in map view at different depths. Top panel shows synthetic input model; bottom panel shows recovered model at different depths, indicated below and above the map. Black and white areas are higher and lower P-wave velocities relative to the 1-D initial reference model [*Quintero and Kissling*, 2001], respectively. White triangles mark seismic stations. White and black circles mark the position of the subducted seamount. Good recovery of the shape and amplitude of the synthetic input model indicates good resolution in the Gulf of Nicoya area.

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.

[11] Increase in normal stress across the plate interface due to subduction of seamounts may give rise to two opposite effects [*Scholz and Small*, 1997]: For a seismically coupled subduction zone, the increase in normal stress will lengthen the recurrence interval and increase the magnitude of large subduction earthquakes. Conversely, in the case of a seismically decoupled subduction zone an increase in the normal stress will lead to local coupling. This may be expected to produce large subduction earthquakes that are limited in magnitude by the size of the asperity formed by the seamount. The central part of Costa Rica has been classified as a seismically decoupled area [*Protti et al.*, 1994] (Figure 1) because of the absence of very large subduction zone earthquakes (Mw > 7.5) and the relatively high rate of small earthquakes associated with subduction of the Cocos plate. The Gulf of Nicoya area is a place of high seismicity, where, in addition to the 1990 event, two large subduction earthquakes (1939 and 1882) occurred with a similar intensity pattern [*Protti et al.*, 1995].

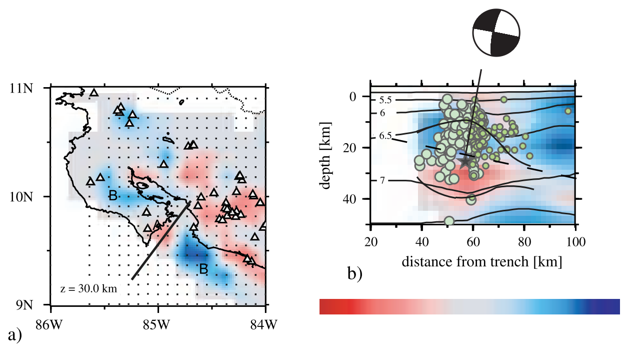

Figure 3. Tomographic results shown in horizontal plane section and vertical depth section. (a) Perturbations of P-wave velocities relative to 1-D initial reference model [*Quintero and Kissling*, 2001] shown in a horizontal plane section at 30 km depth. Perturbations are in per cent (see color scale). Filled rectangles mark positions of grid nodes used to parameterize the velocity model. Black line marks vertical depth section shown in b). (b) Perturbations of P-wave velocities shown in vertical depth section through the inferred subducted seamount. Scaling of perturbations is same as in a). Labeled contour lines mark absolute P-wave velocities in km/s. Contour interval is 0.5 km/s. Thick lines mark the extent of the proposed subducted seamount. The top of the subducted oceanic crust (dashed line) was inferred from wide-angle refraction profile [*McIntosh et al.*, 2000; *Ye et al.*, 1996]. Black star marks relocated hypocenter location of the mainshock of the Gulf of Nicoya earthquake using the 3-D velocity model of this study. Focal mechanism of the mainshock [*Dziewonski et al.*, 1991] is shown in cross-sectional view. Dark green circles mark hypocenter locations of well-located aftershocks within the network. Size of the circles corresponds to location accuracy of ±2 km. Light green circles mark hypocenter locations of aftershocks located outside the network. Size of the circles corresponds to location accuracy of ±5 km.

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.

[15] **Acknowledgments.** We wish to thank the staff of OVSICORI-UNA, RSN, INETER, UPA and CASC center for making the seismological data available. We thank S. Wiemer, C. Kopp, and C. Rowe for their valuable comments on the manuscript. Reviews of C. Ranero and an anonymous referee greatly improved the manuscript.

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