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Along-strike variability in the seismogenic zone below Nicoya Peninsula, Costa Rica

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[1] At the subduction zone in northwestern Costa Rica, the seismogenic zone lies directly beneath the Nicoya Peninsula, allowing for near source seismic studies of earthquake activity. We located 650 earthquakes along the seismogenic plate interface using a dense seismic network in the vicinity of the Nicoya Peninsula. Using these data we constrained the updip limit of the seismogenic zone there and found a transition in depth, 10 km in the south to 20 km in the north, that occurs where the subducting oceanic crust changes from warmer Cocos-Nazca Spreading center (CNS) origin to colder East Pacific Rise (EPR) origin. We argue that the temperature of the incoming oceanic crust controls the seismogenic updip limit beneath Nicoya, Costa Rica; subducting colder oceanic crust deepens the seismogenic updip limit. *INDEX TERMS:* 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 7209 Seismology: Earthquake dynamics and mechanics; 7220 Seismology: Oceanic crust; 7230 Seismology: Seismicity and seismotectonics. **Citation:** Newman, A. V., S. Y. Schwartz, V. Gonzalez, H. R. DeShon, J. M. Protti, and L. M. Dorman, Along-strike variability in the seismogenic zone below Nicoya Peninsula, Costa Rica, *Geophys. Res. Lett.*, *29*(20), 1977, doi:10.1029/2002GL015409, 2002.

1. Introduction

[2] The seismogenic zone in subduction zones can be defined as the seismically active portion of the thrust interface between subducting and overriding lithospheric plates. It is important to understand this region as it is where nearly all of the world's great earthquakes (magnitude > 8) occur [e.g., *Ruff*, 1996]. Though the seismogenic zone can pose tremendous seismic hazard, not much is known about controls on behavior and frequency of earthquakes beyond inferred fault slip and focal mechanisms from recent large earthquakes. This is because the seismogenic zones are difficult to study as they generally begin around 100 km offshore and end near the shoreline [e.g., *Ruff and Tichelaar*, 1996]. However, ophiolitic complexes form the Nicoya and Osa Peninsulas in Costa Rica, extending the shoreline very close to the trench (and in the case of Nicoya, directly over the seismogenic zone), making this locale ideal to study with land-based seismic and geodetic techniques. Through these local studies, a better understanding of the seismogenic zone geometry and areas of strong coupling can be determined, yielding valuable information for determining maximum allowable earthquake magnitudes, recurrence rates and rupture dynamics.

1.1. Controls on Seismogenic Zone Boundaries

[3] It is commonly thought that stick-slip behavior is responsible for earthquakes along the seismogenic zone and that the behavior is at least partially temperature dependent [e.g., *Scholz*, 1990]. While subducting, the plate interface heats up through conduction when the subducting plate contacts and rides beneath the hot lower crust of the overriding plate. As the interface heats, hydrous minerals transform, becoming dehydrated and changing their frictional properties from stable sliding to stick-slip, thus generating the seismogenic updip limit [*Peacock and Hyndman*, 1999; *Moore and Saffer*, 2001]. Thermal models along the Cascadia, Japan and Middle America trenches show that the updip limit of seismicity occurs around 100°–150°C [e.g., *Hyndman and Wang*, 1993; *Harris and Wang*, 2002].

[4] Two mechanisms for the downdip limit of the seismogenic zone have been proposed. If the downgoing slab intersects the mantle wedge, possibly consisting of serpentinite and other hydrous minerals, it allows stable sliding frictional behavior [e.g., *Ruff*, 1996; *Peacock and Hyndman*, 1999]. Alternatively, if the slab interface becomes hotter than 350°C, the point at which the interface is believed to transition from stick-slip to stable sliding, before reaching the mantle wedge, it could shallow the downdip limit [e.g., *Ruff and Tichelaar*, 1996; *Scholz*, 1990]. Though earthquakes occur along the interface beyond the downdip limit in either model, events can continue to as much as 100 km depth within the slab, where temperatures are substantially lower.

1.2. Nicoya-CRSEIZE

[5] The Costa Rica Seismogenic Zone Experiment (CRSEIZE) is a combined seismic and geodetic project, collaboratively run by UC Santa Cruz, UC San Diego, Observatorio Vulcanológico y Sismológico de Costa Rica and the University of Miami, to image the seismogenic zone along two segments of the plate interface at the Middle America Trench (MAT). To accomplish this, we established two seismic networks transecting the trench. The first network was a 3-month (Sept. through Nov., 1999), 20 station, on-shore and offshore deployment near the north shore of the OSA peninsula, and encompassing the aftershocks from the August 20, 1999 $M_W = 6.9$ underthrust earthquake. The second network was designed to transect the seismogenic zone, allowing for increased detection of local earthquakes across the plate

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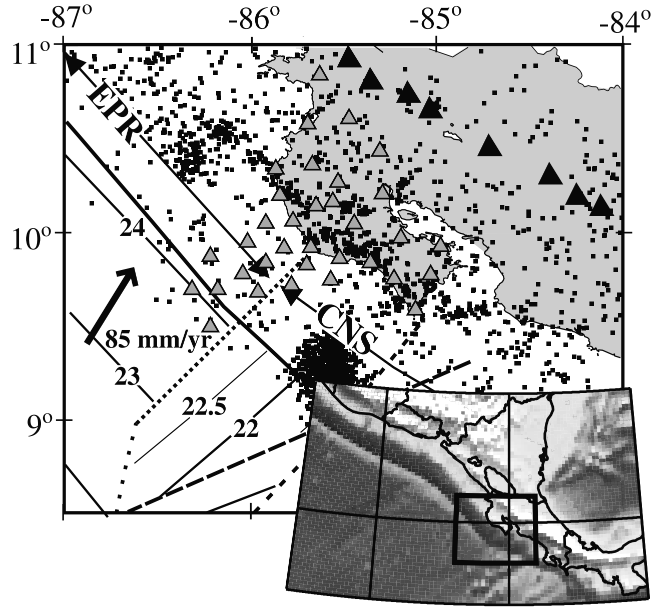

Figure 1. Shown are Nicoya-CRSEIZE earthquakes (black dots), active volcanoes (black triangles), the Nicoya-CRSEIZE seismic deployment (grey triangles), isochrons, denoting ages across the Cocos plate [*Barckhausen et al.*, 2001], and an arrow, denoting relative velocity of Cocos-Caribbean plate shortening [*DeMets*, 2001]. Inset shows location of the Nicoya Peninsula to Central America and the MAT.

interface. Seismometers were deployed from the Cocos Plate just seaward of the MAT to mainland Costa Rica, crossing the Nicoya Peninsula (Figure 1). The land network consisted of 20 broadband short-period instruments and ran from December 1999 to June 2001. The ocean-bottom seismometer (OBS) network operated from December 1999 to June 2000. CRSEIZE also consisted of GPS campaigns across Costa Rica. Here we report results from the Nicoya segment of the seismic portion of the CRSEIZE experiment.

2. Event Detection and Relocation

[6] We use the Antelope Software package [*www.brtt.com*] to organize seismic waveforms, perform automated and analyst event detections, generate initial locations, and compute local magnitudes (M_L). Arrival triggers based on short-term:long-term amplitude ratios at each station are subsequently correlated with a minimum of 5 stations to produce event detections. Because of high background noise levels, it was necessary to inspect waveforms for the entire time series and identify *P* and *S* phases missed or inaccurately picked by the automated technique. Preliminary earthquake locations are obtained using travel-time minimization in the generalized one-dimensional velocity model, IASPEI91. Most events beneath Nicoya are between M_L 1.7–2.1.

[7] Because it is important to obtain accurate earthquake locations across the seismogenic plate interface, we relocate events using *Protti et al.*'s [1996] three-dimensional P-wave velocity model (PROTTI96), derived using travel-time tomography between local earthquakes and a Costa Rican national network. To relocate events within PROTTI96, we use the program SIMULPS [*Evans et al.*, 1994], holding the velocity model fixed and keeping $V_p/V_s = 1.75$. This is done because few crustal events have been analyzed, thus we are unable to determine a robust independent velocity structure. Using SIMULPS, we relocate 2644 of the original 3100 earthquakes determined using $\sim$30% of the data from several time periods between 1999 and 2001. Of these 2644 earthquakes, 650 locate beneath the Nicoya Peninsula. Another 1050 are aftershocks of the July 21, 2000 $M_W = 6.4$ outerrise earthquake that occurred after the retrieval of OBS stations and southwest of our land network. Most of the remaining events occur offshore Nicaragua.

[8] For the 650 events beneath Nicoya and nearest the seismogenic zone location errors are small with a median horizontal error $\sigma_h = 0.3$ km and vertical error $\sigma_z = 0.4$ km. We checked the robustness of the SIMULPS solutions beneath the peninsula by comparing results with those from HypoDD [*Waldhauser and Ellsworth*, 2000]. HypoDD calculates locations by minimizing the difference in travel-time residuals between neighboring events, thus it is not affected by error due to inaccuracies in the velocity model between earthquake clusters and stations. Using the singular value decomposition method of minimizing residuals within HypoDD we obtain lower location errors (median $\sigma_h = 0.1$ km and $\sigma_z = 0.2$ km) than with SIMULPS, however this method has little constraint on the absolute location of events. We compared normalized event locations from both SIMULPS and HypoDD by removing the mean location of all comparable events and determining the average offset between same events. We find relatively small offsets ($\delta h = 0.8$ km, $\delta z = 1.4$ km). There still exists, possible systematic errors from analyst phase detections and unmodeled S-wave velocity structure. These errors are not likely to change earthquake locations within the network by more than 2 kms, and general large scale features will persist.

3. Geometry of Interplate Seismicity

3.1. Updip Limit

[9] Figure 2 shows the 2644 earthquakes located within the PROTTI96 velocity model. Of these, 544 low-error events ($\sigma_{h,z} < 0.5$ km), are shown in black and form a sub-linear cluster paralleling the Nicoya shoreline. It is possible that the time period examined here is not representative of activity over the entire seismic cycle, however, it is an assumption of this paper that these earthquakes represent the seismogenic zone beneath the Nicoya peninsula. This is supported by the geometry of these events forming a dipping plane where the seismogenic plate interface is expected (A-D in Figure 2). In the northern part of the peninsula (slice A), seismogenic zone earthquakes begin near 20 km depth and deepen eastward to about 30 km depth. More diffuse, probably intraslab, seismicity continues along the same deepening path from about 36 km to 60 km depth. However, projections southward (slices B-D) show the seismogenic updip limit shallowing to about 10–13 km depth with a few earthquakes as shallow as 8 km. To better illustrate the variation in the updip limit, Figure 3 shows a projection (slice E) of low-error seismicity along-strike. Note that the southward shallowing of the updip limit occurs at the elbow of the Nicoya shoreline, which corresponds to the

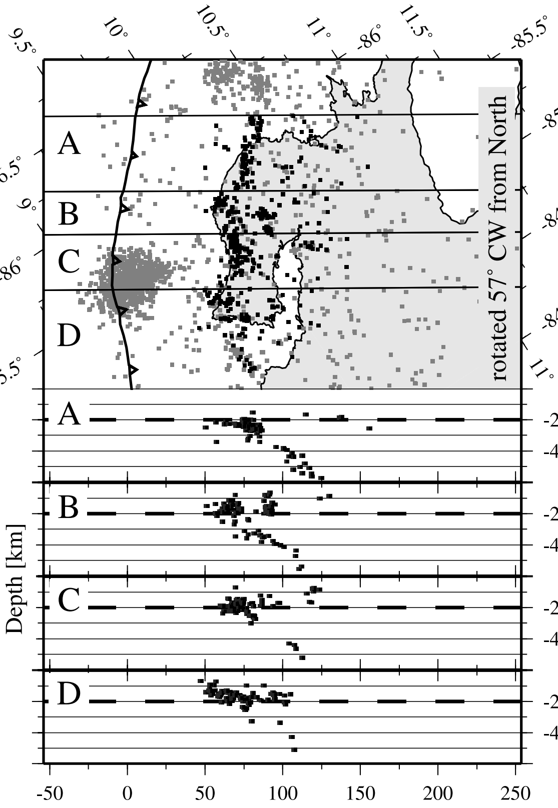

Figure 2. Nicoya Peninsula [top] showing the MAT. Earthquake cluster in lower left corner is aftershock of an M_w = 6.4 outerrise event and do not represent seismogenic zone activity. Black cubes represent 544 low-error events which are also shown in slices A-D projected in cross-section [bottom].

transition between subduction of EPR crust in the north to CNS crust in the south (Figure 1).

3.2. Downdip Limit

[10] The downdip extent of seismicity is not clear, however, low-error seismicity projected in Figure 2, sections A, C and D, terminates at about 30 km depth before continuing deeper. This downdip limit of the seismogenic zone is consistent with the intersection of the subducting crust with the mantle wedge as imaged by seismic profiling along the northern Nicoya Peninsula [*Sallares et al.*, 2001].

[11] Our value of ~30 km depth for the downdip limit is much shallower than the 60 km depth corresponding to the intersection of the 350°C isotherm and plate interface in *Harris and Wang* [2002], however, they argue that this portion of their thermal model is poorly constrained due to a lack of continental heat flow data. This lends support to a downdip limit of the seismogenic zone controlled by contact with a hydrated mantle wedge. It is likely that the seismicity deeper than ~40 km (shown in the slices of Figure 2) occur within the the subducting slab thus giving a false sense of slab bending.

4. Discussion

[12] Figure 4 shows locations for earthquakes less than and greater than 20 km depth beneath the Nicoya Peninsula and their correlation with the change of subducting oceanic crust origin from CNS to EPR as described by *Barckhausen et al.*, [2001]. Here, earthquakes shallower than 20 km depth (light circles) occur almost exclusively in the southern portion of the Nicoya Peninsula and the onset of these shallow events is coincident with a change in the origin of the subducted crust. Though both these crusts are of similar age at the trench (CNS slightly younger), and both have relatively smooth topography west of Nicoya, there still appear to be some differences between the two that control the depth at which interplate earthquakes can nucleate.

[13] It is commonly thought that stick-slip behavior, responsible for earthquakes along the seismogenic zone, is at least partially temperature dependent [e.g., *Scholz*, 1990]. This may be the case along the seismogenic updip limit where the onset of seismicity may be controlled by temperature dependent phase transitions from hydrous to dehydrated minerals and the transition from stable sliding to stick-slip frictional behavior [e.g., *Hyndman and Wang*, 1993; *Peacock and Hyndman*, 1999; *Moore and Saffer*, 2001].

[14] Heat flow measurements of the EPR crust, just seaward of the MAT at Nicoya indicate that the upper crust here is colder, generally 10–40 mW/m^2 [*Vacquier et al.*, 1967; *Langseth and Silver*, 1996; *Fisher et al.*, 2001], than the ~100 mW/m^2 expected for 20–25 Ma oceanic crust [*Stein and Stein*, 1992]. *Fisher et al.* [2001] argue that hydrothermal circulation across the EPR crust near Nicoya is likely responsible for crust that is about 70% cooler than expected. Heat flow is highly scattered but averages 110–120 mW/m^2 on CNS generated crust near the trench offshore

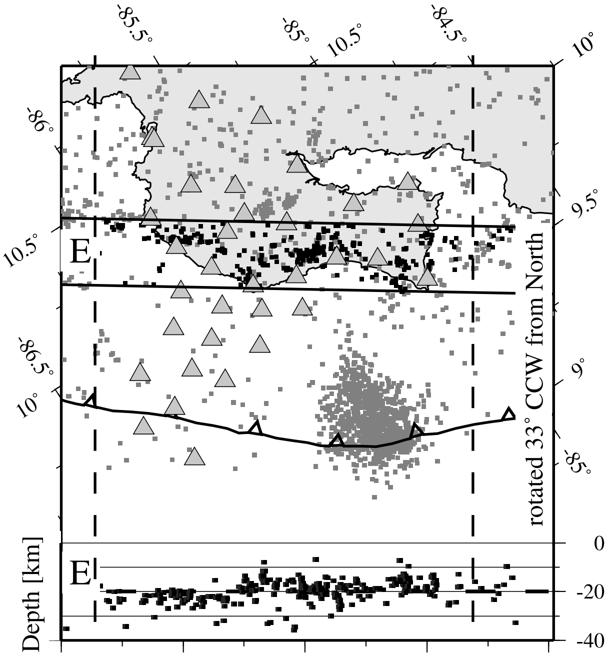

Figure 3. [top] Earthquakes within slice E correspond to the shallow events in Nicoya's seismogenic zone. [bottom] Of these, the low-error earthquakes are projected in cross-section. Note change in depth of updip seismicity near the bend in Nicoya shoreline. Earthquakes outside the vertical dashed lines are outside the network.

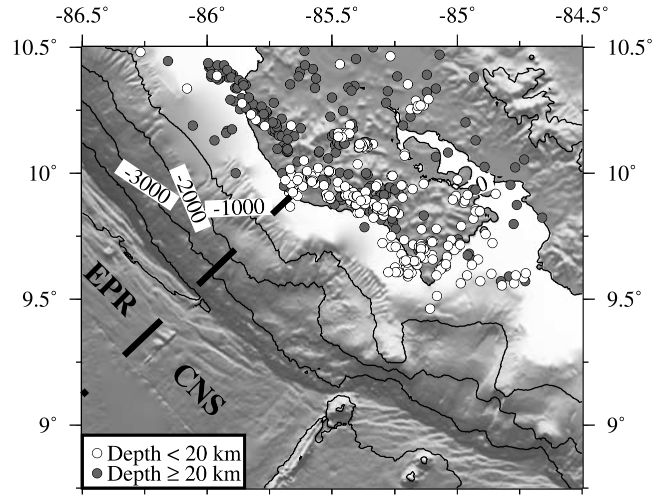

Figure 4. Earthquakes shown atop high resolution bathymetry and topography around the Nicoya Peninsula [*Ranero and von Huene*, 2000]. Circles are low-error earthquakes occuring above (white) and below (grey) 20 km depth. Seismogenic zone earthquakes shallower than 20 km are predominantly in the south, starting at the EPR to CNS transition (dashed line).

the southern Nicoya Peninsula [*Vacquier et al.*, 1967; *Fisher et al.*, 2001]. Thus, EPR crust beneath Northern Nicoya is likely colder than CNS crust beneath southern Nicoya. *Harris and Wang* [2002] model Cocos plate subduction beneath Nicoya and find that different assumptions about the depth of hydrothermal circulation can predict significant temperature variations along the subduction interface, thus changing the depth of intersection of the 100°C isotherm with the plate interface. Increasing the depth of hydrothermal circulation from 0 to 2 km depth, which is supported by local heat flow measurements, can push the 100°C isotherm interface, and potentially the updip limit of the seismogenic zone, from 10 down to 20 km depth.

[15] In conclusion, we find that changing subducting oceanic crust origin from warmer CNS in the southern half to colder EPR in the northern half of the Nicoya peninsula changes the seismogenic updip limit from 10 km in the south to 20 km in the north. Though these crusts are of similar ages, they were formed at different ridges and enter the trench in different thermal states, with EPR crust being considerably colder. If the updip limit of the seismogenic zone is controlled by temperature at the interface, then the extensive hydrothermal circulation seen on the EPR crust has been occuring for at least the past 500 ka — the time it would take to subduct crust from the trench to 20 km depth along the Nicoya Peninsula.

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