Chapter 1

Introduction

Historically, highly destructive large magnitude ($M_w$>7.0) underthrusting earthquakes nucleate along the shallow segment of subduction zone megathrust fault, and this region of the plate interface capable of stick-slip behavior is termed the seismogenic zone. Seismogenic zone earthquakes generate at least 80% of the total worldwide seismic moment release [e.g., Pacheco and Sykes, 1992] and pose significant seismic hazard, especially to low-lying coastal areas susceptible to additional damage from an associated tsunami. Globally, the updip and downdip limits of rupture within seismogenic zones vary significantly, suggesting that a complex interaction of processes controls the generation of shallow underthrusting seismicity. The updip limit, marked by the transition from stable or aseismic slip to stick-slip behavior, may occur between the trench axis and 15 km depth below sea level, while the downdip transition to stable sliding occurs between 10 km to >40 km depth [Zhang and Schwartz, 1992; Pacheco et al., 1993; Tichelaar and Ruff, 1993]. Seismogenic limits at subduction margins have primarily been identified through poorly constrained offshore seismicity recorded locally by land-based stations, through regional and teleseismic earthquake location studies, and by identifying characteristic rupture geometries of large and great earthquakes. Such studies provide few constraints for differentiating between the thermal, mechanical, hydrological, and compositional interactions potentially responsible for controlling seismogenic zone activity.

Local-scale earthquake location studies of small magnitude earthquakes provide high-resolution images of individual seismogenic zones and lend insight into subduction processes [e.g., Nishizawa et al., 1990; Hino et al., 1996; Eberhart-Phillips and Reyners, 1999; Husen et al., 1999, 2000, 2002; Shinozawa et al., 1999; Obana et al., 2003]. Microseismicity or aftershock studies using data collected on high-density, local arrays provide high spatial resolution of small magnitude earthquakes with improved depth estimates that can define the geometry and volume of seismogenic zones. The question remains, however, does the updip and downdip extent of interseismic earthquakes and/or aftershock seismicity reflect seismogenic zone ‘limits,’ or the potential rupture area of high magnitude earthquakes. We seek a clearer understanding of the spatial and temporal variability in seismogenic zone processes, the location, magnitude, and mechanisms of seismicity along the subduction thrust, and the degree and spatial variability in plate coupling over the seismic cycle. These constraints can be used in conjunction with other geophysical and geochemical data to better understand subduction zone processes.

The Costa Rica-Nicaragua segment of the Middle America subduction system is a focus site of the NSF MARGINS and International Seismogenic Zone Experiment (SEIZE). Offshore western Costa Rica-Nicaragua oceanic Cocos Plate subducts beneath continental Caribbean Plate at the Middle America Trench. The margin exhibits significant along-strike variability in seafloor morphology, plate geometry, and temporal characteristics of seismicity across a short (<400km) segment of trench, and it has been proposed as a region of active subduction erosion. Two peninsulas, the Osa and Nicoya,
overlie the seismogenic zone offshore Costa Rica, making the margin particularly well suited for combined land and ocean geophysical studies (Figure 1.1). Earthquake locations within the Costa Rica-Nicaragua seismogenic zone are poorly constrained, especially in depth, by regional onshore short-period networks, and studies of Wadati-Benioff seismicity generally show a cloud-like pattern of earthquakes around the shallow plate interface [e.g., Protti et al., 1994; Protti et al., 1995a; Quintero and Kissling, 2001; Husen et al., 2003]. In an effort to increase the quality of seismic and geodetic data in the region and provide improved understanding of seismogenic zone processes, the University of California-Santa Cruz, the Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI-UNA), Scripps Institution of Oceanography (SIO), the University of Miami, and Forschungszentrum für Marine Geowissenschaften (GEOMAR) undertook a series of seismic, geodetic, and fluid flux experiments along the Middle America Trench from 1999-2001 (Figure 1.1). Termed the Costa Rica Seismogenic Zone Experiment (CRSEIZE), the passive seismic arrays included deployment of land and ocean bottom seismometers (OBS) across central Costa Rica and the Osa Peninsula and across the northern Nicoya Peninsula between September 1999 and June 2001 (hereafter the Osa and Nicoya experiments). Oceanic fluid flux meters were collocated with the OBS to record flow rates into and out of oceanic sediments for comparison with local and regional seismicity.

This thesis investigates seismogenic zone structure along the southern segment of the Middle American subduction zone offshore Costa Rica utilizing CRSEIZE seismic data. Chapter 2 provides an overview on seismogenic zone studies to date and outlines the major geologic and tectonic features of the margin offshore Costa Rica. In order to understand seismogenesis along the subduction thrust it is necessary to define incoming plate characteristics reaching seismogenic depths (i.e., bathymetry, sediment composition, and thermal history), constrain mechanical processes occurring prior to seismogenesis, and characterize the chemistry of materials transported through the subduction system and output along volcanic arc. Chapter 2 includes an overview of recent studies aimed at understanding these questions along the Costa Rica margin and a discussion of historic seismicity and current seismic hazards. The chapter places CRSEIZE within the broader framework of seismogenic zone studies, and it provides descriptions of the Osa and Nicoya experiments and details initial data processing within the Antelope Datascope software package.

Chapter 3 focuses on initial one-dimensional velocity characterization of the Osa and Nicoya regions through simultaneous inversion of $P$- and $S$-wave arrival time data for earthquake location and origin time, $P$- and $S$-wave velocity ($V_P$ and $V_S$), and station corrections. One-dimensional (1D) inversions provide information on data quality and data inversion stability, and the study provides velocity models for use in relative relocation calculations and as initial conditions for three-dimensional (3D) local earthquake tomography. Results provide first-order characterization of lateral variability in updip and downdip limits of seismicity along the Middle America seismogenic zone. The Nicoya 1D velocity models are additionally compared to velocity models resulting from receiver function analysis at Global Seismic Network station JTS to better constrain the depth to and velocity contrast across the continental Moho; results confirm the
observations by Sallarès et al. [2001] that the forearc mantle wedge in northern Costa Rica is serpentinized.

Chapters 4 and 5 focus on high-resolution earthquake location studies of the Osa and Nicoya experiments respectively. Chapter 4 presents aftershock relocations of the 1999 Quepos underthrusting earthquake recorded by the Osa experiment. I relocate these earthquakes using a combined grid-search algorithm and finite-difference travel time calculator using an a priori 3D $V_p$ model developed from $P$-wave refraction data and compare absolute locations to relative earthquake relocations utilizing the Osa Peninsula 1D velocity models. Results emphasize that incoming plate bathymetry plays a key role in controlling both the location of large magnitude earthquakes in central Costa Rica and in controlling fine-scale features in aftershock rupture patterns.

Chapter 5 presents a three-dimensional local earthquake tomography study for the Nicoya Peninsula segment of the Middle America subduction zone. $P$-wave arrival time and $S$-$P$ travel time data are used to simultaneously invert for earthquake location and origin time, $V_p$ and $V_p/V_S$, and station corrections. The high quality and spatial variability of the dataset allow resolution along the updip and downdip edges of the locked plate interface. Results confirm that the updip limit of seismicity along the Nicoya Peninsula varies in depth from south to north by ~5 km, spatially correlating to variability in thermal structure on the downgoing Cocos Plate [Newman et al., 2002], and confirm the location of a hydrated, possibly serpentinized, forearc mantle wedge at >30-35 km depth [Sallarès et al., 2001]. The downdip edge of plate interface seismicity occurs updip of the Cocos Plate/continental Moho intersection and to onset of the brittle/ductile transition between 300-350ºC. Microseismicity does not illuminate the along-dip width of the seismogenic zone beneath the Nicoya Peninsula, and correlations of relocated seismicity with geodetic modeling suggests the onset of seismicity occurs ~20 km landward of maximum locking across the plate interface.

Chapter 6 describes comparisons between seismic noise and variable fluid flux rates along the Nicoya forearc as recorded by the OBS and collocated fluid flux meters. Using tools developed to measure volcanic tremor, the chapter explores the effects of fluid movement within underlying oceanic sediments on seismic signal and correlates changes in fluid flux rates to local and regional seismicity. Along the Nicoya Peninsula, fluid flow rate excursions lasting ~14 days recorded above the frontal prism positively correlate with the level of seismic noise recorded by the collocated OBS, suggesting rapid and episodic fluid flow, but the flow events do not correlate with local, regional, or teleseismic earthquakes.

Combined, the studies presented here provide fine-scale constraints on microseismicity along the Costa Rican margin and insight into spatial and temporal variability in seismogenic zone activity along an erosive and seismically active segment of the Middle America Trench. Along the Nicoya seismic gap, small magnitude earthquakes do not occur across the along-dip width of the seismogenic zone during the interseismic period just as aftershocks of the 1999 Quepos underthrusting earthquake may not rupture the along-dip extent of the seismogenic zone in south-central Costa Rica. Local variations in frictional stability due to dehydration and fluid migration along the plate interface over the course of the seismic cycle lead to small-scale heterogeneity in
seismogenesis. Within the Middle America subduction zone offshore Costa Rica, these processes lead to correlations between the location of interplate seismicity and the degree of geodetic locking along the plate interface to variability in incoming plate bathymetry, mechanical strength of the upper plate, temperature along the subduction thrust, and the hydration state of the forearc mantle.
Figure 1.1 The Costa Rica Seismogenic Zone Experiment. Seismic experiments consisted of two passive on/offshore seismic arrays that recorded small magnitude earthquakes along the Middle America Trench. The southern Osa experiment primarily recorded aftershocks of the $M_w$ 6.9 8/20/99 Quepos earthquake (yellow star; Harvard CMT mechanism). The northern Nicoya experiment recorded background microseismicity within the Middle America Trench and both the main shock and aftershock series of the $M_w$ 6.4 7/21/00 outer rise earthquake (yellow star; Harvard CMT mechanism). Broadband stations: boxes; Short-period stations: triangles. Open shapes indicate stations that did not successfully record data. Fluid flux meters were collocated on all OBS. GPS campaign sites: blue diamonds. Red circles: initial earthquake locations using the global IASP91 $P$- and $S$-wave velocity models.