The Seismogenic Zone Experiment

BY MASATAKA KINOSHITA, GREGORY MOORE, ROLAND VON HUENE, HAROLD TOBIN, AND CESAR R. RANERO

Most of the world's great earthquakes are inter-plate underthrusting events in the subduction zones of convergent margins. As the December 2004 Sumatra earthquake and Indian Ocean tsunami demonstrated, subduction-zone earthquakes represent one of the greatest natural hazards on the planet. Large destructive earthquakes that occur on land release cumulatively far less seismic energy than subduction-zone earthquakes. Although plate tectonics provides the underlying kinematic explanation for subduction-zone earthquakes, only a narrow portion of the plate-contact zone actually generates them—the so-called *seismogenic zone* (Figure 1). Increased awareness of the destructive power of subduction-zone earthquakes has resulted in a rapidly growing research effort to learn about the mechanics and dynamics of faulting processes that integrate rock mechanics, seismology, geodesy, frictional physics, and fluid-fault interactions. To a first approximation, we understand that, because subduction-zone earthquakes are capable of rupturing large areas, they release the great majority of Earth's seismic energy. We do not, however, understand the factors that occasionally lead some earthquakes to rupture extremely large areas, resulting in truly great ($M > 9$) subduction-zone events, while others rupture much smaller areas, producing events of $M < 7.5$. Furthermore, we do not know the relative roles of fault area, seismic coupling, seismic versus aseismic slip, asperities (areas of the two plates that are locked together), type and thickness of subducted sediments, and fluid flow.

Despite recent advances, no unified theory of fault slip accounts for earthquake nucleation and propagation, or mechanisms of strain release across the spectrum of observed deformation rates, which range from seconds to years. Consequently, the question of whether precursory signals exist for major earthquakes, even in theory, remains under discussion. Progress on these topics is severely limited by a lack of information on ambient conditions and mechanical properties of active faults at depth. Scientific ocean drilling, with the potential to sample the deep parts of subduction zones, has thus far only probed the very beginning stages of material transformation that affect the seismogenic zone. Thus, expectations are high for future discoveries with the deep riser drilling that is planned over the next several years. Here, we first outline the framework of seismogenic zone studies,

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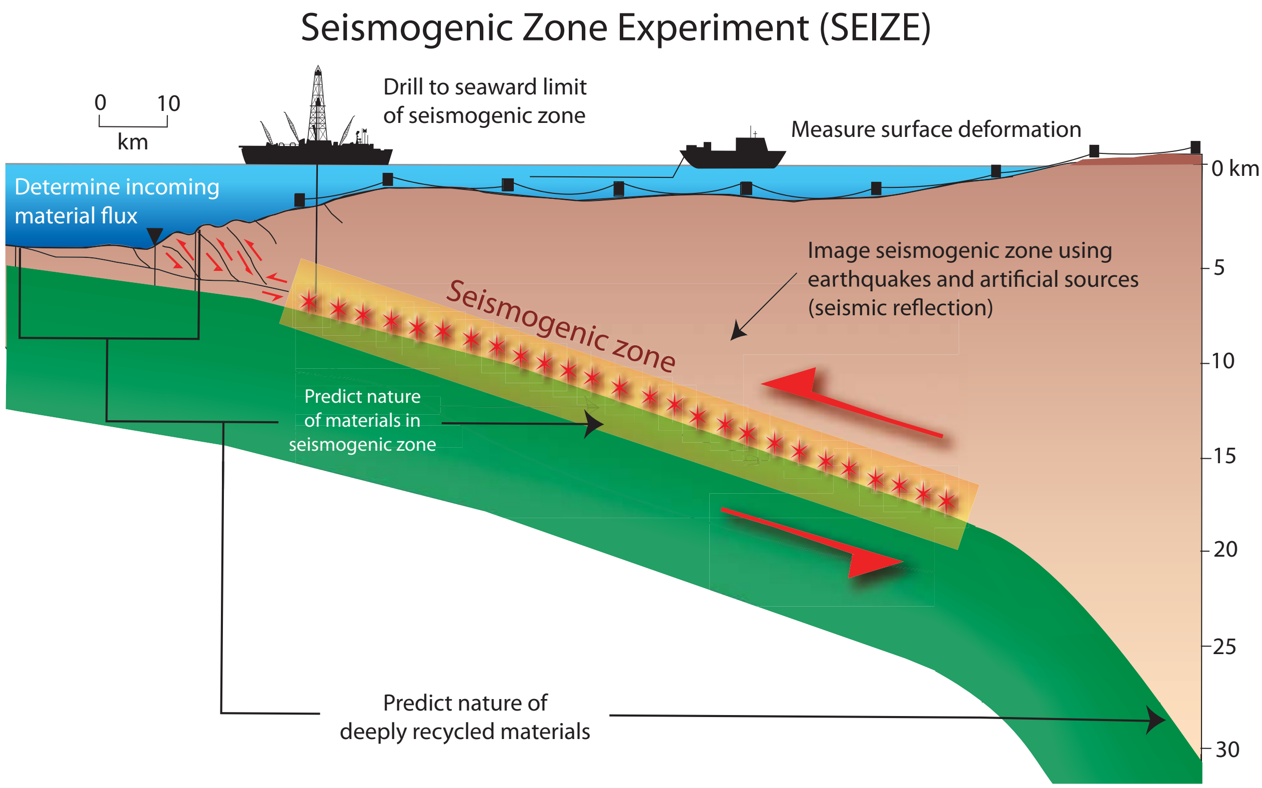


Figure 1. Goals of the Seismogenic Zone Experiment (SEIZE) are show in this figure. Although plate tectonics provides the underlying kinematic explanation for subduction-zone earthquakes, only a narrow portion of the plate-contact zone actually generates them. It is called the seismogenic zone. Both earthquakes and seismic reflection techniques can image the seismogenic zone; however, drilling into the seismogenic zone will be essential to answer critical questions about the materials and conditions that control the onset of earthquakes. Source: MARGINS, 2004.

then discuss the significant outcomes of Ocean Drilling Program (ODP) drilling along two transects, one in Japan and one in Central America, and then present the rationale and plans for future seismogenic zone drilling during the Integrated Ocean Drilling Program (IODP).

THE EXPERIMENT

Investigating the seismogenic zone of convergent margins provides both fundamental scientific challenges and is of great societal relevance. Accordingly, several scientific projects to investigate the mechanics of earthquake initiation on land and at sea have been implemented during the past 20 years. A broad international initiative, the Seismogenic Zone Experiment (SEIZE), has focused multidisciplinary investigations on great subduction zone earthquake processes (MARGINS, 2004). The ultimate goal of SEIZE is to understand the factors leading to the largest and most-destructive earthquakes. To do this, SEIZE must determine what controls (1) the maximum size of earthquakes; (2) the up-dip and down-dip limits of rupture during great subduction-thrust earthquakes; (3) the overall distribution of seismic energy release during a subduction earthquake; and (4) the propagation and slip rates of earthquakes and the distribution of fast, slow, tsunamigenic, and silent earthquakes in time and space.

The need for SEIZE to focus resources on one or two localities lead to the development of site-selection criteria: (1) the region must include historic large thrust earthquakes; (2) the subduction thrust must be imageable by seismic reflection techniques over much of the seismogenic zone; (3) the subduction thrust must be at drillable depth, not only near its seaward terminus but also into the seismogenic zone; and (4) the availability of data from previous geological and geophysical surveys and ODP drilling. In addition, proximity to ports, logistical support, and favorable weather conditions are desirable aspects of candidate sites.

Based on these criteria, two sites achieved community consensus, the Nankai Trough off southern Japan and the Middle America Trench off Costa Rica. Both regions have experienced a long history of damaging earthquakes and tsunamis, have an excellent volume of existing seismic reflection and drilling data, and are near major ports that make them easily accessible for study. In addition, the Nankai seismogenic zone contrasts well with the Costa Rica margin because Nankai is accreting thick terrigenous sediments, whereas the trench along Costa Rica has thin sediments and is non-accretionary. The subduction rate at Costa Rica is high, whereas Nankai converges at a slow to moderate rate. These two margins typify convergent margin end-members, so it is hoped that drilling both of them will eventually lead to a comprehensive understanding of seismogenic zone processes.

SEIZE—AN OCEAN DRILLING PERSPECTIVE

A shallowly dipping subduction zone provides a fault zone that is accessible to study by a combination of drilling, and seismological and geodetic monitoring. Where trenches contain abundant sediment, the input to the subduction zone is accessible much like access at the beginning of a conveyor belt. Once subducted, the sediment undergoes compaction, lithification, and dehydration reactions during transport to the seismogenic zone. Therefore, the processes that control the partitioning of strain, the flow of fluids, the formation and behavior of faults, and the onset of seismic slip can be forward modeled. At convergent margins with little trench sediment input, subducting materials include rock derived from the base of the upper plate. These rock bodies have not been sampled along an operating margin so material transformations and dynamics are mostly inferential. Although many convergent margins were drilled during the Deep Sea Drilling Project (DSDP) and ODP, the target depths were limited to features shallower than the subduction channel because of non-riser drilling capability. (A riser is a metal tube [pipe] that surrounds the drillstring and allows drilling fluid, such as mud, to circulate in the drillhole. In addition to keeping the hole clean, the riser helps to maintain pressure on the drilled section to keep it from collapsing back into the hole, which is a problem when drilling holes deep into sediment and crust. IODP's new drillship, *Chikyu*, will have a riser.) This section summarizes DSDP and ODP drilling achievements at the Nankai Trough and Costa Rica margin, respectively, using the non-riser drillships, *Glomar Challenger* and *JOIDES Resolution*.

Nankai Trough

One of the key components of SEIZE is to characterize the inputs to the seismogenic zone and to understand their function through the subduction process. DSDP drilled two legs (31 and 87) and ODP drilled three legs (131, 190, and 196) in the Nankai Trough, where the Philippine Sea plate (PSP) is subducting beneath the Japanese islands (Moore et al., 2005). The drillholes provided essential information on the stratigraphy and physical properties of the strata deposited in the Shikoku Basin (SB; northern part of the PSP; Figure 2) and initial accretionary processes.

As the dominantly hemipelagic strata are carried into the Nankai Trough, they are covered by a thick sequence of coarse terrigenous trench sediments, causing rapid consolidation of the SB strata. A décollement zone (a zone where the upper sediments become detached from the substratum) develops within the SB section. The upper SB section, along with the overlying trench sediments are stripped off the PSP and added to the overriding plate, forming a wide accretionary prism. The lower SB strata are carried beneath the prism where they continue to consolidate and dewater. Although the décollement zone would serve as a permeable channel along the subducting plate boundary, it also forms a seal to the vertical transport of fluid, yielding a zone of overpressure at the top of the subducting section that reduces fault friction.

The accreted strata form a classic fold and thrust belt at the toe of the prism. Approximately 75-km landward of the frontal thrust, a zone of out-of-sequence thrust (OOST) or splay faults cuts the prism. At this point, the décollement steps down to the top of the oceanic crust and the underthrusting SB strata are added to the base of the prism (underplated). This point approximately coincides with the updip (seaward) limit of the seismogenic zone. Evidence of fluid migration up the OOSTs, such as chemosynthetic clam colonies, has been found where the faults come to the surface (Ashi et al., 2002), but two attempts to drill holes into the faults along the Muroto Transect (Figure 2) during Leg 190 were unsuccessful due to the existence of thick, poorly consolidated, coarse sands (Moore et al., 2005).

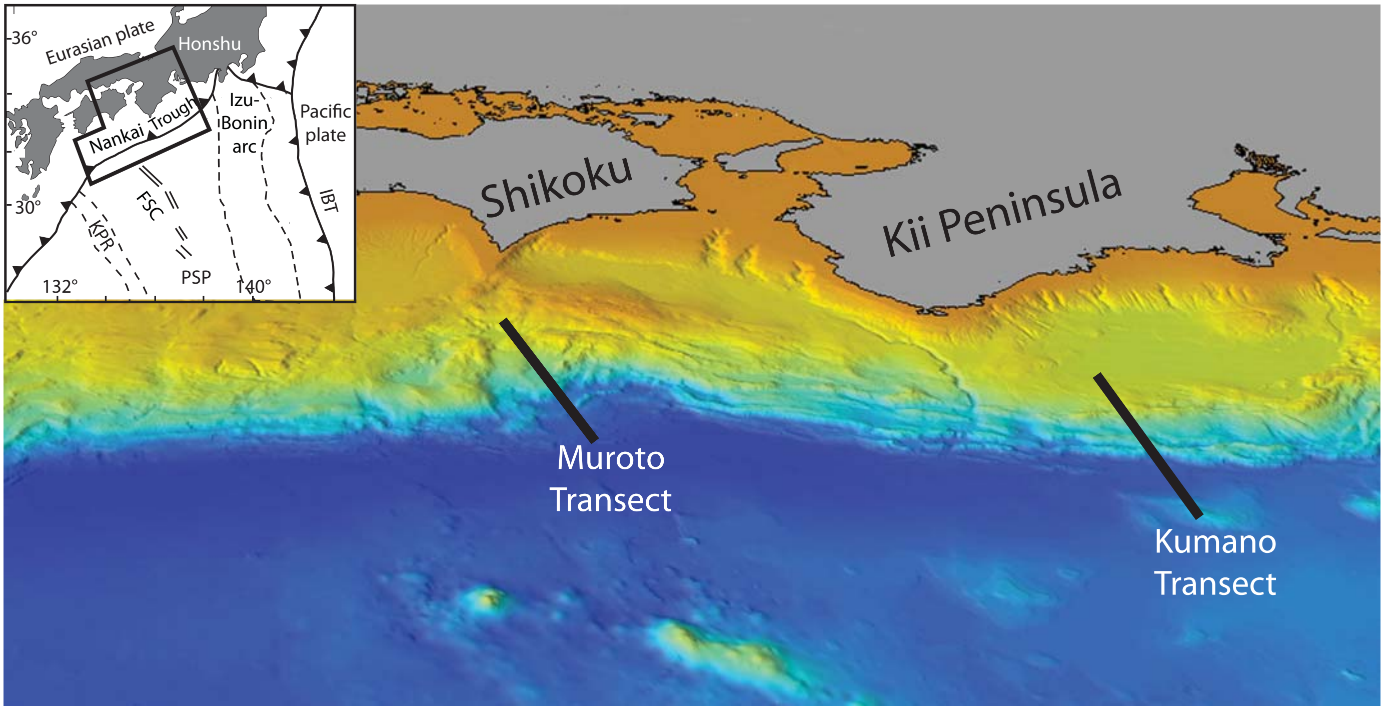


Figure 2. Map of the Nankai Trough region showing the locations of the Muroto (IODP Expedition 131, 190, and 196) and Kumano Transects (pending IODP effort). Inset shows the regional tectonic setting of the Nankai Trough. IBT = Izu-Bonin Trench; FSC = fossil spreading center; PSP = Philippine Sea Plate; KPR = Kyushu-Palau Ridge. As the Philippine Sea Plate moves in a north-northwest direction, it subducts beneath the Southwest Japan arc at the Nankai Trough.

Costa Rica

An understanding of the Central American margin developed over four decades of investigations, beginning with the classic article by Seely et al. (1974). Scientific drilling of the margin in the 1980s recovered Cretaceous igneous rock near the trench axis, showing the non-accretionary character of the Central American margin. Safety constraints and drill capability impeded reaching subducted material along the plate interface. It was clear, however, that essentially all of the sparse trench sediment is subducted consistent with seismic images of the plate interface (e.g., Shipley and Moore, 1986). Sampled trench sediment has 40 percent to 70 percent porosity, so abundant fluids are subducted. These fluids become overpressured and greatly reduce interplate friction until they have been expelled, indicating a first-order interaction between tectonics and hydrology.

Later drilling focused on fluid chemistry and the major objective of ODP Legs 170 and 205 was to understand fluid flow from the chemistry of fluids extracted from recovered sediment cores. Some chemical species in these fluids formed at high temperature, and are inferred to originate near the seismogenic zone. Fluids similar to those from these drillholes were also found associated with kilometer-scale mounds that mark seafloor vents, which are found in the middle slope area rather than near the trench axis. Potential fluid pathways to the mounds revealed in seismic records are normal faults whose roots are located at the updip limit of the seismogenic zone, which is assumed to involve high friction (Hensen et al., 2004). Thus, stress along the plate interface appears modulated by the hydrological system. Where fluid is abundant, the interface is largely aseismic; where fluid has probably drained to a reduced level, the interface appears to be seismogenic.

Ancillary to the investigations of fluids were the paleo-depth histories constructed from studies of benthic foraminifera sampled in the drilled cores. Evidence of long-term (several million years), large-scale (several kilometers) subsidence of the continental slope basement along the Middle America Trench indicates tectonic erosion of the overriding plate (Ranero et al., 2000; Vannucchi et al., 2003, 2004). Subducted materials along the plate interface of erosional margins are likely to have a very different composition from those of accretionary margins. A difference in plate boundary behavior is expected.

Frequent major earthquakes are in some cases located above subducted seamounts. The seismogenic subduction zone is thought to consist of local earthquake asperities surrounded by conditionally seismogenic plate interface areas (Bilek et al., 2003). The seismogenic zone of this convergent margin is modulated by the geology of the subducting plate; however, modification of that geology during subduction and seismogenesis is speculative. The erosional Costa Rica margin displays significant differences with the accretionary Nankai margin in terms of plate interface materials, hydrologic systems, and character of seismicity.

THE SEISMOGENIC ZONE—A KEY IODP INITIATIVE

Access to the interior of active fault zones where *in situ* processes can be monitored and fresh fault rocks can be sampled is of fundamental importance to the understanding of great earthquakes. Because great subduction earthquakes represent one of the most destructive natural hazards on the planet, drilling into and instrumenting an active interplate seismogenic zone is a very high priority in the *IODP Initial Science Plan* (Coffin, McKenzie et al., 2001). Through a decade-long series of national and international workshops, a consensus emerged that both the Nankai Trough and the Middle America Trench off Costa Rica are the best places to attempt sampling and monitoring of the seismogenic plate interface.

Probing the Seismogenic Zone of an Accretionary Margin

The IODP Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) will, for the first time ever, attempt to drill into, sample, and instrument the seismogenic portion of a convergent margin subduction zone fault or megathrust within a subduction zone where great earthquakes have repeatedly occurred (Tobin and Kinoshita, 2006a).

The fundamental goal of the NanTroSEIZE science plan, discussed in the "NanTroSEIZE Project Stage 1 Scientific Prospectus" (Tobin and Kinoshita, 2006b) is to create a *distributed observatory* spanning the up-dip limit of seismogenic and tsunamigenic behavior at a location where $M > 8$ subduction earthquakes occur, thus allowing us to observe the geodetic, seismologic, and hydrogeologic behavior of subduction megathrusts and the aseismic to seismic transition of the megathrust system. This effort will involve the drilling of key elements of the active plate-boundary system at several locations off the Kii Peninsula of Japan, from the shallow onset of the plate interface to depths where earthquakes occur (Figures 2 and 3). At this location, the plate interface and active mega-splay faults, both of which are implicated in causing tsunamis, are accessible to drilling within the region of coseismic rupture in the 1944 Tonankai ($M = 8.1$) great earthquake. The science plan entails sampling and long-term instrumentation of (a) the inputs to the subduction conveyor belt, (b) mega-splay faults at 3.5-km below the seafloor, which may accommodate a major portion of coseismic and tsunamigenic slip, and (c) the main plate interface at a depth of up to 6 km.

The Nankai Trough region is among the best-studied subduction zones in the world. It has a 1,300-year historical record of recurring and typically tsunamigenic great earthquakes (Ando, 1975). Land-based geodetic studies suggest that the plate boundary thrust here is nearly 100 percent locked (Miyazaki and Heki, 2001). Similarly, the relatively low level of microseismicity near the up-dip limits of the 1940s earthquakes (Obana et al., 2004) implies significant interseismic strain accumulation on the megathrust; however, recent observations of very-low frequency (VLF) earthquake-event swarms apparently taking place within the accretionary prism in the drilling area (Obara and Ito, 2005) demonstrate that interseismic strain is not confined to slow elastic strain accumulation.

NanTroSEIZE will sample fault rocks over a range of pressure and temperature (P-T) conditions across the aseismic–seismogenic transition, will analyze the composition of faults and fluids and associated pore pressure and state of stress, and will address partitioning of strain spatially between the décollement and mega-splay faults. NanTroSEIZE will also install borehole observatories to provide *in situ* monitoring of these critical parameters (e.g., seismicity, strain, tilt, pressure, temperature) over time and describe how the interseismic deformation is distributed in time and space.

IODP NanTroSEIZE plans to drill

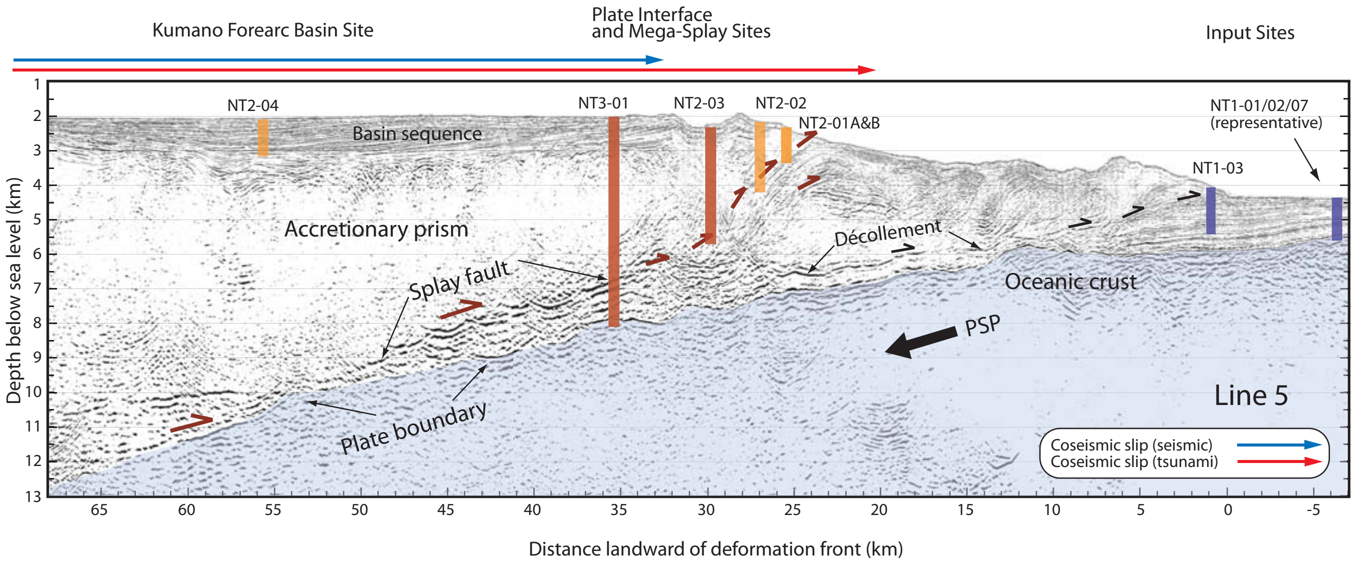


Figure 3. Two-dimensional depth-migrated seismic section showing locations of NanTroSEIZE IODP drill sites. IODP plans to drill at eight sites across the Nankai accretionary complex off Kumano Basin. Blue = incoming plate sections and frontal thrust of accretionary wedge; Orange = mega-splay fault system at different depths, and forearc basin for the uplift history of the mega-splay fault; Red = ultra-deep sites targeting the plate interface in the seismogenic zone and deep mega-splay. Drilling at two deep sites (shown in red) will be made possible with the state-of-the-art riser-capable drilling vessel *Chikyu*. Source: Park et al. (2002).

at eight sites (Figure 3): two incoming plate sections; one at the frontal thrust of the accretionary wedge; three across the mega-splay fault system at different depths; one in the forearc basin for the uplift history of the mega-splay fault; and one ultra-deep site targeting the plate interface in the seismogenic zone. Sampling of the sediments, fluids, and crustal rocks seaward of the deformation front will characterize the subducting plate before deformation. It has been hypothesized that sediment type (especially clay mineral content), fluid content, and basement relief on the incoming plate govern the mechanical state of the plate interface at depth and influence the formation of fault-zone asperities. At two sites there are plans to sample the entire sedimentary section and up to 100 m of the oceanic crust, respectively, on and off of a pre-existing basement high that controls deposition of thick turbidites in the lower part of the stratigraphy. Long-term monitoring of pore pressure, seismicity, and other observations in these boreholes will define the hydrological and stress conditions and microseismic activity at the point where sediments enter the subduction zone.

Four drill sites (NT2-01, NT2-02, NT2-03, NT3-01) targeting the mega-splay fault zone and one site targeting the frontal thrust (NT1-03) are designed to document the evolution of fault rock properties and the state of stress, fluid pressure, and strain at different P-T conditions. These sites will access faults from ~ 500 m to 3,500 m depth below the seafloor.

Drilling at the 5,500–6,000 m ultra-deep site (NT3-01) will pass through both the mega-splay fault system and the basal detachment, bottoming in the oceanic crust rocks of the subducting plate. Drilling of these deep objectives requires novel borehole engineering. It is planned that the sealed borehole observatories at two ultra-deep sites will monitor pore-fluid pressure, strain, seismicity, and other properties to document the physical state of the fault zone and its wall rock environment. These observatories require major engineering development, especially the high-temperature sensing system, and also to make them reliable for long-term monitoring.

In addition to the primary fault-zone targets, one drillhole (NT3-01) will pass through about 1000 m of the Kumano forearc basin section, including an apparent gas hydrate reflector, and several thousand meters of the older accretionary wedge. Two sites together will document the history and growth of the Kumano forearc basin, which has formed as a response to slip on the mega-splay fault system, as well as processes of accretionary wedge growth. The basinal history will shed light on the evolution of this long-lived, mid-wedge fault that may be a primary feature of many subduction-zone forearcs that produce great earthquakes (Wells et al., 2003).

The Erosional Convergent Margin of Costa Rica

As outlined above, the basic changes in structure, physical properties, and fluid content that trigger the stable (nominally aseismic) to unstable slip (stick slip) transition of accretionary margins also occur at erosional margins, but they involve different materials, hydrology, and physical conditions. Where subduction erosion dominates a margin, subducted material comes from the base of the upper plate at depths beyond the sampling capabilities of past scientific ocean drilling. Because of different subducted material input, the mineral alterations along erosional margins involved in seismogenesis may be very different from those at accretionary margins. Zones of active upper plate erosion have never been sampled nor does geophysical data resolve their structure, lithology, physical properties, and fluid content.

The IODP riser drill ship *Chikyu* provides the opportunity to sample for the first time the plate interface in a zone of tectonic erosion. Examining material transformation at greater depth and temperature than previously reached and observing the dynamic behavior of an erosional convergent margin are major objectives of CRISP (Costa RIca Seismogenesis Project). Drilling and instrumentation on either side of the transition from aseismic to seismogenic behavior is planned.

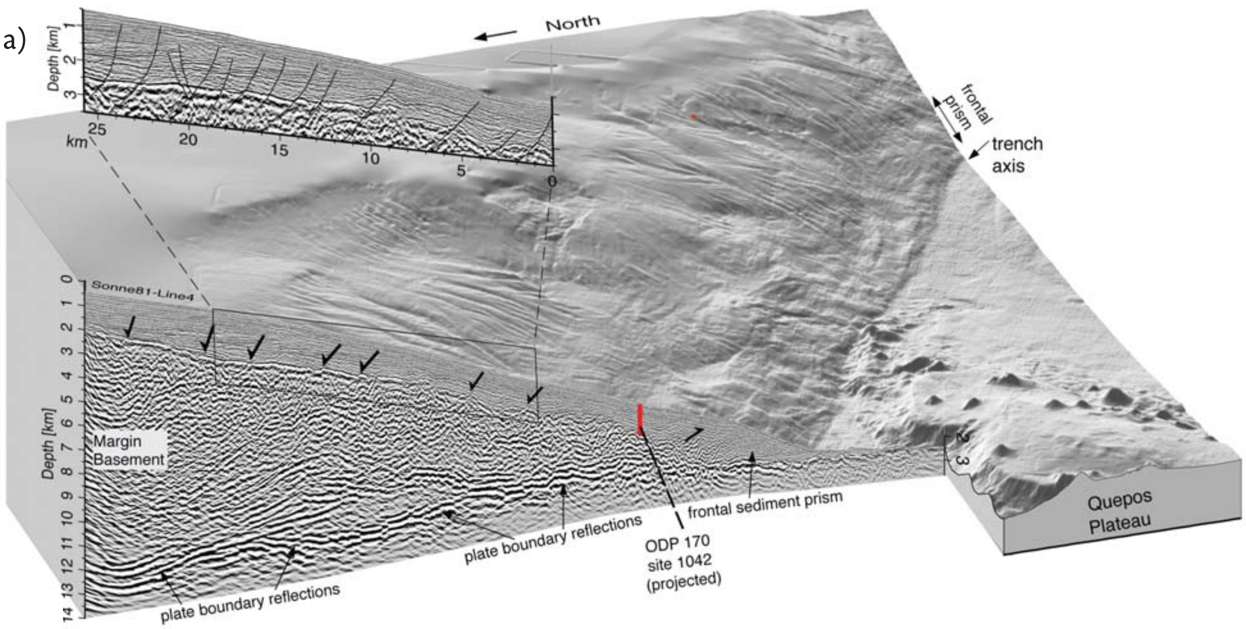
Subduction Erosion

Erosional convergent margins are not as well understood as accretionary ones. The most convincing evidence of subduction erosion is subsidence of the continental slope requiring removal of continental crust along the upper plate's base. A key feature that shows subsidence along the Central America convergent margin is the regional unconformity imaged in seismic records. Drilling on DSDP Legs 67 (1979), 84 (1981), and 170 (1996) revealed that Eocene to Miocene shallow water sediment covers the unconformity (Figure 4). The igneous basement dredged from the lower continental slope of Nicaragua indicates an extension of the continental framework to the trench there as well. Subsidence of the erosion surface from surf zone to trench depths requires crustal thinning by erosion of material along the underside of the upper plate because the seafloor is dominantly a depositional surface. In seismic records, the regional unconformity can be followed continuously from the ODP Leg 170 drill transect off Nicoya to the Osa Peninsula drill transect of CRISP. The CRISP-proposed drilling into the seismogenic zone is clearly in an area of vigorous tectonic erosion.

Fluid Migration

The discovery of mid-slope venting helped constrain the interaction of tectonics and hydrology. The vents produced mounds that were sufficiently large (> 1-km across) to be imaged in multibeam bathymetry. They were also surveyed in detail with near-bottom imagery by researchers in the German research project SFB 574. High-resolution mapping further revealed their seafloor-venting morphology. Cameras just above the seafloor photographed abundant chemosynthetic carbonates and fauna at the vent sites surveyed, which were confirmed with observations from the submersible *Alvin*. Modeling indicates that mid-slope venting balances the margin's hydrological system. Therefore, deep sampling and physical observations of the fluid source materials along the subduction zone are key to understanding the role of fluid in the aseismic to seismic transition.

Venting occurs in an area where normal fault scarps cut the seafloor. Heat flux over and around the mounds is high compared to the regional background, consistent with venting of deeply sourced fluid (Grevemeyer et al., 2004). Pore fluid has a low chlorinity and chemical modeling indicates a derivation from dehydration of clays (Hensen et al., 2004). Clay dehydration occurs deep in the subduction zone and perhaps in the seismogenic zone. First-order estimates of fluid flow across the forearc indicate that most of the fluid released during dehydration reactions in the subduction channel drains at mid-slope vent sites. As indicated above, dehydration of the subducting sediment is proposed as a significant cause for the transition from stable a)



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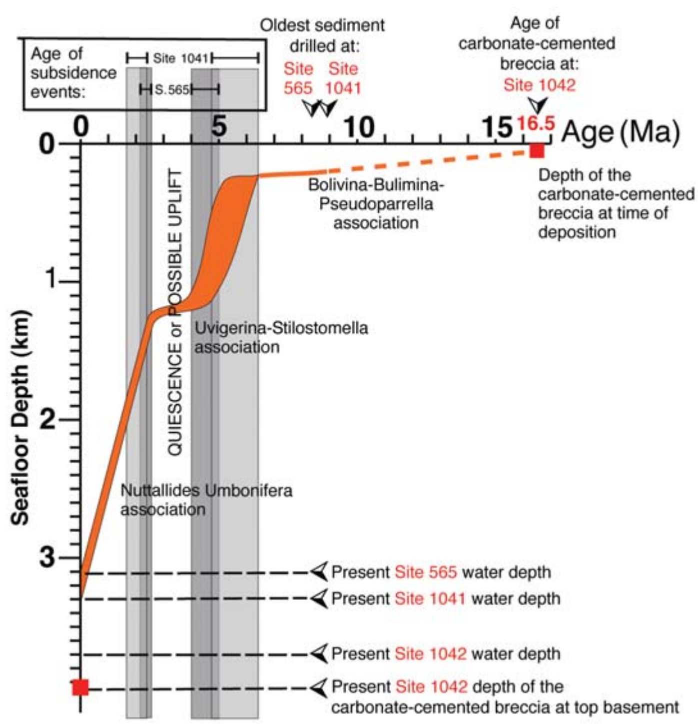

Figure 4. (a) Seismic depth image (pre-stack depth migration) of the Costa Rica margin near Osa Peninsula (Ranero et al., 2000). Basement is igneous rock cut by normal faults (emphasized with lines). Inset on the left shows detail of normal faults displacing the basement unconformity and the slope sediment section. Seafloor topography was acquired with multibeam surveying. (b) Long-term subsidence history of the Costa Rica margin with data from two drill sites offshore Nicoya Peninsula. Paleodepth information was obtained from studies of benthic foraminifera in the slope sediment and it indicates a non-linear subsidence (two main pulses) of about 4 km for the middle continental slope (Vannucchi et al., 2003).

to stick-slip behavior and seismogenesis.

The frequent seismicity in the Costa Rican offshore region makes the area advantageous for studying seismogenesis. In 2002, an array of ocean bottom seismometers, integrated with the local network of seismometers on land, recorded an M_w 6.4 earthquake (Figure 5). This onshore-offshore array provided data for positioning of the earthquake and its aftershocks with greater-than-usual precision (I. Arroyo, in publication). The main shock location could have been beneath the proposed 5-km-deep riser drill hole into the seismogenic zone. Sampling the asperity area of a large subduction earthquake (Figure 6) has not yet been accomplished. Planned IODP deployment of downhole geophones that record signals from surface ships will generate a three-dimensional seismic image around the drillhole with a radius of several kilometers. Estimates of physical properties in this rock volume can be derived from seismic-attribute analysis. This experiment will provide an unprecedented data set that will improve the understanding of seismogenesis.

CRISP Drilling Strategy

Near the Osa Peninsula, the seismogenic zone can be reached with scientific drilling because the subduction zone has a shallow dip and high temperature, resulting in large earthquake hypocenters at depths accessible to the riser ship *Chikyu*. CRISP is structured into non-riser (Program A) and riser (Program B) drilling stages that systematically progress from shallow to deep drilling (Figure 6). Program A drilling will establish erosion rates and characterize lower-plate oceanic igneous rock (its structure and hydrology) before the plate is subducted. Program B riser-drilling-site locations will be constrained by Program A results, including downhole instrument records, conventional geophysical experiments, rock mechanics laboratory experiments, and forward modeling. Beneath the mid-slope, Program B drilling will reach 3 km subseafloor to sample for the first time the subducting eroded debris along the stable slipping ("aseismic") plate interface. The debris becomes a benchmark for material at the beginning of the transition to

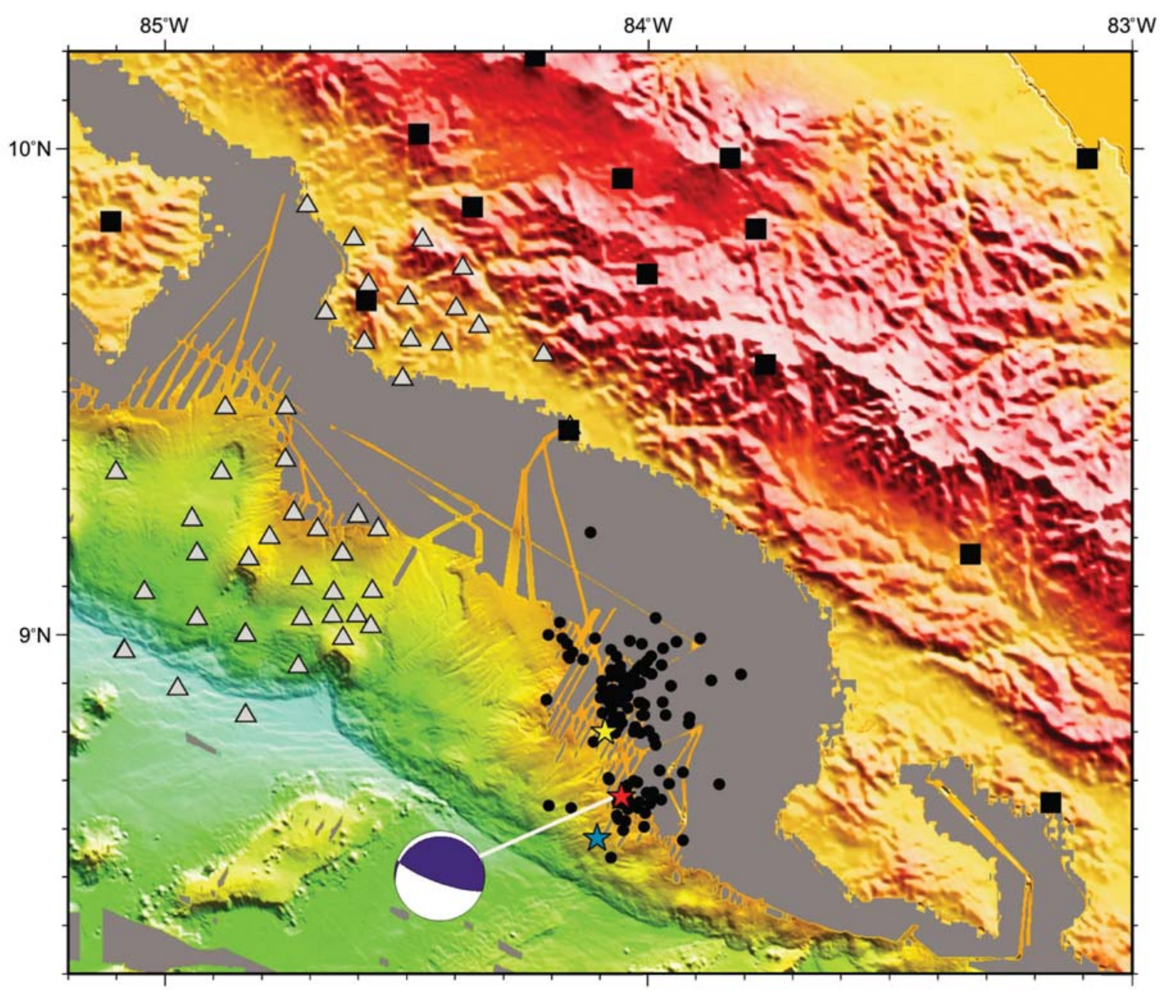

Figure 5. Location of the main shock and aftershocks of the 2002 M_w 6.4 earthquake. Triangles indicate the array of ocean bottom seismometers that recorded the earthquake; black squares are seismometers of a local network. Early locations of the main shock, without the offshore seismographs, are shown with yellow and blue stars

seismogenic behavior. Thus, conditions in the zone of stable slip can be compared to those in the zone of unstable slip and provide observations of material transformations such as clay mineral diagenesis and accompanying fluid flow critical to understanding seismogenesis. The Program B riser drilling site is at water depths of 500 m and at a location with optimum environmental operating conditions, which may enable the nucleation area of a large earthquake to be sampled. Riser hole results will enable laboratory experiments and forward modeling that can indicate conditions deeper in the seismogenic zone. If found attractive for further investigation, these modeling results can then be verified with ~ 7-km-deep drilling at a site on the Osa Peninsula under the auspices of the International Continental Drilling Project.

With a limited sediment supply, fast convergence rate, abundant seismicity, subduction erosion, and optimal mid-latitude operating conditions, the Middle America Trench off Costa Rica offers excellent opportunities to investigate causes of earthquake nucleation along erosional margins. CRISP will contribute to analysis of great earthquakes. The Middle America Trench drilling results will be integrated with deep drilling of other fault zones to establish primary and first-order causes of seismogenesis.

CONCLUDING REMARKS

During IODP, drilling during both NanTroSEIZE and CRISP will attempt to sample and instrument the seismogenic portion of plate-boundary faults and an associated megathrust within two

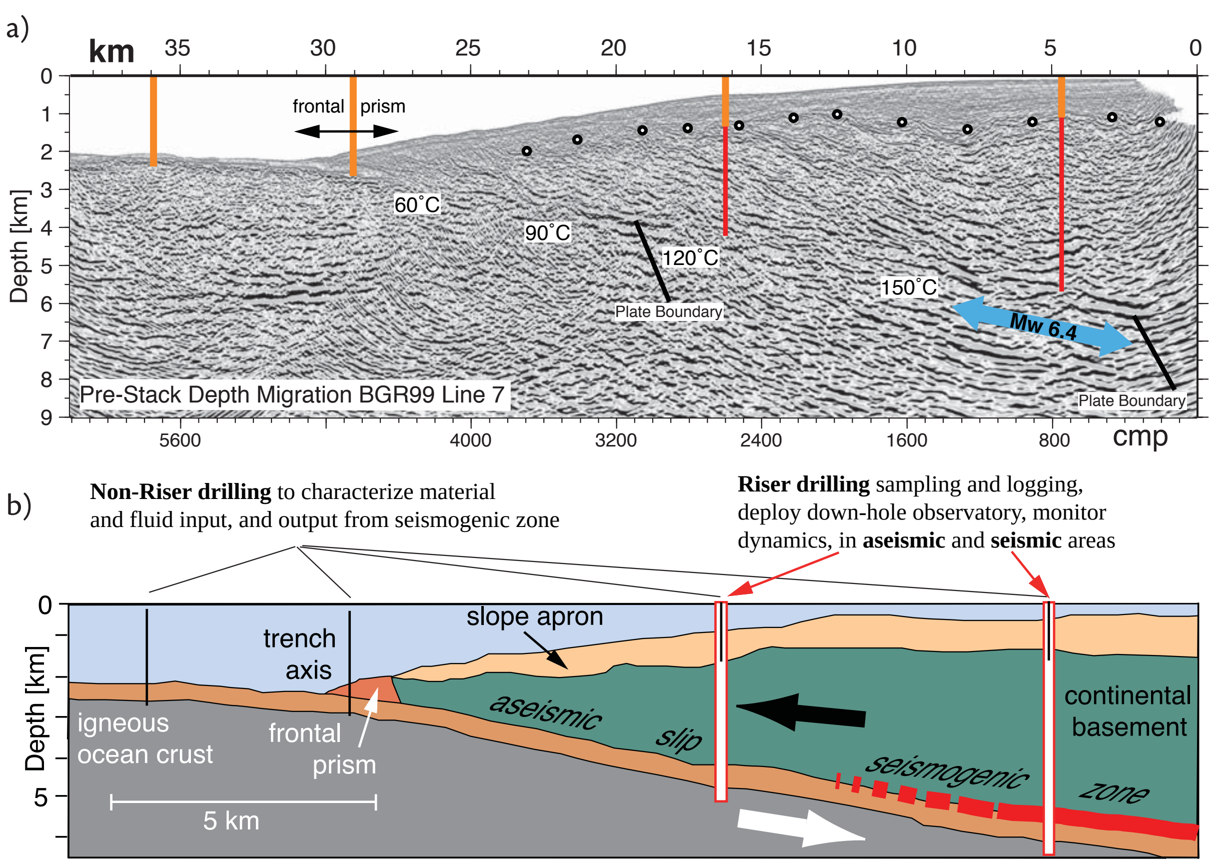

Figure 6. (a) Depth image across the location of proposed drill sites (see Figure 2). Shallow non-riser sites are shown in orange and deeper riser holes in red. Note that drilling of the deepest hole may penetrate the nucleation area of the 2002 M_w 6.4 earthquake (approximate location shown by blue arrow). (b) Cartoon with main geological units, based on the seismic image in (a), showing the plan to drill on either side of the updip limit of the seismogenic zone..

very different subduction zones where great earthquakes have occurred repeatedly. Drilling will yield both geophysical logs and physical samples of rocks, sediments, and fluids. Logging and borehole imaging will determine *in situ* physical properties and help define stress state (e.g., through borehole breakout and tensile fracture studies). Sampling the inputs and splay faults at several depths, and the plate interface at great depth, will provide key data on the evolution of fault-zone composition, fabric development, and lithification state as a function of pressure, temperature, and cumulative slip. Finally, long-term monitoring through downhole instrumentation will yield time-series datasets after the drilling disturbance signals have subsided, possibly including the pre-seismic, near-term indications of a future great earthquake. Ideally, thermal signals, fluid pressure, geochemical tracers, tilt and volumetric strain, microseismicity, and time-varying seismic structure will be monitored. Both NanTroSEIZE and CRISP will span a number of years and many individual expeditions to achieve all of the proposed scientific objectives, with onboard and shore-based scientific teams matched to the goals of each sub-expedition.

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