3.2 Initiative Summary: Seismogenic Zone

Image seismogenic zone using earthquakes and artificial sources (seismic reflection/refraction)

Seafloor observations and monitoring

Drill to seaward limit of seismogenic zone

Measure surface deformation

Predict nature of materials in seismogenic zone

Characterize incoming materials

Seismogenic Zone

~30+ km
3.2 SEIZE Initiative Summary: 1
3.2 SEIZE Initiative Summary

3.2 SEIZE Initiative Summary

Dense heatflow measurements

Sparse heatflow measurements

3 month OBS deployments

ODP drill sites

3D seismic, swath bathymetry + dense heatflow

Deep seismic

MCS

Initiative Progress Review: Seismogenic Zone (SEIZE)

Original Goals

The Seismogenic Zone Experiment (SEIZE) was developed to study the portion of the shallow subduction plate interface that is locked and accumulates elastic strain, periodically released in large or great, and often tsunamigenic, earthquakes. The original SEIZE science plan goals were updated following the MARGINS SEIZE Theoretical Institute in 2003 (MARGINS Initial Science Plan, 2004). The basic questions addressed fundamental processes and controls acting on the seismogenic zone, affecting: 1) the distribution of seismic energy release during subduction zone earthquakes, 2) the heterogeneous distribution of locking patterns and strain release on the plate interface, 3) rates of fault slip and propagation for fast, slow, tsunamigenic, and silent earthquakes, and 4) temporal changes in strain, fluid pressure, and stress during the seismic cycle. Two focus sites, the Nankai Trough and the Costa Rica margin, were chosen as end member examples of tectonic and geologic settings that exhibit significantly different seismogenic behavior, providing important opportunities for comparison. The Costa Rican margin is characterized by tectonic erosion, low terrigenous sediment input, and relatively small (M6.5–7.5), frequent (50-75 yr recurrence interval) earthquakes, whereas the Nankai Trough is characterized by tectonic accretion, high input of terrigenous sediment, and larger (M8-8.5), less frequent (150-200 yr recurrence) events.

Comprehensive review and synthesis of the many achievements of the MARGINS SEIZE program took place at the 2007 Integrated SEIZE and Subduction Factory Workshop in Heredia, Costa Rica (Silver et al., 2007) and the 2008 Next Decade of the Seismogenic Zone Experiment Workshop at Mount Hood, Oregon. Both meetings were also valuable for identifying new perspectives and opportunities for future SEIZE research, guiding the summary provided here.

Major Accomplishments

Major breakthroughs and key results in the MARGINS-SEIZE program have come from both MARGINS funded science and integration of SEIZE efforts with the work of the broader community, through allied studies at non-focus sites and international collaborations, especially with German, Costa Rican, and Japanese scientists.

A new understanding of the updip limit of the seismogenic zone (Figure 1): A defining premise of the initial SEIZE program was the hypothesis that thermally controlled clay transformations (from smectite to illite) may control the updip limit of the seismogenic zone. This hypothesis was driven by (1) the coincidence of modeled 150°C isotherm along subduction megathrusts with the observed seismic front along many subduction zones (e.g., Hyndman et al., 1997), and (2) the completion of thermally-driven dehydration of smectite to illite by temperatures of 120°C-150°C (e.g., Pytte & Reynolds, 1988). However, MARGINS funded laboratory studies indicate that illite and illite-rich natural shales are actually velocity strengthening materials unable to host unstable slip (i.e. nucleate earthquakes). This study was the first direct test of this widely held hypothesis, and the negative result has prompted significant reconsideration of possible mechanisms to explain the updip limit of the seismogenic zone, for example, lithification, cementation, and/or progressive slip localization (McKiernan et al., 2005; Saffer and Marone, 2003; Moore and Saffer, 2001).
Thermal controls on the updip limit are still likely important, as the correlation between thermal structure and the onset of seismicity is now well-established, from both field studies of exhumed subduction faults and geophysical and seismological studies at the focus sites. New hypotheses related to temperature have emerged, required to explain a coincidental link between silica mobilization, declining fluid pressures, and the onset of the seismogenic zone at temperatures of 125°-200°C (Moore et al., 2007). Additionally, the onset of microseismicity along the Nicoya Peninsula in Costa Rica changes abruptly along strike, coincident with a discontinuity in subducting oceanic crust age, and presumably temperature (Newman et al., 2002). The onset of seismicity and geodetically defined locking also clearly correlate with the thermal state of the incoming plate (Spinelli and Saffer, 2004; Schwartz and DeShon, 2004).
Finally, combined geodetic and seismological studies at the Costa Rica focus site indicate that the concept of single updip limit is too simplistic. Instead, microseismicity, large earthquakes, and geodetically locked zones delineate different updip limits, suggesting a complex interplay of processes govern fault mechanics and slip behavior along the megathrust, some of which are potentially linked to dehydration reactions within the downgoing plate (Schwartz and DeShon, 2007).

Pore pressure transients associated with seismicity: A series of direct observations at long-term hydrologic observatories (CORKS), both at the Nankai and Costa Rican margins, have documented transient pore pressure and seafloor fluid flow signals associated with seismicity (Davis et al., 2006; Brown et al., 2005). The observations at Nankai include both a secular signal that may reflect interseismic strain accumulation, and short period transient signals that correlate with newly discovered VLF earthquakes (e.g., Ito et al., 2006). Notably, IODP drilling and installation of a long-term observatory is planned at a site directly above the location of VLF events recorded in 2004; the observatory will monitor seismicity, strain, pore pressure, and temperature.

Seismicity variations with basement topography: Central American margin seismicity (i.e., earthquake magnitude and recurrence) is highly segmented by along-strike variations in the incoming Cocos plate (e.g., Protti et al., 1995; Bilek et al., 2003; Bilek, 2007), and possibly the upper plate as well (Marshall et al., 2007). Beneath Nicaragua the relatively smooth subducting plate generated at the East Pacific Rise (EPR) produces frequent earthquakes (typically 50-75 years) of variable size (typically M6.5 – M7.5) and variable source duration. The transition between the smooth EPR generated seafloor and rough CNS generated seafloor is currently subducting beneath northern Costa Rica, offshore of the Nicoya Peninsula. South of the Nicoya Peninsula, beneath central Costa Rica, the rougher plate generated along the Cocos-Nazca spreading center (CNS) subducts with a number of large seamounts, which produces more frequent (~few years recurrence) fast earthquakes up to M=6.5. These new observations suggest a control on the heterogeneity of the shallow seismogenic zone related to incoming plate variability.

Modeling Efforts: Several modeling studies have combined a variety of datasets collected through MARGINS efforts to benefit the SEIZE goals. Studies have examined the hydrologic, mechanical, and chemical effects of sediment dewatering or co-seismic deformation (Spinelli et al., 2006; Screaton et al., 2002; Screaton and Saffer, 2005; Saffer and Screaton, 2003; Screaton and Ge, 2007; Brown et al., 2005). Other efforts have modeled the thermal history of subducting material to predict locations of mineralogic transitions and seismicity (Peacock, 2003; Spinelli and Saffer, 2004; Schwartz and DeShon, 2007; Kummer and Spinelli, 2008; Saffer et al., 2008).

Interdisciplinary Activities: Links between seismogenesis and subduction volatile fluxes are key elements of the SEIZE questions, especially those focused on the temporal and spatial variability of fault slip. Within SEIZE, there have been several linked observations that are greatly improving our understanding of slip processes, including correlations between pore pressure transients, non-volcanic tremor, and slow slip (Brown et al., 2005). Likewise, combined seismic and geodetic observations along the Costa Rica margin have led to a new view of the updip limit, as microseismicity defines a deeper limit than the shallower estimates provided by GPS and large magnitude earthquake rupture (Schwartz and DeShon, 2007). Preliminary studies integrating basic petrologic and fluid processes have suggested tantalizing though very tentative correlations between the location of locking and microseismicity and specific devolatilization reactions (e.g., Spinelli and Saffer, 2004; Schwartz and DeShon, 2007).
Site Specific Accomplishments: Nankai Focus Site

One of the cornerstones of the SEIZE initiative is the NanTroSEIZE drilling activities offshore of the Kii peninsula, designed to measure and sample within and adjacent to the active seismogenic zone (Tobin and Kinoshita, 2006). Such observations will provide important ground-truth about fault zone materials as they progress towards seismogenic depths. Although the NanTroSEIZE program falls under the IODP umbrella, Nankai drilling operations are clearly allied with MARGINS SEIZE objectives, and the two programs have benefited from joint funding of studies, in particular, site surveys. We summarize several major milestones here:

Commercial acquisition and processing of 3D seismic volume offshore of Kii Peninsula: The 3D seismic survey over the location of IODP seismogenic zone drilling provides improved constraints on the geometries and properties of the megasplay fault system, establishing the regional character and context for drilling (Figure 2). Furthermore, detailed imaging of the megasplay fault system reveals its steep rise from the decollement zone to the seafloor, demonstrating its potential to contribute co-seismic offset at the seafloor that can produce devastating tsunamis (Moore et al., 2007).

Completion of the initial IODP NanTroSEIZE expeditions: The first three NanTroSEIZE expeditions (Expeditions 314, 315, and 316, all non-riser) have now been completed. The recent expeditions establish the groundwork for future deep drilling and planned observatories through the subduction megathrust at Nankai. Drilling has also provided the first look at the properties and composition of the

Figure 2: 3D data volume showing relations of in-sequence thrusts of the frontal accretionary prism (blue lines) and younger out-of-sequence branches of the splay fault (black lines). The top of a thrust sheet that has been folded above a lateral ramp in the frontal prism is cut off by the younger megasplay fault (see G.F. Moore et al., 2007 and nugget).
megasplay fault and more frontal fault structures for comparison, and have exposed the history of slip along the megasplay fault and its influence on surrounding structures (Kimura et al., 2008).

Continued work on previously acquired seismic data and drill cores: MARGINS research has benefited from further analysis of seismic data collected elsewhere along the Nankai margin, as well as previous ODP drilling and coring, in particular, along the Muroto and Ashizuri transects. Mineralogic analyses of older drill cores provide the basis for new thermal and geochemical modeling to track the progression of diagenetic reactions within the accreting and subducting sediments (Spinelli and Underwood, 2005; Spinelli et al., 2007; Saffer et al., 2008), clarifying the mechanisms responsible for pore volume loss and strength changes during accretion that may influence the stress conditions along the margin. Additionally, a 3D seismic volume along the Muroto transect has enabled estimation of porosities and effective stresses, which suggest the nearly undrained state of the underthrust sediments and overlying decollement zone up to ~20 km downdip of the deformation front (Tobin et al., 2006).

Such high underthrust pore pressures provide a plausible mechanism to explain the apparent weakness of accretionary wedge decollements, and may suppress stick-slip behavior in the outer portion of the accretionary wedge. These various hypotheses remain to be tested through direct drilling and sampling of the fault zone itself, which is currently directed at the Kii drilling site transect.

Site Specific Accomplishments: Central America Focus Site

Major scientific progress in Central America has been facilitated by strong international collaborations (e.g., with Nicaraguan, Costa Rican, and German research institutions), and by joint SEIZE and SubFac investigations. Research efforts in the area have produced data ranging from centimeter-scale outcrop observations to 100 km scale tomographic studies, building a framework spanning the entire seismogenic zone. Here, we highlight some key recent and ongoing studies.

CRSEIZE: Integrating hydrology, geodesy, and geophysics: The CRSEIZE project instrumented the Costa Rica plate boundary with seismometers, GPS, and fluid flow meters (Figure 3) to better resolve the nature and distribution of plate boundary deformation and seismicity (e.g., DeShon et al., 2006; Schwartz and DeShon, 2007; Norabuena et al., 2004). The results contribute to our new understanding of the updip limit of seismogenic zone (see above). Importantly, silent slip events were also detected
beneath Costa Rica through onshore GPS deployments, and in contrast to many other settings (e.g., Dragert et al., 2001), these events appear to originate in the shallow portion of the subduction zone, immediately updip and downdip of the currently locked zone (Norabuena et al. 2004). Non-volcanic tremor (NVT) has also been detected in Costa Rica in OBSs positioned offshore near the toe of the accretionary prism (Brown et al., 2005), although the connection between NVT and silent slip in this setting is still unclear. Elsewhere, deep NVT has been attributed to fluid generated by dehydration processes in the slab (Obara, 2002), and the same may be true in this shallower setting (Schwartz and DeShon, 2007). Interestingly, a strong correlation has been observed at Costa Rica between shallow NVT and hydrologic transients measured at flowmeters collocated with the OBSs (Brown et al., 2005), and in CORKs near the trench (Davis et al., 2006). This intriguing correlation has been modeled as a poroelastic response to tectonic loading due to slow slip along the plate interface near the up-dip limit of the seismogenic zone (Brown et al., 2005).

**Thermal modeling links fluid flow and microseismicity:** Numerical modeling studies also suggest a causative link between hydrologic processes and the location of the up-dip limit of seismicity. These include the effects of hydrothermal cooling of the subducting plate (Harris and Wang, 2002; Spinelli and Saffer, 2004; Kummer and Spinelli, 2008), the role of lateral temperature variations in driving fluid flow (Spinelli and Saffer, 2007), and the tentative link between microseismicity at Costa Rica and dehydration reactions (Schwartz and DeShon, 2007).

**To what extent were goals achieved?**

The findings highlighted above demonstrate how extraordinarily successful MARGINS SEIZE efforts have been in understanding the complex seismogenic zone processes and controls. Research efforts have addressed each of the specific questions posed at the outset, with particular attention on Nankai and Central America. Nonetheless, the ambitious goals of the Seismogenic Zone Experiment have yet to be fully achieved. Major gaps include the direct sampling and measurement of the active seismogenic zone, which, however, are currently planned as part of future IODP NanTroSEIZE drilling operations. In addition, several of the SEIZE questions relate to temporal and spatial variations in fault processes that will require long-term and widely distributed observatories. Preparatory studies and surveys at the two focus sites have set the stage for such observatories, and new tools and methodologies, including seafloor geodesy (Figure 4), co-located instrumentation (e.g., flowmeters, strainmeters, and seismometers), and coordination with other long-term observatory infrastructure, e.g., OOI and SAFOD. Another component of SEIZE studies that is still incomplete is the integration of observations and results from the two focus areas, as well as from allied sites (e.g., Sumatra and Cascadia). Such efforts are dependent on consistent availability of multiple datasets from diverse settings, many of which are still being acquired.

Fortunately, the SEIZE initiative is entering an extremely active phase, particularly as results of field studies, seismic surveys, and drilling yield data and samples for laboratory examination and model development. Planned and proposed drilling efforts at the two focus areas, and ongoing research around the world, will eventually allow direct comparisons of compositional, thermal, and stress conditions along megathrusts in diverse settings. Currently, fluid flow at seeps in the Nankai Trough is already being quantified, and deformation and seismicity are being recorded at the Nicoya Peninsula. Long-term measurements of strain, seismicity, and fluid pressure in IODP boreholes (tentatively slated for installation in 2010) will provide additional data on the relationships between seismicity, fault slip events, deformation, fluid pressures, and fluid flow. Similar continued observations, through MARGINS-
funded and other research, will further increase our understanding of the range of fault slip events and their relationships to other quantifiable parameters.

![Image](image_url)

**Figure 4** Moored buoy deployed in August ‘08 offshore from Scripps (right) with seafloor transponder system (right) for precise, continuous measurements of seafloor horizontal and vertical motion (Brown, Chadwell, Send, Tryon).

### Potential Future Directions

Without a doubt, the SEIZE scientific community has benefited profoundly from the concentration of resources and efforts in the two focus areas of Nankai and Costa Rica, and there is strong motivation and substantial momentum to continue these focused efforts. However, recent events and observations across the research field have delineated significant new phenomena and opportunities that were not fully appreciated when the original SEIZE objectives were defined. We present here a sampling of these opportunities, many of which were posed in recent workshop discussions. We note, however, that the ultimate directions of SEIZE research in a successor program must be defined by the broader community through planning workshops.

**Explanations for the range of fault slip rates and processes:** One of the most fundamental changes in our perspective relates to moment release on active fault zones. We now recognize a much wider range of fault slip behaviors and rates than previously imagined, forcing a huge advance in thinking (Figure 5); we have moved from classic definitions of coseismic slip and creep to a wider spectrum of behaviors that includes silent earthquakes, slow slip events (SSE), episodic tremor and slip (ETS), low frequency earthquakes (LFE), and very low frequency earthquakes (VLF). A key question is how these slower time constant events fit with the coseismic release during normal earthquakes, or if these slow events comprise an entirely new class of seismic moment release, fundamentally different from normal earthquakes (Ide et al., 2007).

Cascadia and Japan are the “type locations” for these events based on the early observations (e.g. Heki et al., 1997; Dragert et al., 2001; Obara, 2002; Ito and Obara, 2006), although these types of events have now been documented at other subduction zone systems (Mexico, Alaska, Costa Rica) and along strike slip faults (San Andreas). Both MARGINS focus areas exhibit these phenomena: Nankai (LFE, VLF, SSE, tremor) and Central America (SSE). Community understanding of slow-slip fault behaviors and
their underlying physics are still in the early stages, and MARGINS studies can provide the context for integrating these observations, yielding in situ and laboratory derived mechanical, geochemical, thermal, and hydrologic data, as well as microseismicity and geodetic observations. In particular, MARGINS SEIZE investigations can constrain processes along the shallow portion of the seismogenic zone, which is most relevant to tsunami generation.

Figure 5: Recent observations over many different time and length scales demonstrate a wide range of slip behaviors on active fault zones, particularly near the updip and downdip limits of normal earthquakes.
Sumatra margin: Three major earthquakes off of Sumatra in the last 4 years, also have helped to focus the world’s attention on seismogenic zone processes and their impacts on society. The most notable was the Mw 9.2 Dec. 26th 2004 rupture that generated the 3rd largest ever recorded earthquake and the associated devastating tsunami. This earthquake was the best recorded mega-subduction zone earthquake and thus offers great opportunity for characterizing these rare, extreme events. Although the Sumatra margin lies outside of the two MARGINS SEIZE focus sites, there are clear connections to SEIZE objectives, and to broader societal issues. US researchers have been quick to establish collaborations where opportunities exist, and have participated in international surveys targeting the margin.

One of the most important considerations for MARGINS research is that, relative to the length of the seismic cycle, the Sumatra earthquake JUST happened, and therefore the margin is in a rapidly evolving post-seismic state. Capturing these processes in real time can lead to fundamental insights into the properties and evolution of the plate boundary system. It is therefore critical to deploy whatever resources are available to observe the system while it is so active.

Several other aspects of the recent Sumatra earthquakes are also directly linked to SEIZE objectives. The 2004 event had the longest duration of rupture ever recorded (>10 minutes), and the longest aftershock zone ever recorded at approximately 1300 km (e.g. Ishii et al., 2005). Within this rupture extent, significant heterogeneity exists in the coseismic slip distribution, consistent with afterslip patterns that show discrete segmentation along the 1300 km rupture length. There is also strong evidence for stress transfer along the Sumatra margin, resulting in sequential ruptures. And finally, the tsunami generated by the 2004 earthquake was very complex, which could be explained by several phases of fault slip or slip partitioning onto multiple faults within the forearc. The dearth of regional surveys, unfortunately, provides little clarity about the causes of these phenomena. The rapid evolution of the Sumatra margin today provides an outstanding opportunity to test models derived from previous MARGINS studies, for example, of the causes of seismogenic zone heterogeneity or “patchiness” (e.g., Lay and Bilek, 2007) and their impact on moment release distribution and slip behavior. Resolution of these questions will require further study of this margin, and the MARGINS SEIZE community is well positioned to contribute to this effort.

Cascadia Margin: Opportunities also exist to integrate MARGINS SEIZE research efforts around the world with research initiatives focused on the North American continent. The Cascadia margin bears strong similarities to both the Nankai and Sumatra margins, and has benefited from the convergence of a variety of geophysical, geodetic, and paleoseismologic studies, funded outside of the MARGINS structure (e.g., EarthScope, among others). Such studies are gradually unraveling the history of rupture and segmentation along the Cascadia margin (Goldfinger et al., 2008), and revealing the state of stress and strain along the margin today (Dragert et al., 2004; Wang in Dixon & Moore, 2007). Such efforts will certainly continue in the future, and stronger integration with SEIZE investigations in any successor program would be mutually beneficial.

Integrated subduction zone studies: Coordinated geophysical and geodetic studies of subduction margins around the world that lie at different points within their seismic cycles also offers the potential to study stress and strain evolution of convergent margins throughout the seismic cycle in a relatively short period of time (e.g., Sumatra lies in a post-seismic state; Cascadia is arguably in a pre-seismic state; many other margins lie in between). The MARGINS SEIZE community is well positioned to carry out such comparative investigations, in cooperation with many international partners.
Numerical modeling: Ongoing observatory and fault zone drilling operations carried out through MARGINS and allied seismogenic zone efforts, provide unparalleled opportunities to see into the seismogenic zone. However, the limited spatial and temporal coverage of such observatories justify numerical modeling efforts that can help to integrate and extrapolate the results, providing important constraints and predictions for further hypothesis development and testing. With new insights into the spectrum of fault slip behavior, rheologic modeling, e.g., of rate dependent slip behavior will become particularly salient, as demonstrated by initial dynamic rupture simulation [e.g., Segall and Rice, 2006]. Future effective modeling efforts will require careful integration of field, observatory, and laboratory studies; thus an important goal for future seismogenic zone efforts will be to promote interactions among these different groups.

With consideration of some of the opportunities outlined above, and our enhanced understanding of the complex interplay of properties and processes that control the seismogenic zone, we offer several key questions that might guide future SEIZE investigations:

**Key Questions for the Seismogenic Zone**

1. *What controls the observed wide spectrum of fault slip behaviors; specifically their spatial distribution and their variation throughout the seismic cycle?*

   Detailed observations in a variety of fault zones, but in particular, subduction zones, indicate that fault slip also occurs during silent earthquakes, episodic tremor and slip, low frequency earthquakes, and very low frequency earthquakes. It is unclear how these slower time constant events relate to coseismic slip during normal earthquakes. What processes or properties facilitate them, e.g., rock composition, stress change, pore fluid release or migration, etc.?

2. *What is the role of fluids in controlling fault rheology?*

   It has been hypothesized that metamorphic dehydration, pore pressure, and their distribution affect slip behavior and fault strength, but direct tests of many of these hypotheses remain to be conducted. Fluid release and pore pressure evolution, possibly mediated by sediment composition and thickness, basement topography, or thermal structure, may play defining roles in controlling fault rheology.

3. *What governs along-strike variations in moment release in great earthquakes, and similar variations in interseismic locking?*

   Variations in seismicity and interseismic deformation along- and across-strike have been correlated with lower plate roughness and age, upper plate structure and lithology, and contrasting properties and processes within the fault zone. Are these correlations universal or local? Are there other factors, for example, pore pressure distributions, that strongly influence or control these variations, and if so, how?

4. *What causes the observed temporal variations in seismogenic zone behavior and plate boundary deformation in interseismic, coseismic, and post-seismic periods?*

   Integrated onshore-offshore surveys, e.g., at Nicoya, Nankai, Cascadia, and elsewhere, demonstrate distinct fault behaviors and surface deformation in each setting, often varying along strike. Are
these indicative of where these margins lie within the seismic cycle, and if so, what controls their behaviors? Comparative studies along several margins at different stages within the seismic cycle can help to establish a unified understanding of evolving processes at subduction margins.

5. *What are the state of stress and absolute strength of subduction faults and wall rock?*

New results suggest strong spatial variations in stress at the Nankai margin from borehole breakouts, extremely low apparent stress drops (< 0.1 MPa) for VLF events, and dynamic triggering of tremor at Cascadia suggestive of low effective stresses. How are these observations related to overall fault strength, fault composition and subduction inputs, and fluid pressure?

6. *What is the geology of the seismogenic zone and its transitions?*

In particular, what is the character of the upper plate, and the composition, fabric, architecture, and physical properties of fault rock, and how does it influence fault mechanics and rheology, and strain accumulation and release?