The Seismogenic Zone Experiment (SEIZE) Workshop

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FINAL REPORT

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EXECUTIVE SUMMARY

Most of the world's great earthquakes and tsunamis initiate in the zone of underthrusting or seismogenic zone of subduction zones. The Seismogenic Zone Experiment (SEIZE) hopes to understand the relationship between earthquakes, deformation, and fluid flow in this environment. SEIZE will address the following questions: 1) What is the nature of asperities? What are the temporal relationships between stress, strain, and fluid composition throughout the earthquake cycle? 3) What controls the up-and downdip limits of the seismogenic zone? 4) What is the nature of tsunamigenic earthquake zone? 5) What is the role of large thrust earthquakes in mass flux of material into (and out of) the subduction system?

SEIZE will proceed by focused investigations combining earthquake seismology, seismic reflection imaging, and geodetic studies in and around a limited number of seismogenic zones. Sampling the incoming material combined with laboratory experiments and modeling will be used to predict the nature of the fault rock in the seismogenic zone. Waveform models of the seismic images will be used to predict physical properties of the seismogenic zone. Deep riser drilling will be used to test these models, lead to a better understanding of our questions about the seismogenic zone, and calibrate techniques for monitoring changes in fault zones during the earthquake cycle.

Seismogenic zones selected for focused study must have historic earthquake activity, be imagable by seismic reflection, be geographically accessible, and ultimately be penetrable with a riser drillship. At the SEIZE workshop application of these criteria to candidate localities targeted the Japanese Islands (Nankai Trough and Japan Trench) and Central American (Costa Rica and Nicaragua) for SEIZE programs. The extraordinary infrastructural investments, the large societal relevance, the seismic imaging possibilities, and the drilling potential in the Japan area require focus there. Central America, especially Costa Rica offers exceptional opportunities for seismic, volcanic and geodetic monitoring, can be imaged and drilled, and contrasts geophysically with the Nankai Trough locality in Japan. Japan Trench and Nicaragua have generated tsunamigenic earthquakes warranting investigation. Investigations in the Nankai Trough in Japan will have direct application to understanding the societally relevant, currently quiescent but paleoseismically active Cascadia seismogenic zone of the Pacific Northwest.

Introduction

In 1995 an International Lithosphere Program (ILP) workshop on "Dynamics of Lithosphere Convergence" reviewed the progress achieved in recent studies on convergent margins. One result of this workshop was an international research program **SEIZE** (Seismogenic Zone Experiment) to study the seismogenic zone of great thrust earthquakes at convergent margins (Fig. 1). Here we report the results of a subsequent workshop in 1997 that led to the refinement of the SEIZE research objectives and selection of localities for concentrated investigation.

Most of the world's great earthquakes are inter-plate underthrusting events in subduction zones. Although plate tectonics provides the underlying kinematic explanation for these underthrust earthquakes, only a small portion of the plate contact generates earthquakes -- this portion is the ***seismogenic zone***. Understanding the seismogenic zone provides both fundamental scientific challenges and is of great societal relevance. Accordingly, SEIZE focuses multidisciplinary investigations on such earthquake processes. The most important source of information about the seismogenic zone is, of course, seismicity. Yet, understanding of these seismic processes requires studying many aspects of the related geology and geophysics.

Seismologists have determined that the size of an underthrust earthquake is related to the fault area that ruptures in any one event. For the largest events, the entire length of the seismogenic zone is ruptured, it is then the along-strike rupture width that determines the final size of the event. Large earthquakes are more important than all the smaller events, both from a scientific and societal perspective. About 20 great underthrust events with M_w 8.2 have occurred in the 20th century; the number increases to 42 by counting underthrust events with M_w 8.0. The uneven distribution of these large thrust events (Fig. 2) is one manifestation of the diversity of subduction zones. Many localities are of seismological interest for geophysical and geological investigation (Appendix I). Potential SEIZE field sites include areas of great earthquakes and smaller more frequent earthquakes.

A shallowly dipping subduction zone thrust provides a large fault surface that is accessible to study by a combination of drilling and ongoing monitoring using passive and active seismology. These thrusts are part of the subduction conveyor belt, in which we can sample the incoming sediment that 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 are relatively accessible.

RESEARCH OBJECTIVES

The 1995 ILP workshop report outlines the following research objectives for SEIZE: I. to establish the relationships between **earthquakes** and: (1) structural geometry, (2) distribution of stress and strain, (3) thermal structure, and (4) nature of fluxes of the fluids and solids in and across diverse seismogenic zones; and II. to formulate testable quantitative models of how the shallow subduction cycle works, including the complex interactions among the multiple processes. During the SEIZE workshop in 1997, we refined these objectives into a number of topical questions:

What is the Physical Nature of Asperities?

Seismologically asperities are areas of higher slip during the earthquakes. They have been interpreted to be "stronger" regions of a fault that have resisted motion during the interseismic period; thus, asperities may be seen by other methods such as geodesy, seismicity, and imaging by seismic reflection. What is the physical nature of asperities? Are they distinct rocks (e.g., basalt vs. sediments)? Are they areas of different frictional properties than non-asperities? Are they independent of materials, for example being controlled by fault geometry, or a fluid-pressure? Are they permanent at least until the next seismic cycle?

Many of the above questions also apply to the nature of the "weaker" seismogenic zone that fills in around the asperities. One extreme view is that the asperities and "weaker" regions are almost identical; perhaps only a subtle variation of frictional characteristics is responsible for their different macroscopic behavior. These questions bear directly on how and where creep occurs within the seismogenic zone. There are some subduction zones where significant creep is required -- yet these regions are seismogenic since small events are scattered throughout the seismogenic region. Therefore, the physical nature and effective constitutive law for both "asperities" and the intervening "weaker" regions are key targets of the SEIZE initiative. It would be extremely useful for hazard estimates to know in advance what are asperities and what are the diagnostic signs of an asperity within a segment.

What are the Temporal Relationships Between Stress, Strain and Pore Fluid Composition Throughout the Earthquake Cycle?

Obtaining a better understanding of the cycle of stress and strain accumulation and release along subduction plate boundaries is a key objective of SEIZE. Strain monitoring with comprehensive onshore GPS networks and utilization of newly developed sub-sea geodetic technologies can be invaluable for identification of regions of strain accumulation along the plate boundary and determination of the rate at which strain accumulation is occurring. Such studies will be essential in defining regions of potentially high seismic hazard and distinguishing these regions from those of aseismic subduction. Moreover, by eventually drilling into potentially seismogenic subduction zones, we will obtain critically important data on the state of stress, pore pressure and the composition of pore fluids. Such data bear directly on the physics of faulting and earthquake nucleation and will provide new insights into the manner by which temporal fluctuations of pore pressure and stress are related in earthquake processes.

In subduction systems, a number of investigations suggest that certain seismogenic zones, and certainly their seaward extension or "d&eacutecollements," are **"weak"** faults. Data collected by SEIZE can determine if and why seismogenic zones are weak and will have direct feed-back to programs addressing similar questions along the **San Andreas fault** or other similar crustal faults

What Controls the Updip and Downdip Limits of the Seismogenic Zone of Subduction Thrusts?

The updip and downdip limits of rupture in great subduction-thrust earthquakes are important factors in seismic and tsunami hazard. The downdip limit determines the landward extent of the seismic source zone, which is important for great earthquake hazard at inland cities. The seaward updip limit is important for tsunami generation. For some earthquakes there is slow rupture of the updip portion of the thrust that generates tsunamis but less prominent seismic waves, i.e., "tsunami earthquakes." Thus the updip portion of the thrust interface, seaward of the high frequency seismic rupture limit is an important part of the study.

A number of physical and compositional explanations have been proposed for these limits and an important part of this study is a comparison of model limits to the actual updip and downdip limits of the seismogenic zone, especially for past great earthquakes. Equally important is to seek observable changes on the subduction thrust at these limits, for example by using multichannel seismic reflection techniques. The updip and downdip limits of the seismogenic zone may be determined from:

(a) the rupture area of past great earthquakes, from earthquake waveform modeling, from the distribution of aftershocks, from tsunami modeling, and from dislocation modeling of coseismic geodetic data;

(b) the interseismic locked zone determined from dislocation modeling of interseismic geodetic data;

(c) the updip and downdip limit of intermediate and smaller magnitude thrust events. Updip limits appear to range from near the trench to depths of about 10 km. Downdip limits appear to range from less than 10 km for some island arc margins to over 40 km depth for some areas of subduction beneath continents.

For the updip seaward limit, initial attention was focused on the boundary between the unconsolidated accretionary prism sediments and crystalline forearc crust. However, increasing structural data on indicate that, in at least some areas, a portion of the seismogenic zone lies beneath the accretionary prism. Thus the updip limit must be controlled by some change in physical properties on the thrust. Recent attention has been given to chemical-mineralogical changes, especially the dehydration of stable sliding smectite clays to seismogenic illite-chlorite at 100-150°C. Another possibility is the transition of shales to slates at about 200-250°C where the dehydration reactions are more complete and the rock strengths are sufficient to support substantial elastic strains. Pore pressure increase downdip is another candidate; fluid pressures are high and may approach lithostatic in the seismogenic zone exerting control on effective stress.

Proposals for the downdip limit include: (a) thermally activated stable sliding above 350°C for crustal composition rocks (with a transition to perhaps 450°C). This transition is observed in laboratory studies and in the maximum depth of earthquakes in continental areas or (b) stable sliding caused by serpentinite in the forearc mantle (if the mantle corner is reached before 350°C). Large amounts of water must be expelled upward into the overlying forearc mantle, so extensive serpentinization is expected. Serpentinite appears to exhibit stable sliding at temperatures below about 500-600°C.

The relative importance of these potential controls is presently unknown. To assess these parameters, we need to understand what controls variations in temperature, pore pressure and mineralogy on the subduction thrust, and how these interrelated influences determine the stability field of the thrust plane. These variables include the thickness of insulating sediment on the incoming crust, the age of the subducting oceanic plate, the convergence rate, the thrust dip profile, the porosity and permeability and fluid flux and migration paths along the décollement, and the radioactive heat generation and thermal properties of the overlying forearc.

What is the Nature of Tsunamigenic Earthquake Zones?

In most subduction zone segments, the seismogenic zone where earthquakes nucleate does not extend all the way to the trench axis. There is a narrow strip of aseismic plate boundary from the trench down to a depth of a few kilometers, where seismic moment release is rare. When great and large earthquakes rupture the seismogenic zone, they generate tsunamis that can be quite hazardous. Empirical and theoretical relations have established a connection between the size of underthrust earthquakes and their tsunamis. On occasion, an underthrust event generates a tsunami much larger than expected. There are still several competing hypotheses for this anomalous behavior, one of which is that these earthquakes have their slip concentrated at very shallow depths. For a few events, it has now been shown that the tsunami was generated by slip in the shallowest aseismic region. An excellent example is the 1992 Nicaragua earthquake, where Figure 3 shows that the slip was concentrated near the trench while the aftershocks were scattered through the more typical seismogenic zone. This observation shows us that the upper "aseismic" zone is capable -- at least in some places and some of the time -- of being seismogenic. Thus, a good target of investigation for SEIZE would be rupture zones of tsunamigenic earthquakes such as the 1992 Nicaragua event or the 1896 Sanriku event. For hazard estimates it would be extremely useful to know the structural/tectonic characteristics of a subduction segment capable of a tsunamigenic earthquake, such as convergence rate, sediment supply, structure of the top of the oceanic plate, accretion rate, and upper plate structure.

What is the Role of Large Thrust Earthquakes in Mass Flux?

A fundamental process of subduction zones is the transfer of material from one plate to the other. In the upper part of subduction zones, including the seismogenic zone, this can take the form of the addition of material from the subducting plate to the base of the overriding plate by underplating, with consequent uplift. Alternatively, removal of material from the base of the overriding plate by a number of processes leads to tectonic erosion, manifested by subsidence. It is not known whether major thrust earthquakes are part of the mechanism of either of these processes or whether they arise purely from slip between the two plates with no transfer of material. If it is the latter, then the regions of the slip surfaces of the earthquakes would be zones of no transfer of material. The association of areas of rupture with regions of the forearc known to exhibit subcretion or tectonic erosion, however, suggest that large thrust earthquakes are involved in either one or perhaps both of these processes. The primary information needed to resolve this issue can be provided by seismic reflection images to show the structures, in combination with an accurate location of the slip surface (to within a few tens of meters) relative to the seismic image, and measurement of the change in shape of the sea floor above the zone of subcretion or tectonic erosion.

CRITERIA FOR SELECTION OF PRIMARY SEIZE FIELD AREAS

Following the approach proposed by the MARGINS Program, SEIZE must focus in a few locations to maximize the essential multidisciplinary interaction and integration. This does not exclude studies in other regions, especially those examining the variability among subduction zones, and the causes of this variability. A major goal of this workshop was to select prime locations for SEIZE. The following factors are important for site selection:

Seismicity: Large Events

A fundamental requirement of the SEIZE program is high quality earthquake data, especially from the seismogenic zone thrust. Desirable features/information includes:

(a) Well-studied recent large earthquakes that allow definition of the updip and downdip rupture limits and the rupture parameters. Any study should utilize data from the global seismiographic network, local seismic networks, tsunamis, and geodetics.

(b) Relatively frequent events, especially with the potential to capture an earthquake during a reasonable duration of monitoring.

(c) Degree of seismic coupling or the ratio between seismic and aseismic slip.

(d) Segmentation of rupture areas.

(e) Data from small earthquakes. These results provide important information, for example in defining the stress field.

Imaging and Characterizing the Seismogenic Zone by Multichannel Seismic Reflection

Multichannel seismic reflection is the most important technique for imaging the seismogenic zone. Thus, the ability to obtain reflections from the subduction thrust over much of the seismogenic zone is critical. The data should be of sufficient quality to allow structural interpretation of the thrust zone downdip and along strike, and quantitative modeling of physical property variations in and around the thrust zone. Most of the subduction zones that are likely targets have at least some multichannel reflection data.

Seismogenic Zone Drilling

Drilling to the seismogenic zone is a means of testing predictions of remote sensing, experiments, and models. Criteria to be considered for drilling include:

(a) What is the minimum sub-bottom depth of the seismogenic zone and water depth? The updip limit and therefore vertical depth of the seismogenic zone is best defined by seismic and tsunami data; lacking such data, postulated limits such as 125°C (clay dehydration) may be used. The present ODP drill ship has a practical borehole limit of 1-2 km, with a total drill string (water plus borehole) of about 8 km; up to 3 km boreholes may be possible in the future with the present ship. The proposed Japanese drill ship with a riser will have a total drillstring length of ~12 km, initially with a maximum riser length (water depth) of 2.5-2.8 km.

(b) Can the formation be drilled with good core recovery? It is important that drilling conditions allow penetration into the zone of interest and that samples are able to be recovered.

Available Survey and Drilling Data

The present data available is important both for subduction zone and local site selection and for the program design. Data acquired in the past also represents a significant investment that does not need to be repeated. Important data include:

(a) Multichannel seismic surveys (note importance of quality, penetration, 2-D versus 3-D, etc.); also seismic structure by seismic refraction, wide angle, OBS etc.

(b) Earthquake, and tsunami data analysis (see above)

(c) ODP/DSDP drilling and data analysis

(d) Heat flow and other thermal data

(e) Swath bathymetry, acoustic imaging

(f) Land geodetic data to define the landward rupture limit (and perhaps seaward in a few places); also marine geodetic data

(g) Onshore surveys and studies that allow offshore-onshore integration (especially where seismogenic zone extends across the coast).

Infrastructure and Logistics

(a) A long annual weather window for survey and study. A long window will also allow the possibility of a rapid response to great events (also currents and other local conditions)

(b) Accessibility of local marine geoscience institutions and ships. Local institutions reduce the cost of many programs and increase the availability of ships and other facilities.

Nature of Subduction

Subduction parameters provide a context for each candidate site and for comparing and constraining potential locations. Some of the important parameters are:

(a) amount and type of incoming sediment

(b) sediment accretion versus erosion

(c) convergence rate, incoming plate age, thrust dip angle, is a volcanic arc present (and type)

(d) the thermal regime (related to age of incoming plate and incoming sediment thickness)

(e) how much diversity is represented along-strike

(f) steady state subduction (not rapidly changing, or recent developments or other complexity)

Implementation Strategy

The Seismogenic Zone Experiment must consist of several integrated components designed to characterize the key features of a specific seismogenic zone. Typical field components would consist of earthquake seismology, seismic reflection imaging and refraction velocity studies, shallow and deep drilling, long-term monitoring and geodetic measurement, and on-land studies of exhumed seismogenic zone. Evaluation and even design of the field components will require experimental and modeling studies.

Earthquake Seismology

Characterization of the seismogenic zone at subduction zones can potentially be accomplished seismically with three methods: 1) seismic tomography; 2) earthquake wave form inversion; and 3) active source imaging and velocity studies. Characterization of the seismogenic zone using earthquake waves as sources is the method that has yielded nearly all we now know about subducted slabs. Unfortunately, the location of shallow earthquake sources at subduction zones, and thus much of characterization, depends on teleseismic arrivals at distant stations and arrivals from stations on land, which are nearly always located on only the landward side of the trench. Such location estimates are likely to have systematic errors associated with them, which are difficult to detect and correct. To properly characterize this zone with earthquake arrivals, sensors are required close to the sources and at a variety of azimuths and distances. This requires that permanent ocean bottom seismic stations be established, some of which should be seaward of the trench axis. Technology exists to establish such stations, which can also double as tsunami detectors and monitors of other geophysical parameters. For many applications, data from these stations should be transmitted to shore in real-time. Seismologists can resolve focal mechanisms from teleseismic waves of earthquakes with a magnitude greater than 5.5 Ms (magnitude from surface waves). Source processes can be resolved from broadband waveform inversion of earthquakes with magnitudes greater than 7 Ms and also inversion of tsunamis recorded at tide gauges. Measurements should also include the recording of S-

wave transmission through the seismogenic zone, including S-wave splitting, to estimate fracture orientation and to monitor changes in stress state.

By extending seismic recording arrays offshore we can monitor the buildup of stress in the oceanic crust as the earthquake cycle progresses. In regions up-plate from an asperity, this stress buildup has caused intraplate focal mechanisms to take on a stronger compressional component than would otherwise be present. Although extraction of focal mechanisms using OBS data has been complicated by uncertain performance of horizontal components, focal mechanisms from intra-plate earthquakes can be recovered using 3-4 instruments. Where earthquakes are monitored regionally with modern broadband instrumentation, source processes are routinely being determined to for events with magnitudes as small as 3.5. While this can be done from shore to some extent, in a subduction zone, 3-component OBS's would greatly extend capabilities.

Recent observations in California have revealed the presence of seismic waves controlled by a low-velocity layer of fault gouge in a strike-slip fault zone. This waveguide supports dispersive wave propagation in the same fashion as does a low-velocity crust overlying mantle. Very effective excitation of the waveguide occurs since the source is located within the waveguide. Simple modeling as a single layer between two half-spaces has allowed extraction of fault zone thickness and the shear velocity of the infilling material. In the California example, a fault thicknesses of 120-170 meters and shear velocities of 0.7-0.85 km/sec have been observed from interface waves. Lower-resolution body-wave studies yield 1-2 km wide zones with shear velocities of 2-3 km/s and Vp/Vs ratios of 2-2.3.

We can expect similar physics to govern subduction fault zones. Low-frequency guided waves traveling up slabs have been observed on broad-band seismometers located on islands. On land, the trapped waves were recognized by their phase velocity, so use of this phenomenon will require a linear array of OBSs in the trench, and, as necessary, enough land and sea seismic stations to provide usable locations. Depending on the distribution of sources and receivers, the potential for two-dimensional tomography exists. If asperities (strong regions) have a velocity structure that is different from regions that are freely slipping (or nearly so), they should be imagable by two-dimensional tomography, depending on the source-receiver distribution.

Reflection Seismology

Imaging of the seismogenic zone at depths of 10-20 km in subduction zones will require new experimental designs. In its simplest form, the imaging must define the top of the down-going slab and structures within the base of the overriding plate, from the deformation front, landward through the seismogenic zone. These will help define the geometry of the subduction zone, possible asperities, and erosion and accretion at the base of the overriding plate, and properties of the fault zone. We must have the ability to observe seamounts and thrust packages at vertical scales of ~500 m and lateral extent of ~1 km at depths of 10-20 km.

Seismic sources must be large to penetrate to the needed depths, yet contain a broad-band spectrum of energy to preserve resolution and allow waveform inversions of the seismic reflections. Seafloor swathmapping imparts a 3D aspect that greatly constrains interpretations and helps locate seismic lines in areas of minimal out-of-plane effects. Multichannel seismic (MCS) reflection methods, particularly 3D acquisition and processing have been shown to provide high-quality images of the d&eacutecollement and structures above and below. Although there is always a desire for higher resolution and deeper penetration, the method is limited in depth by attenuation and source strength,

and in resolution by frequency content of the source. The reflection and refraction techniques become more powerful when combined than when applied separately. Closely spaced ocean bottom seismographs/hydrophones (OBS/H) along a modern normal incidence reflection line have been used to extend structure to depth and the velocity data aid processing. These data will also provide background velocities to combine with reflection waveform analysis. The few examples of such combined data indicate possible imaging down to the depths where great earthquakes nucleate.

The best way to obtain high-quality images is by using 3D seismic reflection, particularly with enhanced processing such as 3D dip-moveout and 3D prestack migration. These techniques require high quality data as well as high-performance computing capability. Use of a high capacity, broad source, a ~6 km streamer, and OBS(H) at perhaps 500 m spacing would likely be necessary for adequate images. With extensive pre-stack processing, the 6 km streamer will provide adequate images of shallow structure, although velocity information will be limited. Where the structures above the seismogenic zone are more complex (probably the more common case), first order corrections for the overlying structure are essential. If the shallow structure is not properly accounted for, reflection amplitudes and waveforms of deeper events will be severely distorted. Short of a full 3D program, a swath 3D approach could correct for some of the structural complexities. A high capacity broad-bandwidth source, densely spaced OBHs along a dip line, and a multiple-streamer ship shooting a series of parallel lines (the number and spacing would have to be determined from modeling) would produce exceptional observations.

The use of multi-OBS/H enables us to get fine images of the seismogenic zone. On the basis of recent experiments, OBS/Hs spaced along a 2D line every 500 m with the combination of tomography might give a reasonable 2D image, but still suffering from the 3D effects. However, such densely-spaced OBS/H provide the information to develop a proper velocity field for the entire margin. This is essential to the full characterization of the margin and is an important method to improve locations of microearthquakes.

Geodetic Methods

A fundamental measure of slip on the seismogenic zone is the deformation of the surface of the overriding plate from the trench to the backarc. Measurement of the surface deformation can be interpreted, through appropriate models, into maps of locked and slipping portions of the seismogenic zone. The geodetic measurements must be able to measure deformation rates that may approach a few cm/yr in both horizontal and vertical dimensions over 100-200 km range from the trench. Traditional methods such as leveling only measure the vertical component and must be carried out over long distances to tie into a stable plate interior. GPS is currently the premier method for determining 3D displacements in a global reference frame. Simple models of elastic, interseismic strain at seismogenic zones feature rapid subsidence nearest the front of it diminishing in rate inland and crossing over to uplift roughly above the deepest extent of the locked zone. The horizontal expressions of such elastic strain models predict a smoother transition, with the near trench portion of the overriding plate moving mostly with the downgoing plate velocity and decreasing towards the stable plate interior. The vertical component of motion can be highly diagnostic of the dip of the seismogenic zone; to be most effective, measurements must be made to ~100 km of the trench to define the down-dip extent and within a few tens of km to define the updip extent of the seismogenic zone. In the case of land-based GPS, choosing a location where the coastline extends as close to the trench as possible is a great advantage towards "imaging" the locked and slipping portions of the seismogenic zone. In the marine environment, underwater sound transmission can be used to tie seafloor reference points to seasurface

platforms whose positions are simultaneously determined with GPS. Results from initial tests imply that uncertainties in velocity vector estimation should be 5 mm/yr. or less. Besides standard GPS campaigns carried out at year-scale separation, any geodetic monitoring of the seismogenic zone requires the incorporation of continuously operating GPS receivers both to more quickly recover the quasi-steady-state interseismic deformation and to provide the potential to measure any transient strains related to co- or post-seismic deformation.

ODP Penetrations

Although depth-limited, ODP penetrations must be an integral part of SEIZE. Subduction zones are conveyor belts, moving materials from the surface through the seismogenic zone to great depth. Therefore, ODP-style penetrations of about a km can sample the materials that ultimately become the fault rock of the seismogenic zone. A SEIZE program will require a series of holes to characterize the incoming sediments and rocks, and their associated fluids.

The d&eacutecollement zone, which has been repeatedly penetrated by drilling, is the shallow, seaward manifestation of the seismogenic zone megathrust. Fluids sampled from d&eacutecollement zones are known to have migrated from the seismogenic zone. Therefore, sampling and ultimately instrumentation of this structure provides access to the pulse of the seismogenic zone.

In addition to sampling the incoming material and monitoring, relatively shallow ODP penetrations can opportunistically provide information on deeper levels of subduction zones related to the seismogenic zone. For example drilling into diapirs can sample material brought up from great depths, and constrain the pressure-temperature conditions in the forearc. Deeply sourced fluids sampled at shallow depths in monolithologic forearcs may provide unique information about processes at depth. Drilling into out-of-sequence thrusts in areas of slope erosion can access deeper levels of faults than normal accessible by ODP.

Borehole Observatories

SEIZE will benefit greatly from emplacement of permanent observatories including seafloor seismic observatories and borehole monitoring devices. Technology for construction of such observatories at subduction zones exists, and can be accomplished with an electro-optical cable to provide power to experiments and communications to shore. Although initially expensive, savings in ship time, and the constant availability of real-time data make emplacement of observatories practical where cable lengths are relatively short.

Instrumented, hydraulically-sealed boreholes (CORKs) provide a real-time record of sub-surface transient events manifested by temperature, pressure, and pore-water chemistry anomalies. At the very least, these records will establish the "steady-state" hydrologic conditions in various parts of the formations that host seismogenic zones, including the faults themselves. They may also define precursor, co-seismic, or post-seismic signals related to seismic events, since it is almost certain that hydrologic signals are sensitive to changes in stress, ground motion, and fault-zone slip. During SEIZE, it will be essential for CORK data to be correlated with synoptic OBS or borehole seismometer results. In addition, other downhole sensors (which may require emplacement or periodic replacement) can be incorporated with a wireline-deployable CORK. These complementary sensors might include hydrophones, geophones, tiltmeters, strain gauges, or chemical sensors. Hydraulic access through the CORK accommodates a continuous osmotic fluid sampler or periodic

borehole fluid extraction for time-series determinations of pore water chemistry.

Active hydrogeologic tests, conducted by submersible or ROV through the hydraulic port on the CORKs, provide in-situ determinations of formation transmissivity/permeability and storativity. The duration of these tests can be extended to minimize effects of drilling and maximize the radius of investigation. Furthermore, the in-hole tidal signal variations can be used to investigate mechanical/hydrologic properties of the tested interval.

Although the existing CORKs seal the borehole as a single volume and allow conditions to be monitored in a single interval of open hole or perforated casing only, monitoring and testing of multiple intervals (which require sophisticated casing strings and drillstring packers) is necessary if the variations with depth of the fluid regime is to be delineated in a single hole.

Riser-Type Deep Drilling

Drilling into a seismogenic zone or relevant deep objectives that are inaccessible by the current capability of JOIDES Resolution is one of the major goals of the SEIZE. Proposed Japanese riser drill ship (OD21 drilling vessel) provides us an opportunity to achieve this goal. Experience gained through DSDP/ODP drilling indicates that convergent margin borehole condition is generally quite hostile. Unstable hole conditions were often met due to swelling clay, overpressured pore fluid, stress-induced hole collapse, etc. Such instability has been a large obstacle not only against core recovery but also logging and long-term measurements. In order to overcome such hostile environments, especially in deep holes and for continuos monitoring of formation pressure, a drilling-mud circulation system (riser system) has to be deployed.

Current OD21 specifications are as follows: The riser will be implemented in two phases, initially at a 2500-2800m length and later 4000m length. The drill string will be 12000 m in length. A blowout prevention (BOP) system at the seafloor will control hydrocarbon risk. Normally, a seven-inch casing liner will be set at the bottom.

In the first phase of OD21 (2003-2008), it is desirable to achieve a deep convergent hole with 2500-2800m water depth and about 6000m penetration at a target seismogenic zone. Site survey and preparatory experiments should be launched well ahead to obtain convincing evidence for the location and geometry of target seismogenic zone.

Field-Based Observations of Paleoseismogenic Zones

Field studies of onland analogues can provide critical information about rock properties and alteration products over the ranges of P-T conditions relevant to the seismogenic zone (~125°-400°C). On land observations will feed into conceptual models of the seismogenic zone that can be initially tested by seismic reflection techniques, and ultimately by drilling. Particular attention should be focused on structural packages that may represent the paleo-d&eacutecollement and on out-of-sequence faults that display large amounts of vertical displacement of the paleotemperature structure. Analyses should focus on contrasts among hanging wall, footwall and associated shear zones. These contrasts may be defined by differences in deformation fabrics, vein mineral paragenesis, fluid inclusion microthermometry, vein density and orientation, alteration of organic matter, and phyllosilicate diagenesis. Constraints on timing of faulting can be established using such methods as fission track geochronology.

Laboratory Experiments

A laboratory-based program is critical to the success of SEIZE to link the various indirect measurements to in situ conditions of the seismogenic zone. The composition, temperature, stress, and mechanical state of the rocks and fluids of the seismogenic zone will all have to be inferred from remotely-sensed data, such as measurements of surface heat flux, seismic velocity and reflectivity, fluid fluxes, and geochemical signatures. The relationships among these proxies remain insufficiently known to extrapolate chemical and physical data collected at shallow levels to infer conditions existing at seismogenic depths. SEIZE must therefore include a comprehensive program of laboratory experiments documenting relevant physical-chemical processes and elastic and material properties, at in situ temperature, stress, and fluid pressure. These experiments should involve sediments and laboratory-generated analogs, altered oceanic basement, serpentinites and their exhumed equivalents, representative of the d&eacutecollement zone and underthrust sequences. The experimental data will provide important input to hydrologic and mechanical modeling efforts, which will in turn help focus experimental investigations.

Important fundamental processes that need to be examined through laboratory experiments include:

- **Steady-state fluid-rock reactions and their kinetics, partition coefficients, and isotopic fractionation factors.**

- **Thermally and physically activated mineral dehydration reactions and their impact on rheological boundaries.**

- **The changes in relationships among seismic velocity (Vp and Vs), attenuation, density, fluid content and composition, and stress during compaction, diagenesis, metamorphism, and deformation, necessary to infer the physical meaning of seismic images and wave propagation.**

- **The linkage of chemical and physical processes to changes in porosity, permeability, stress, and rheology, crucial to a complete understanding of the temporal and spatial changes in seismogenic behavior and interplate coupling (e.g., velocity strengthening/weakening relationships, seismic/aseismic stress release).**

Modeling

Because access to the seismogenic zone is limited, models will be essential for integrating the field observations and laboratory results. Initially the models will be important for guiding data collection needs. New observations and parameter values can be used to refine the existing models and guide further sampling and experiments. For example existing tectonic models are often only constrained by onshore geodetic data. The addition of strain and tilt data from offshore observatories will improve our ability to use these models to understand the seismic deformation cycle. Another example concerns the need for refining existing models of fluid pressure. New laboratory results and drill core observations of the average composition of the oceanic crust will constrain the mass of fluids and rate of release over the seismogenic zone. As our level of knowledge about the important processes grows, it is anticipated that new models will be required that account for multiple coupled processes. These would include, for example, the coupling of pore pressure, stress, and temperature, or coupled fluid flow, chemical reactions, and transport. Moreover, some existing models will need to be extended from two to three dimensions to account for variations along strike of important controlling processes.

Simulations will be required on a range of scales from the borehole to the entire subduction zone. Models of borehole hydrologic data provide needed input to larger scale hydrologic models of the entire margin. Smaller scale process models such as rupture dynamics or sediment consolidation provide insights into the important controls on larger scale observations. The ultimate goal is to have models that test hypotheses about the nature and extent of the seismogenic zone. Models on such a large scale necessarily require many simplifications compared to the natural system. The insights needed to determine which simplifications are possible come from comparing smaller scale models with observations.

Potential Field Sites

Proponents for potential SEIZE sites here outline the cases for their localities in the context of the selection criteria outlined above.

Cascadia

Seismicity: The current interplate seismicity is extremely low; the thrust plane is the quietest of all subduction zones with respect to shallow thrust earthquakes on the plate boundary (Fig. 4, Fig. 5). However, there is considerable paleoseismic evidence of large earthquakes and associated tsunami in the past, the most recent being about 300 years ago. The potential of future great earthquakes (Mw 8-9) and tsunamis is of great societal concern. Two low angle thrust events have occurred in the past 5 years. The Petrolia earthquake (Mw 6.8) was at the plate interface or just above it in the overlying accretionary prism. The rupture area of this event is well determined, as is the crustal response to strain release. A smaller event (Mw 4.6) occurred offshore Cape Blanco in April 1996. It was a low angle thrust at a depth corresponding to the top of subducting crust.

Geodetic leveling data and limited GPS are consistent with strain accumulation at the northern and southern parts of the subduction zone. Geodetic uplift rates are an order of magnitude greater than marine terrace uplift rates, indicating that the strain is elastic and thus must be released by slip on the megathrust. Modeling of upper plate strain field has placed constraints on coupling stress on the megathrust.

Seismic Imaging: Several academic and industry seismic reflection lines show strong d&eacutecollement reflections extending into what should be the seismogenic zone. Recent profiles in Washington imaged the slab to ~18 km depth at a distance of ~100 km from the deformation front, and may include most or all the seismogenic zone.

Drillability: Sampling the seismogenic zone in Cascadia will require riser drilling. Depth to d&eacutecollement near the deformation front is around 2 km off Washington in 1.8 km water depth. It is about 6 km some 60 km east of the deformation front in 1500 m of water. Therefore there is a broad, accessible region that must capture the seismogenic zone as defined by the thermal regime and onshore geodetic data. DSDP Leg 18 and ODP Leg 146 penetrated the accretionary prism.

Present Data: There is a considerable amount of recent data -- MCS, OBS, onshore/offshore, onshore active source, broadband teleseismic, regional wave propagation -- on a network of lines along and across the entire forearc and arc. Extensive industry, USGS, and academic reflection data fill in the

remaining parts of the margin. Swath bathymetry and side-scan data exist over almost all the area. Seven ODP and DSDP sites have been drilled. Site 892 has a CORK and is ready for installation of experiments or monitors. The EMSLAB experiment measured conductivity across the margin in Oregon, with results that agree with seismic results. Thermal data are available from conventional heat flow, drilling, and BSR proxies. There is also considerable multidisciplinary work on LITHOPROBE transect.

Geodetic measurements have a 70 year onshore record. Installation of permanent GPS sites is underway, with annual measurement campaigns conducted since 1992. There is a pending proposal for a large network, and this is the site of the only seafloor geodetic measurements in the world.

Vertical sections have been sampled through the accretionary complex in the Olympics and Northern California. Extensive previous structural mapping, determination of deformation rates, submersible sampling, hundreds of cores and 12 industry test wells provide geologic framework.

Infrastructure and Logistics: There are numerous ports in this area, two major oceanographic institutions with ships, one smaller one, as well as NOAA and Canadian facilities and ships. There is a demonstrated rapid-response capability (e.g., RIDGE). The is the possibility of piggybacking with RIDGE to use a cable to support long-term observations, and installation of seafloor observatory has been proposed (TECFLUX) to study gas hydrates at Site 892.

SOSUS hydrophone arrays are available to monitor seismicity from the seaward side down to M=2 level. Data collected by US Navy are processed and distributed by NOAA, providing coverage superior to land based networks.

Nature of Subduction: The margin varies from slow or non accretion, to rapid accretion. Reconstructing the temporal history of accretion is now possible with new reflection data and sample transects. Subduction parameters (dip, age, etc.) are well known. Cascadia is the hottest subduction thrust overall, shifting the seismogenic zone to shallow levels. The volcanic arc has significant systematic along-strike variability that can be correlated to crustal structure and other forearc parameters. The potential seismogenic zone shows strong along-strike variability in incoming sediment supply and structural style that may relate to onshore variability of uplift rates, which may be controlling plate locking.

Central America: Costa Rica and Nicaragua

Seismicity: The Nicoya seismic gap (Figs. 6 and 7) has ruptured with M=7.0-7.7 earthquakes at about 50 year intervals (1853, 1900, 1950). The adjacent Nicaragua segment to the north (Fig. 3) has broken recently in a slow, tsunamigenic earthquake in 1992 and the adjacent segment to the south of the Nicoya seimic gap also rupture recently with a M=7.0 earthquake (1990). The incoming plate and sediment sections are similar for Nicoya and Nicaragua. The difference in seismogenic response is as great as can be found anywhere, yet these zones abut. Abnormally low background seismicity of the Nicoya gap contrasts with very high levels of seismic activity in Nicaragua, suggesting an important difference in coupling between these two segments. Understanding the reasons for these differences will clarify our understanding of the seismogenic process.

Seismic Imaging: Offshore 2D and 3D multichannel seismic data has followed the plate interface to near the coastline into the seismogenic zone. An additional wide angle offshore and associated onshore

survey has continued to follow this interface beneath the coastline.

Drillability: The seismogenic zone may be within the depth range of current and planned drill ships as well as land sites on the Nicoya Peninsula. The Nicaraguan tsunamigenic earthquake broke the upper part of the plate interface near the trench, putting it within reach of the present capabilities of the JOIDES Resolution. The seaward edge of the Nicoya seismogenic zone is less well understood, but present estimates put it at a depth of 4-6 km below the sea floor at the mid-slope region. Such depths will require riser drilling. In addition, the seismogenic zone lies at 10-11 km beneath the Nicoya coastline, putting it within reach of onshore drilling. Difficulties in drilling have hampered attempts to penetrate the prism on DSDP/ODP Legs 84 and 170, but these should be alleviated with riser drilling.

Present Data: Earthquake occurrence is presently very well monitored in Costa Rica. The Nicoya gap is flanked on the north by the Nicaragua slow earthquake zone of 1992 and to the south by the 1990 south Nicoya earthquake. The latter has been interpreted as breaking over an asperity related to seamount subduction. No seamounts are subducting beneath the Nicoya segment.

A GPS network has been installed in Costa Rica for several years, with a focus on the Nicoya Peninsula. Several permanent stations are installed, including one on the Nicoya peninsula. The locked zone in the Nicoya gap occurs beneath the peninsula, and it is therefore especially well-determined by geodesy.

A great deal of additional information is available for the Nicoya segment. Heat flow (abnormally low because of fluid circulation into the upper oceanic crust), swath and 3D seismic bathymetry, focused onshore neotectonic studies, ODP drilling (Leg 170), Alvin diving to map cold seep communities, and onshore-offshore data integration are well developed for Costa Rica. In contrast, offshore Nicaragua there is one multichannel seismic line in the area of the 1992 earthquake and a detailed Hydrosweep survey of this region.

Infrastructure and Logistics: Costa Rica has a well-developed geological and geophysical infrastructure. The proximity of these sites to the coast makes them accessible by relatively small vessels if necessary for rapid instrument deployment. Infrastructure is less well developed in Nicaragua relative to Costa Rica. Weather conditions are mild year-round off the Nicoya peninsula, and reasonable most of the time off Nicaragua.

Nature of Subduction: Approximately 450 m of pelagic/hemipelagic sediments on the Cocos Plate pass beneath the toe of the slope. For Nicaragua, 10Be concentrations in erupting volcanics are the highest measured in any arc, implying nearly complete subduction of all incoming sediment. Off Costa Rica, seismic reflection and ODP drilling results show that all incoming sediment passes beneath the toe region. However, lack of 10Be in the Costa Rica arc volcanics implies that the shallower underthrust sedimentary section is accreted above the zone of melting.

Convergence rates off Costa Rica and Nicaragua range from 75-88 mm/yr., increasing southward. The age of the subducting plate is early Miocene. The dip angle increases beneath the Nicoya segment from 3° at the toe to 7-8° under the mid-slope region.

Himalaya: India, Nepal, Bhutan, and China

The seismogenic processes that lie at the heart of the SEIZE initiative are not restricted to water-

covered areas. The type-example of the ultimate end-member of a convergent margin megathrust is the Himalaya collision zone. Here subduction of oceanic crust (Tethys) beneath an Andean-type continental margin (Gangdese) has proceeded to the point of termination by arrival at the trench of the ultimate "asperity," the Indian cratonic lithosphere.

Seismicity: The Himalayan thrust belt has a history of great earthquakes, including the Great Assam event of 1857, perhaps the largest earthquake in recorded history. It has a modern seismogenic zone that corresponds to a low-angle d&eacutecollement beneath a foreland sedimentary sequence, and segmented seismic behavior, at least part of which seems to be related to lateral heterogeneities in the underthrusting Indian plate.

Seismic Imaging: Recent deep reflection profiling (Project INDEPTH) in the Tibetan Himalaya has successfully imaged the deeper, non-seismogenic portion of this plate boundary. Future profiling may trace this image upward across the lower boundary of the seismogenic zone.

Drillability: The Himalaya region has a seismogenic zone near the limit of sampling by drilling (ca 10 km on land).

Present Data: One set of deep seismic profiles has been shot across Tibet. Vast amount of geologic field mapping data are available.

Infrastructure and Logistics: The region represents a stable, easily accessible base for remote monitoring of temporal variations in the seismogenic process directly below. There would be no contamination of fluid/gas samples by sea water.

Nature of Subduction: Key elements of the thrust zone geology are exposed (e.g., the mylonites of the Main Central Thrust).

Japan Trench

Seismicity*:* Background seismicity is high and very well studied (Fig. 8). Large earthquakes include outer rise normal faults (e.g., 1933 event), thrust type and tsunami earthquakes (e.g., 1896). M-7 class earthquakes frequent the area (7 events over last 30 years between 38-41° N). Recently, occurrence of slow slips associated with "fast" event was found. This motion can account for much of the plate motion previously thought of as aseismic motion. Stress field is E-W compression across the whole island arc system.

Microseismicity and seismic structure studies have imaged the plate boundary in detail such as to be able to differentiate events inside, on or above the subducting plate (Fig. 9). Tomographic studies are underway which will correlate structure relative to earthquake characteristics.

Drillability: Previous DSDP drilling clarified the complex subsidence history of the forearc at this tectonic erosional environment. The traditional seismogenic zone here is too deep even for riser drilling. However, the shallower and drillable part of the subduction zone has generated tsunamigenic earthquakes, and could provide insights into these enigmatic seismic events.

Infrastructure and Logistics*:* The seismic and geodetic observation network covering the Japanese islands, already one of the world's most dense networks, is further rapidly expanding to be able to

continuously monitor land deformation and seismicity with unprecedented detail. This database will be extremely beneficial to design any SEIZE experiments. Furthermore, there is a 120 km-long fiber optic cable system to monitor seismicity and tsunamis off northern Honshu. A plan exists to deploy another cable system to augment monitoring the along trench axis variability.

The Japan Trench has been a prime target for seismological study under Earthquake Prediction Program of Japan. However, efforts have not been coordinated towards understanding the seismogenic zone in terms of material properties, fluid fluxes or heat budget; adoption of a SEIZE approach would be very complementary.

Nature of Subduction: Old Pacific plate (120-130 Ma) is subducting at a high rate (~10 cm/yr.) nearly perpendicular to the trench axis.

Mariana-Bonin

Seismicity: The Guam earthquake of August 8, 1993 (Mw = 7.5-7.7), is the most recent large event in the region. The nature of the Guam 1993 event is enigmatic, some investigators interpreting it as a subduction-related thrust event, but others suggesting that the mechanism is indeterminate. Two other large earthquakes have occurred there this century, one on September 22, 1902 is of unknown origin (Ms = 7.4) and another on April 5, 1990 (Mw = 7.5) was a normal fault event located in the down-going plate (11 km depth) at the trench axis Larger earthquakes (M>5) are not frequent in the Mariana region, but sufficient seismicity occurs along the d&eacutecollement to define the Wadati-Benioff zone beneath the Mariana convergent margin and determine the geometry of the plate dip. General seismicity of the region indicates a geometry consistent with a shallow plate dip in the forearc region and a rapid increase in dip under the volcanic front to nearly vertical under the backarc basin.

Seismic imaging: The shallow portion of the d&eacutecollement has been imaged within 15 km of the trench axis. Imaging of the d&eacutecollement in this non-accretionary margins is more challenging than in accretionary margins, because of the highly-deformed, high-velocity material that overlies the d&eacutecollement.

Drillability: The depth to the seismogenic zone in the Mariana-Bonin system is considerably greater than any current or planned drilling capability. The Mariana-Bonin forearc has been successfully drilled on DSDP/ODP Legs 60, 125 and 126. The drill holes in the forearc show interlayered arc tholeiite and boninitic lavas of up to Eocene age in the mid-forearc interlayered with in some cases and overlain by volcaniclastic sediments with little biogenic component (Sites 458 and 459). In the outer forearc (Sites 460 and 461) serpentine materials outcrop near the surface, covered sparsely with reworked debris from the outer forearc.

Present Data*:* Large portions of the Mariana forearc region and the adjacent Pacific Plate have been surveyed using side-scan sonar mapping, MCS and other geophysical surveying techniques. Samples of the seamounts have been collected in numerous submersible dives (Alvin and Shinkai 6500), ROV dives (Jason/Medea) and in dredges. Additional geophysical data and side-scan sonar mapping and imaging will be collected in a survey that will take place in August 1997. Leg 60 drilled four sites in the Mariana forearc region and five sites in the backarc basin and volcanic arc at about Latitude 18° N.

Infrastructure and Logistics: Most cruises in the Mariana region use the major harbor of Agana,

Guam as a port of call. Although the region is subject to typhoons for part of the year, the storm tracks generally pass to the south of the region until late in the storm season; only the winter months of the year are statistically at high risk for typhoons.

Nature of subduction: The incoming and overriding plates in the Mariana region are lithologically distinct. The incoming plate is essentially sediment-starved ancient Pacific lithosphere, containing numerous seamounts and two aseismic ridges. The over-riding plate exposes ultramafic rocks (mostly harzburgite) for up to 110 km west of the trench axis. The estimates of convergence rates for the Mariana margin range from 10 cm/yr. for the margin as a whole to variable rates of greater than 5 cm/yr. in the north to 3 cm/yr. in the south. The convergence directions show nearly orthogonal convergence over the southeastern portion of the margin (near Guam) and nearly parallel convergence in the northernmost portion of the Mariana system (at latitudes of about 22°- 23°N).

Nankai Trough

Seismicity: The Nankai Trough subduction zone of southwestern Japan is a vigorous seismogenic zone with recent great earthquakes in 1944 of Ms = 7.9 and 1946 of Ms = 8.0. Recent great events, high thermal gradients and the reflective plate boundary combine to make Nankai Trough a particularly good margin for a large-scale integrated study of seismogenic processes.

The historical record of great earthquakes extends from 684 AD. The recurrence interval is now approximately 100 years, and a northeastern segment not ruptured by the 1944-46 pair of earthquakes is a potential candidate for the next major event. The 1944 and 1946 events are well-studied (Fig. 10). Level-lines before and after rupture provided data on surface deformation that combined with tsunami data have been modeled to define the regions of co-seismic slip. Modern geodetic programs are well-established indicating that seismic coupling is high.

Seismic Imaging: Seismic reflection images from the Nankai Trough are classic in illustrating a fold and thrust system (Fig. 11). Image quality of the d&eacutecollement plate boundary also is exceptional tracing the top of the downgoing plate, and usually the Moho, from the Shikoku Basin to at least the shelf edge. The reflection associated with the plate boundary remains above the water bottom multiple well into the updip portion of the seismogenic zone, producing an exceptionally high quality reflection, a unique setting. Direct waveform inversion could establish how fault zone physical properties vary between the updip aseismic zone and the deeper seismogenic zone. This could also lead to repeat studies by 4-D seismic reflection to examine changes in fault properties during the earthquake cycle.

Drillability: Previous ODP drilling has shown that the sedimentary sequence, at least at the toe of the trench, is readily drillable. A 1300 m hole was completed with excellent core recovery. The shallowest updip limit of the seismogenic zone is approximately 3 km below the seafloor where the water depth is 4 km. Within the OD21 water depth limit of about 2.5 km, a 7-8 km deep hole would be required to reach the seismogenic zone. Other targets on out-of-sequence faults, that root in the seismogenic zone, could provide targets of intermediate depth suitable of deep JOIDES Resolution drilling.

Present Data: Because of the long history of destructive earthquakes in Japan, the seismological community has long-established and new modern seismometers arrays. There is a long history of geodetic surveys throughout the region and a recently installed large-scale permanent GPS program (over 1000 instruments throughout the Japanese islands). There is also a long-established tsunami

(tide-gauge) program. Extensive swath mapping and side-scan data exist on all offshore areas as well as 2-D seismic surveys. A combination of BSR mapping and heat flow probe data provide an unusually complete representation of the margin heat flow and demonstrate the high thermal gradients associated with the young crust. Active OBS experiments have produced successively higher quality velocity models of much of the offshore area. Three DSDP/ODP drilling legs provide a data set for assessment of the incoming sedimentary section and updip aseismic portion of the fault. Data from drilling and related geophysics have been used to develop some of the best models of fluid flow and deformation kinematics. The Shimanto Belt onshore Shikoku is a Cretaceous to Miocene analog the modern accretionary prism.

Several additional ODP drilling proposals for shallow drilling in the region are currently in review. A 3-year program of MCS/OBS data acquisition is starting this year to provide further regional coverage along the Nankai margin.

Infrastructure and logistics: There are well placed onshore networks of geodetic and seismic stations, and a strong community of seismologists interested in subduction zone scientific problems. Significant expansion of efforts related to earthquake research is underway in Japan. A key element is the recent installation of cables to a series of seismometers offshore to collect data with a geometry that is essential to define the updip limit of the seismicity. These are the first permanent installations, and the first that will allow proper geometries for location and characterization of the seaward (updip) sections of the fault zone.

The Nankai Trough is less than one day steaming time from Tokyo. A rapid event response program is already in place. The weather is fine, except for typhoons.

Nature of Subduction: The plate convergence rate of 3-4 cm/yr. is sufficient to result in great earthquakes. This margins is accreting clastic sediments from the young Shikoku Basin. Resulting high thermal gradients produce a relatively shallowly dipping subduction zone.

South America: Colombia and Ecuador

Seismicity: In the sector of southern Colombia and northern Ecuador, 4 mega-thrust earthquakes of magnitude exceeding 7.8 have occurred this century (1906, Mw=8.8; 1942, Mw=8.3; 1958, M=7.8; 1979, Mw=8.2). The slip surfaces of these earthquakes extend to the trench or very close to it.

Seismic Imaging: Multichannel seismic reflection lines across the northern Colombia margin show d&eacutecollement reflections extending landward for about 30-40 km from the deformation front to a depth of about 10 km. The amplitude of d&eacutecollement reflector increases landward over the first 10 km from the trench. The wedge in the north is composed of fine scale imbricate structures with a cover of slope drape. In the central section, larger imbricate structures are developed because of the greater thickness of the accreted layer, and there are slope basins developed locally in the cover. New multichannel seismic reflection and onshore-offshore reflection/refraction experiments with OBS and passive recording of seismicity are scheduled for 1998-99 in the sector of Colombia-Ecuador where the 4 mega-thrust earthquakes occured.

Drillability: The subducting oceanic plate is of Miocene age with a background heat flow of 120-130 mW/m^2. If the onset of the seismogenic zone is controlled by clay dehydration at about 125°C, then modeling to match heat flow derived from the depth of gas hydrate BSR indicates that the d&eacutecollement in the seismogenic zone is reached in the northern part of the Colombia margin about 20 km from the trench, at a depth of 2.5 km beneath the seabed in about 3.5 km water depth, within the drilling capabilities of the JOIDES Resolution. Farther landward, in a water depth of 2.5 km, possibly within a future riser drilling capability, the depth of the seismogenic zone is 4.5 km.

Present Data: Data from the area include multichannel seismic reflection lines, academic and industry, GLORIA side-scan sonar coverage of the complete margin, limited EM12D multibeam bathymetric coverage, GPS data on tectonic motions.

By comparison with some margins, the Colombia-Ecuador margin is under-explored. The existing data, however, demonstrate that it has a very high potential for a successful investigation of the seismogenic zone, which is quite shallow at its seaward limit, and of the controls on the mechanisms of large-thrust earthquakes.

Infrastructure and Logistics: Balboa in Panama provides a major nearby port to facilitate marine investigations.

Nature of Subduction: The Nazca plate is subducted beneath Colombia and Ecuador at rates between 50mm/yr in the north and 70 mm/yr in the south. The Carnegie Ridge, is subducted beneath the central part of Ecuador.

In the north, the trench is currently not filled with turbidites but a well-developed accretionary wedge is present. In the central section, at the northern limit of the rupture zones of the mega-thrust earthquakes, the trench has a turbidite fill of up to 2 km thickness and the margin is accretionary. Further south, in the main area of the mega-thrust earthquakes, the trench is still filled but there is little or no accretion. The steepness of the inner-trench slope suggests long-term tectonic erosion. The trench-fill disappears southward on to the northern flank of the Carnegie Ridge.

PREFERRED FIELD LOCATIONS FOR SEIZE

Evaluation of the various candidate sites in terms of the selection criteria suggests areas of initial investigation. Focus in these areas is required to achieve the desired interdisciplinary synergism, and because of the lack of resources to carry out complete SEIZE programs at many sites.

Preferred Sites

The consensus of the workshop was that SEIZE should be focused in Japan (Nankai Trough and Japan Trench) and Central America (Costa Rica and Nicaragua). Specifically, landward of the Nankai Trough, sediments underthrusting the prism can be traced into the seismogenic zone on existing 2D seismic reflection images; therefore, the material properties of the seismogenic zone are predictable. The seismogenic zone here lies within the planned capability of the OD 21 riser drilling ship. In the Central America region, the Nicoya Peninsula lies over the seismogenic zone and offers an exceptional opportunity for seismic recording and GPS monitoring. The seismogenic zone is located at 10 to 12 km beneath the Nicoya Peninsula, and lesser depths offshore. The Costa Rica margin contrasts well with the Nankai seismogenic zone because the former is non-accretionary and the latter is accretionary, the underthrusting section of the former is dominated by pelagic sediment, whereas the latter is dominantly terrigenous, the former is converging at a high rate whereas the latter is at a slow to moderate rate, the former has a low and the latter a relatively high thermal gradient. Both the Japan Trench and the Nicaragua Trench have produced tsunamigenic earthquakes, with shallow seismogenic zones worthy of study; as these tsunamigenic seismogenic zones are within the drilling capability of the *JOIDES Resolution,* they can be investigated in the near future; The Central American localities have potential to fulfill goals of MARGINS in crustal recycling and SEIZE. In the Japanese Islands the large number of seismic stations both on land and underwater, the extensive GPS network, and an abundance of other available data provides overwhelming scientific investment that a SEIZE program can build on. Both the Japanese and Central American regions have active scientific communities that can develop strong SEIZE efforts; success in proposal-writing by these groups will narrow SEIZE activities. As the prime localities become clearer, various inter-related and piggy-back studies can be quickly initiated to achieve the desired focus (see **COMMUNICATION AND DATA ACCESSIBILITY,** below). Focused scientific activities at prime SEIZE localities will have immediate transfer to other convergent margins

Application of SEIZE to Other Sites Such as Cascadia

The criteria for site selection articulated above exclude, to greater or lesser degrees, many thrust-seismogenic subduction zones that are for many reasons very worthy of study. In many cases, this is a simple consequence of either the inability of existing tools and technologies to image or access the seismogenic parts of the thrust rupture events and hence the lack of important constraints on where and how rupture occurs.

Understanding rupture potential and mechanism at these other sites is clearly no less important than at the site selected for exhaustive study, however, and thus one of the most important goals of an observational effort like SEIZE, focused perhaps on a single subduction thrust site, will be to effectively extend the understanding of the fundamental mechanisms of seismic rupture to other sites. To accomplish this, great effort must be given to ensuring that the major results can be generalized. Great consideration must also be given to the many variables that control the seismogenic behavior of these variables is small, or the number of variables that can be studied, is small at any given site. Expanding some critical experiments to other sites will be necessary.

Cascadia is a good example of a subduction zone with substantial seismic hazard that may benefit from application of SEIZE results. The Nankai Trough is similar to Cascadia in many respects, excepting the latter does not have historical earthquakes. Lessons learned in the Nankai trough may permit association the material properties of the seismogenic zone with particular temperature, pressure and lithological conditions. This should lead to an understanding of how those conditions manifest themselves in geophysical and geological observations such as seismic reflectivity, deformation style, heat flow, etc. For example, a detailed quantitative comparison of the d&eacutecollement reflection in Nankai and Cascadia, once a ground-truthed model for the Nankai reflection is available, will provide considerable insight into the seismogenic potential of Cascadia. If these geophysical and geological characteristics of the seismogenic zone in Nankai can be adequately determined, these characteristics can be used to identify location and area of potentially seismogenic portions of the Cascadia margin.

Communication and Data Accessibility

Another important aspect of SEIZE is to improve communication and data accessibility to the community. A SEIZE Web site will be created and maintained as part of the MARGINS Office (currently at the University of Hawaii). The SEIZE Web site will provide the following: (1) information concerning upcoming field expeditions and experiments, (2) a data base and/or pathways to access data recently acquired by SEIZE, and (3) a news bulletin board to foster communication across the different disciplines in the SEIZE community. By making information concerning upcoming cruises and field experiments available in a timely fashion, other researches can capitalize on these opportunities and secure funds to participate in these projects or design piggy-back projects. In addition, we envision that recently acquired SEIZE data and/or pathways to access the data will be available on the Web site in a timely fashion after acquisition. This time frame will vary for different data types. However, cruise reports and updates of ongoing experimental and theoretical research will be available. Existing data acquired in the SEIZE natural laboratory will also be compiled, cataloged, and entered into the data base. Rapid dissemination of data and new ideas will help focus the community, which, in turn, will lead to a more interdisciplinary approach toward studying the seismogenic zone. For example, the occurrence and distribution of a large earthquake within the study region should be documented and made available over a time scale of hours to all participants; preliminary images of the d&eacutecollement zone should be released as they come available. Data availability, together with the news bulletin board, will improve communications between observationalists, experimentalists, and theoreticians. This enhanced communication will allow us to determine what are the critical observations and experimental inputs necessary for constraining models of the seismogenic zone and what are the first order model predictions that can be tested. Such an iterative approach between modeling and data analysis is the necessary first step towards developing realistic quantitative models of the seismogenic zone.

International Cooperation

In a number of areas, national and international projects to study the seismogenic zone are already underway or planned. Insights into the seismogenic zone obtained from these studies will have direct applicability to this initiative, both in terms of experimental design and variability in seismogenic zone parameters. In order to achieve the long-term scientific goals of SEIZE, international cooperation has to be coordinated. The following scheme of cooperation is envisioned:

a) International cooperation in scientific planning and program design layout,

b) Assist in international collaboration in scientific program activities,

c) Coordination in technology development,

d) Close cooperation with ODP and OD21,

e) Data sharing and data analysis coordination.

We propose establishment of an international steering committee to coordinate activities. Clearly a data handling system or center should be established to promote international planning, exchange of data. Adequate international data handling capacity may require augmentation of the Web site proposed above to be resident at the US MARGINS office.

Impementation Plan

Table 1 shows an example of an implementation plan for a typical Seismogenic Zone field Experiment.

APPENDIX: EXAMPLES OF SEISMOGENIC ZONES WITH EARTHQUAKES APPROPRIATE FOR SEIZE

The earthquake seismological community attending the workshop provided valuable insights on what areas of the world would be most favorable for SEIZE from the seismological perspective. Selection of preferred sites depended on additional criteria, such as available marine data, logistics, etc. Nevertheless, the following list provides seismologically compelling targets where the marine geological/geophysical community might initiate investigations. The key seismological criteria used in compiling this list are:

a) a recent well-characterized "large" earthquake;

b) sufficient number of somewhat smaller earthquakes that help define the seismogenic zone;

c) a clear boundary between asperity or rupture area of recent large event and an adjacent segment that is capable of large earthquake occurrence,

d) tsunamigenic earthquakes which occur in the shallowest strip of the plate interface, usually thought to be seismic

Not all the regions match all criteria, and there may be other segments that are good candidates. Nonetheless, this list of about twenty sites shows the range of opportunities for a focussed SEIZE experiment. In this list earthquake magnitudes are described as follows: M = generic magnitude, Ms = magnitude determined from surface waves, Mw = magnitude determined from seismic moment, Mt = magnitude determined from tsunami waves.

Kuriles to Hokkaido

This subduction zone consistently generates many large events (M>7), and the entire zone has been ruptured in a recent (1958 to 1973) sequence of great earthquakes. The asperity distribution is well determined There have been tsunamigenic events near the trench, and the rupture zone of the great 1963 Kurile earthquake has just begun to re-rupture with the Dec. 1995 Kuriles (Mw=7.9) event. This region is one of the best sites to study the seismogenic zone.

Nicaragua

1992 tsunamigenic earthquake here behooves marine investigation because of the little-understood behavior of that event. Aftershocks here define a larger and away--from-the-trench zone, while the tsunami waveform modeling suggests that the fault is very close to the trench and has a rather narrow slip zone. Other highly tsunamigenic earthquakes apparently have similar characteristics.

Nicoya gap, Costa Rica

High convergence rates, short (~50 years) recurrence times, the last events in 1900 and 1950, currently a mature seismic gap. Slip inversion of the last event, 1950, is not yet done, and would be desirable. *Some* geodetic coverage (1994, 1996 and 1997 GPS epochs, more planned). Because of high convergence rate and a seismic gap, this area has high potential for SEIZE. Earthquakes here are not too large, the largest known was on October 5, 1950, (Ms=7.7), others were rather in the Ms=7.0-7.4 range. If the smaller, Ms=7.0-7.4 events are more typical for that segment, the average repeat time is ~22 years.

Mexico

High convergence rates and the shortest recurrence times in the world make Mexico a very attractive place for SEIZE. In particular the Guerrero gap (100¡-101¡W, last broken 1899-1911), with a small event in 1995, and a cluster of recent M~5.0-5.5 compressional events toward the trench, may be an asperity. Oaxaca, especially east Oaxaca (last Mw-7.8 event in 1928), forms a mature seismic gap now. The other interesting area is one of the well-defined asperities in the 1985 Michoacan Mw=8.1 earthquake.

Sumatra

There were 2 earthquakes about Mw=8.5 during the last century; GPS is being used to understand the large-scale heterogeneities asperities. The area interesting for SEIZE would be either the barrier between these two earthquakes, of one of the asperities.

Nankai Trough:

Comparatively well inverted for slip (tsunamigenic, seismic, geodetic). Last large events 1944, 1946. Good geodetic coverage of the contemporary deformation of the upper plate. Excellent history of past large/great earthquakes. It will be important to understand the asperities and intervening weak regions to test models of the tendency of doublet earthquakes here.

Japan Trench (Sanriku region)

Diverse sequence of large and great earthquakes. Northernmost segment ruptured in the 1968 event, and the southern part of this zone re-ruptured in the 1994 event, which did *not* re-rupture the primary asperity of the '68 event. Great opportunity to study asperity and large earthquake re-rupture, though one caveat is the atypical nucleation at the shallow edge of the seismogenic zone-also an advantage for drilling.

Central Chile

Valparaiso 1985 M=8.0 event with a few seismic/geodetic slip inversions. Segment south of the rupture zone broke last in 1943 and is currently considered a mature seismic gap. A place on the southern border of the 1943 rupture area might benefit from known rupture/new event situation.

Jalisco

1995 earthquake ruptured approximately 2/3 of the area that failed in 1932 by the largest known Mexican subduction earthquake. High convergence rate, young, hot subducting plate. Extremely limited small seismicity in at least 20 hears previous to that event. Tectonic conditions somewhat similar to the Cascadia subduction zone, though with much shorter recurrence times of large/great events and comparatively little sediment. Comparisons would improve our knowledge of Cascadia.

Columbia-Ecuador border

1906 event, refractured by the 1942, 1958 and 1979 (largest) earthquakes. Slip histories (asperities) known (especially well the 1979 event). Perhaps most interesting for SEIZE would be the south-east end of the 1906 rupture, a possibly structural barrier that stopped both the 1906 and 1942 earthquakes. Also, the 1942 area might be ready to break again. South of that place, large/great earthquakes are historically unknown and would provide a good contrast with the 1906/1942 area. It would also be good to understand the physical nature of what stopped the two large earthquakes in 1906 and 1942). Perhaps equally interesting would understanding of the physical nature of well-defined asperity of the 1979 event.

North Island and northern South Island of New Zealand

The subducted crust in this region thickens from oceanic in the north to near-continental in the south. The buoyancy of this thicker crust results in the seismogenic underlying the land area. It is thus very amenable to study and many dense seismograph and GPS deployments have been undertaken. These reveal significant changes in sediment accretion and tectonic erosion along strike. There is abundant seismicity, and large earthquakes recurred in 1855 and 1931. Both these events are unusual in that they appear to have originated near the down-dip end of the seismogenic zone and ruptured through the overlying plate, rather than continuing along the plate interface. This and not fully typical oblique subduction boundary would not perhaps be the best place for a SEIZE experiment, however it is an excellent place for the study of the interaction of large/great earthquakes.

Alaska Peninsula

The region from Kodiak to the Shumagins broke in 1938 (Mw~8.0) and the region from Kodiak east ruptured in the great 1964 Alaska event (Mw 9.2). To the west, the Shumagin segment has shown numerous small events but no gap-filling ones since at least 1917 and possibly 1788. Several M~7 events have occurred in the last 30 years through this zone, and estimates of recurrence suggest high seismic potential. Substantial geodetic data and some paleoseismic measurements exist throughout the region. Rupture of large events appears affected by a boundary of the Shumagins. There are very detailed geodetic/seismic/tsunami inversions of the Alaska 1964 event. Placing a SEIZE experiment on the very large and well-documented main asperity could be interesting, but perhaps that zone, because of the size of the asperity, is rather unusual in the world (Kamchatka 1952 might be similar). Therefore a better site would be a smaller Kodiak asperity with recurrence time ~60 years, of the area of the 1938/1917 events (currently mature seismic zones).

In 1946, off Unimak, a moderate Mw 7.4 event spawned one of the most destructive tsunamis of this century (Mt~9.2). This event filled a small part of the gap between the 1957 great event to the west and the 1938 Alaska Peninsula event. That area would be of interest similar to the area of the Nicaragua 1992 earthquake, advancing our knowledge of the shallow tsunamigenic events that are accessible to study.

Central Aleutians

The last great event ruptured several hundred km of plate interface in 1957. (Mw=8.6). Two recent events in 1986 with 8.1, in 1996 with 7.9) ruptured the two western portions, suggesting a change of fault mode from giant to large events. The rest of the 1957 zone, east of the 1986 rupture, is a prime candidate for M~8 events in the near future. Little geodetic work has been done owing to limited land areas.

New Guinea to Santa Cruz Islands

This long twisting set of set or small subduction zones displays a rich variety of large earthquake behavior, and associated tectonic variability of and age of subducted lithosphere. There many underthrust events with M>=7.5 and several of these occur as doublets and multiplets in the Solomon Islands zone. This area also displays a mature seismic gap with compressional outer rise events and (eastern New Britain), and one key example of the "failure" of long-term earthquake forecasting methodology (Santa Cruz Islands). In fact, another large earthquake occurred in the Santa Cruz Islands region in 1997. Thus this region presents several good opportunities for SEIZE where significant along-strike changes occur over short distances.

Cascadia-Petrolia

Presence of large/great subduction earthquakes is proven here by paleoseismological studies and the tsunami records found recently in Japan of the earthquake from 1700, the only large (M>7) subduction event being the Petrolia earthquake of 1992 which occurred in the southernmost end of Cascadia. Seismologically, Cascadia is too atypical to be a good place for SEIZE, and the Petrolia area is actually a more interesting site for SEIZE in view of its recent rupture with a shallow seismogenic zone.

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