Focusing on the Protoseismogenic Zone of Erosional Convergent Margins

Great earthquakes in subduction zones occur after stable slip in the protoseismogenic zone transitions to the unstable slip that characterizes seismogenic zones. Subducted material input to seismogenic zones affects this transition. Material structure, lithology, and physical properties change progressively during subduction, and according to current hypotheses, specific material transformations trigger the stable to unstable slip transition. Where accretion dominates a convergent margin, material input is trench sediment that is easily drillsampled.

However, where erosion dominates a margin, material input is unknown because it originates along the base of the upper plate and alters differently. The depth at which material is eroded lies beyond the sampling capabilities of past scientific ocean drilling, so the protoseismogenic zone transformed material has never been drillsampled; nor does geophysics resolve its structure, lithology, and physical properties. The Japanese riser drill ship Chikyu in the Integrated Ocean Drilling Program (IODP) overcomes this difficulty. Preparing a site for deep drilling is a much greater task than preparing the shallower sites of past programs, so this is accomplished during workshops

Thirty-eight scientists from seven nations met in Kiel, Germany, last October at the Forschungszentrum für Marine Geowissenschaften (Geomar) to discuss a program to drill into the protoseismogenic zone, the second stage of the proposed Costa Rica Seismogenesis Project (CRISP). The objective of this complex drilling project is to ultimately drill into the seismogenic zone. Much of the basic geophysical and geological survey data offshore of Costa Rica was acquired by German institutions, but is currently unpublished. Thus, the workshop was held at a convenient location where original data of the German Geological Survey, (BGR), the University of Bremen, and Geomar could be displayed. Geomar is also the home of the Collaborative Research Center 574 (SFB 574), which investigates convergent margin systems of Central America.

To examine the causes of seismogenesis (CRISP Stage 3), one must characterize the protoseismogenic zone (CRISP Stage 2) to provide reference conditions prior to material transformations that trigger large earthquakes. Fluids and material subducted to 15 km will transform as pressure increases and temperature reaches 120150ºC. Stage 2 will introduce technology not yet applied in scientific drilling to explore environments that have never been probed. Drilling is required to understand the proto-seismogenic zone, because plate interface fault structure is not resolved with conventional geophysical techniques. Downhole instruments can measure dynamic conditions and fluid flow close to the plate interface thrust. This aids the search for lowlevel signals that indicate changing stress in the seismogenic zone. Such observations are consistent with advanced scientific objectives of IODP, and are a step in the successive stages of the CRISP proposal that ultimately targets drilling an erosional margin seismogenic zone.

In the first half of the workshop, new results from investigations during the past year were presented and discussed to update participants for discussion of CRISP Stage 2. Shinichi Kuramoto summarized the expanded capabilities of Chikyu and emphasized the long time--up to 4 years--required to prepare a site for deep drilling.

Studies of earthquake seismology in the proposed drill area indicate the difficulty of working with only landbased data. Five different groups are investigating seismicity in the area, and a disparate location for the M 6.4 earthquake of 2002 and its aftershocks emphasized the need for longterm offshore instrumentation. A previous on and offshore network study, for example, showed several location inaccuracies $\geq$ than 10 km without marine instruments. Interpreters of the 2002 earthquake results cannot differentiate between slip on the plate interface or on an intra-slab fault. Many epicenters cluster along a subducted ridge that uplifts the continental slope and outer shelf. Defining and characterizing the updip end of the seismogenic zone here will require longer ocean floor instrument records.

Global Positioning System (GPS) geodesy shows that locking extends into the area of proposed drilling and corresponds roughly with distribution of the 2002 aftershock seismicity. A proposed proxy for the updip end of the seismogenic zone is a 100150ºC temperature. Current simple models place the 150ºC isotherm near the beginning of aftershock seismicity. Considerable probe and bottom simulating reflection (BSR) heatflow data are available for the threedimensional modeling in progress that will improve temperature constraints. Thermal gradients measured during Stage 1 drilling will help locate critical isotherms even more precisely. Siting the Stage 3 deep hole in the seismogenic zone will require ocean floor instrument networks to record seismicity and stress.

A review of the latest overview and stage 1 proposals concentrated on erosional processes and the model proposed for testing. Indirect measurements of material strength show that the overriding plate shear strength can be greatly reduced near the trench axis, reaching the levels found in ocean sediment. It is proposed that overpressured fluids have intruded fractures along the plate interface that further weaken the upper plate by hydrofracturing. This loosens fragments that are dragged into the subduction channel, forming a layer of cataclastic terrigeneous material input to the seismogenic zone. The data supporting the model, which also form the site survey for Stage 1 and 2 drilling, were displayed, and participants reviewed the proposed drill sites.

During the second day, investigations of the Geomar-based Collaborative Research Center 574 were reported. Widespread sea floor vents form mud mounds in the middle slope that are identified in multibeam bathymetry along the entire Middle America margin. Along Costa Rica, nearbottom sidescan mapping shows a mound at least every 2-3 km. Benthic fauna, fluids rich in H_2S, and methane mark vents, and at one vent, the flow was estimated at 300 cm/yr. Isotopic composition indicates clay mineral dehydration at temperatures between 85ºC and 130ºC rather than dissociation of gas hydrate. The most likely source for these fluids is subducted sediment seismically imaged at depths > 12 km along the plate interface. The SFB 574 group has proposed fluid sampling of the mounds to the IODP.

Another study of the SFB group concerns partial mantle serpentinization of the incoming oceanic plate. Evidence for normal faults that extend into the mantle and are related to plate bending was recently reported in Nature. Seismic refraction evidence for strongly reduced mantle velocities in this region, as well as gravity anomalies, are consistent with ~25% serpentinization near Moho depths. From study of exhumed fossil slabs, it appears that de-serpentinization occurs at >90 km depth, triggering gabbroeclogite transformation.

Finally, the researchers of the SFB presented results concerned with subduction zone output. The chemistry of water in primitive melt inclusions includes signs of subducted sediment, eroded upper plate debris, and igneous ocean crust. The Galapagos signature present in central Costa Rican volcanoes is spatially and temporally related to the subduction of the Galapagos Hotspot Track. It originates at least in part from subducted seamounts and from early Cenozoic Galapagostype rock accreted to the upper plate that is later eroded along with other components. Cenozoic volcanic products have compositions consistent with a longterm erosional environment along the Middle America Trench.

An overview of deep fault drilling in other environments concluded the scientific part of the workshop. The Nankai Trough (NanTroSEIZE) proposal was presented by Harold Tobin, and he asked the question of how the up-dip end of the seismogenic zone can be defined at the scale of a drill hole. The most likely solution appears to be multiple lines of evidence including geodesy, microearthquake distribution, and temperature. Hypotheses to be tested relate to material changes and material states. The complementary differences between Costa Rica and Nankai are rapid versus slow plate convergence, input of trench sediment versus erosional debris, the importance of splay thrust faults in Nankai versus normal faults of middle America, and different depths of the seismogenic zone.

Jan Behrmann presented current projects of the International Continental Drilling Program (ICDP), including drilling along the San Andreas Fault that shows seismogenesis within 2 km of the surface. Drilling in deep mines of South Africa will probe faults that have produced magnitude 5.2 earthquakes. The ICDP offers the possibility of including sites on the Osa peninsula near the proposed IODP transect where the middle of the seismogenic zone is ~7 km deep.

Stage 2 drilling will probe an unsampled environment of fault behavior in the protoseismogenic zone, the last area of stable slip prior to seismogenesis. Since scientific drilling has only reached subducted trench sediment and not erosional material, drilling will characterize shear zone mineralogy and structure in a new environment. Laboratory experiments with materials recovered from the plate interface will help foretell conditions of stickslip in an erosional seismogenic zone prior to Stage 3 drilling.

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