NanTroSEIZE: The IODP Nankai Trough Seismogenic Zone Experiment

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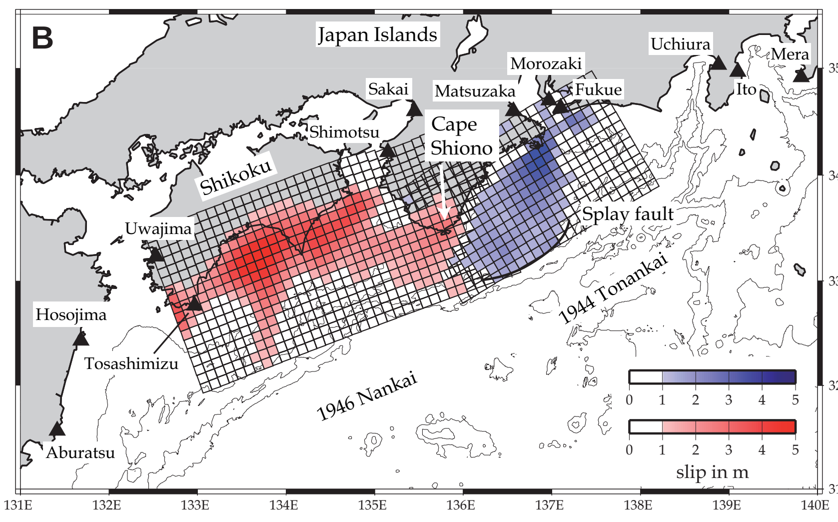
Introduction: The Seismogenic Zone Initiative

The IODP Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) will, for the first time ever, attempt to drill into, sample, and instrument the seismogenic portion of a plate-boundary fault or megathrust within a subduction zone. Access to the interior of active faults where *in situ* processes can be monitored and fresh fault zone materials can be sampled is of fundamental importance to the understanding of earthquake mechanics. As the December 2004 Sumatra earthquake and Indian Ocean tsunami so tragically demonstrated, large subduction earthquakes represent one of the greatest natural hazards on the planet. Accordingly, drilling into and instrumenting an active interplate seismogenic zone is a very high priority in the IODP Initial Science Plan (2001). Through a decade-long series of national and international workshops, a consensus emerged that the Nankai Trough is an ideal place to attempt drilling and monitoring of the seismogenic plate interface. The first phase of NanTroSEIZE drilling operations has now been scheduled for the late summer of 2007. It involves parallel deployment of both the new U.S. Scientific Ocean Drilling Vessel (SODV, this volume) and the riser drilling vessel *Chikyu*.

The fundamental goal of the NanTroSEIZE science plan (http://ees.nmt.edu/nantroseize) is the creation of a distributed observatory spanning the up-dip limit of seismogenic and tsunamigenic behavior at a location where great



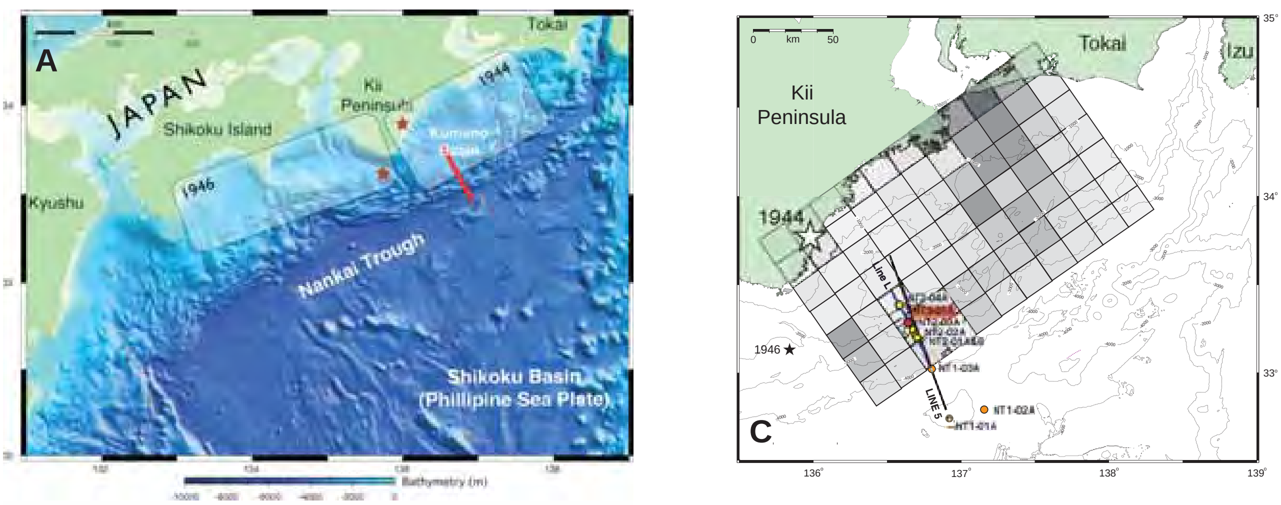


Figure 1-A. The Nankai Trough region of southwestern Japan is the locus of subduction of the Philippine Sea plate beneath Honshu and Shikoku islands. Shaded boxes are the generalized slip areas of the last two great subduction earthquakes (stars represent epicentral locations for earthquake nucleation). Red line is location of seismic reflection section of Figure 2.
Figures 1-B and C. Coseismic slip (B) and tsunami source (C) inversions of the 1944 Tonankai earthquake by Ichinose et al., (2003) and Baba and Cumming (2005), respectively. Both show that the coseismic displacement had a large component of shallow slip (seismic asperity) up-dip of the nucleation region. The NanTroSEIZE drilling transect targets this apparent asperity region. The shallow high-slip zone corresponds to the location of the mega-splay fault (see fig. 2), suggesting that it may have been the locus of coseismic slip.

subduction earthquakes occur, thus allowing us to observe the hydrogeologic behavior of subduction megathrusts and the aseismic to seismic transition of the megathrust system. This will involve drilling of key elements of the active plate boundary system at several locations off the Kii Peninsula of Japan, from the shallow onset of the plate interface to depths where earthquakes occur (Figs. 1 and 2). At this location, the plate interface and active mega-splay faults implicated in causing tsunami are accessible to drilling within the region of coseismic rupture in the 1944 Tonankai (magnitude 8.1) great earthquake. The most ambitious objective is to access and instrument the Nankai plate interface within the seismogenic zone. The science plan entails sampling and long-term instrumentation of (a) the inputs to the subduction conveyor belt, (b) faults that splay from the plate interface to the surface and that may accommodate a major portion of coseismic and tsunamigenic slip and (c) the main plate interface at a depth of up to 6 km.

NanTroSEIZE shares many of its goals with the San Andreas Fault Observatory at Depth (SAFOD, this volume) project. This burgeoning interest in active fault drilling is taking place in the context of rapidly growing research efforts on the mechanics and dynamics of faulting processes that integrate rock mechanics, seismology, geodesy, frictional physics and fluid-fault interactions. Despite recent advances, there is at present no unified theory of fault slip to account for earthquake nucleation and propagation, nor to explain the mechanisms of strain across the spectrum of observed deformation rates ranging from seconds to years. Consequently, the question of whether precursory signals exist for major earthquakes, even in theory, remains controversial. Progress on these topics is severely limited by a lack of information on ambient conditions and mechanical properties of active faults at depth. Extant rheological models for how faults behave depend on specific physical properties at the fault interface and in the surrounding rock volume. Coefficients of friction, permeability, pore-fluid pressure, state of stress and elastic stiffness are examples of such parameters that can best (or only) be measured through drilling and through geophysical sensing of the surrounding volume.

Why the Nankai Trough?

Subduction zones like the Nankai Trough (Fig. 1), on which great earthquakes (M≥8.0) occur, are especially favorable for study because the entire width (dip extent) of the seismogenic zone ruptures in each great event, so the future rupture area is perhaps more predictable than for smaller earthquakes. The Nankai Trough region is among the best-studied subduction zones in the world. It has a 1300-year historical record of recurring and typically tsunamigenic great earthquakes, including the 1944 Tonankai (M=8.1) and 1946 Nankaido (M=8.3) earthquakes. The rupture area and zone of tsunami generation for the 1944 event are now reasonably well understood (Fig. 1; Ichinose et al., 2003; Baba and Cummins, 2005). Land-based geodetic studies suggest that the plate boundary thrust here is strongly locked (Miyazaki and Heki, 2001). Similarly, the relatively low level of microseismicity near the up-dip limits of the 1940s earthquakes (Obana et al., 2004) implies significant interseismic strain accumulation on the megathrust; however, recent observations of very low frequency (VLF) earthquake event swarms apparently taking place within the accretionary prism in the drilling area (Obara and Ito, 2005) demonstrate that interseismic strain is not confined to slow elastic strain accumulation.

The Kumano Basin region (Fig. 1-A) has been chosen based on three criteria: 1) the up-dip end of the seismogenic zone must be definable based on slip in past great earthquakes, 2) seismic imaging must present clear drilling targets and 3) deep targets must be within the operational limits of riser drilling (i.e., maximum of 2500 m water depth and 7000 m sub-bottom penetration). In the Kumano Basin, the seismogenic zone lies ~6000-m beneath the seafloor (Nakanishi et al., 2002). Slip inversion studies suggest that only here did past coseismic rupture clearly extend shallow enough for drilling (Ichinose et al., 2003; Baba and Cummins, 2005), and an up-dip zone of large slip (asperity) has been identified and targeted (Fig. 1-B). Coseismic slip during events like the 1944 Tonankai earthquake likely occurred on the mega-splay fault rather than on the decollement beneath it, though slip on either plane is permissible given the available data. The mega-splay fault therefore is a primary drilling target equal in importance to the basal decollement zone.

Scientific Objectives

Conditions for stable versus unstable sliding—which define seismic versus aseismic behavior—have long been the subject of research and debate, as has the frictional strength of likely fault zone material. Fault zone composition, consolidation state, normal stress magnitude, pore-fluid pressure, and strain rate may affect the transition from aseismic to seismic slip (e.g., Saffer and Marone, 2003). NanTroSEIZE will sample fault rocks over a range of pressure and temperature (P-T) conditions across the aseismic–seismogenic transition, the composition of faults and fluids and associated pore pressure and state of stress and will address partitioning of strain spatially between the decollement and splay faults. Long-term borehole observations will test whether interseismic variations or detectable precursory phenomena exist prior to great subduction earthquakes.

Drilling Targets

We plan to drill at eight sites (Fig. 2): three target the incoming plate section and frontal thrust of the accretionary wedge, three target the mega-splay fault system at different depths, one will sample the mega-splay uplift history recorded in the forearc basin sediments, and one ultra-deep site targets the plate interface in the seismogenic zone.

Sampling of the sediments, fluids, and crustal rocks seaward of the deformation front will characterize the subducting plate before deformation. It has been hypothesized that sediment type (especially clay mineral content), fluid content, and basement relief on the incoming plate govern the mechanical state of the plate interface at depth and influence the formation of fault-zone asperities. Two sites (NT1-01 and NT1-07) are planned to sample the entire sedimentary section and up to 100 m of the basement, respectively on and off of a pre-existing basement high that controlled deposition of thick turbidites in the lower part of the stratigraphy. Long-term monitoring of pore pressure, seismicity, and other observations in these boreholes will define the hydrological and stress conditions and microseismic activity at the point where sediments enter the subduction zone.

Three drill sites targeting the mega-splay fault zone (NT2-01, NT2-02, and NT2-03) and one site targeting the frontal thrust (NT1-03) are designed to document the evolution of fault rock properties and the state of stress, fluid pressure, and strain at different P-T conditions. These sites will access faults from ~500 m to 3500 m depth below the seafloor. Sealed borehole observatories at some of these sites will monitor pore-fluid pressure, strain, seismicity, and other properties to document the physical state of the fault zone and its wall rock environment. Site NT2-03 will cross the seismically reflective mega-splay at a depth of 3000–3500 m, in a location where slip may have propagated in 1944.

After initial instrumentation at Site NT2-03 site, our attention will turn to the 5500–6000 m deep Site NT3-01. Drilling there will pass through both the mega-splay fault system and the basal detachment, bottoming in the oceanic crustal rocks of the subducting plate. Drilling of these deep objectives requires novel borehole engineering. Project scientists envision a multi-path approach to allow collection of both logs and cores from deep target zones, as well as implementation of a comprehensive monitoring system (Fig. 3), and we are working with the borehole engineers to determine how best to implement this ambitious plan.

In addition to the primary fault zone targets, Site NT3-01 will pass through about 1000 m of the Kumano forearc basin section, including an apparent gas hydrate reflector, several thousand meters of the active accretionary wedge, and a zone of potential underplated rocks below the splay fault. Sites NT3-01 and NT2-04 together will document the history and growth of the Kumano forearc basin, which has formed as a response to slip on the mega-splay fault system, as well as processes of accretionary wedge growth. The basinal history will shed light on the evolution of this long-lived, mid-wedge fault that may be a primary feature of many subduction zone forearcs that produce great earthquakes (Wells et al., 2003).

Drilling will yield both geophysical logs and physical samples of the rocks, sediments, and fluids. Logging and borehole imaging will determine *in situ* physical properties and help define stress state (e.g., through borehole breakout and tensile fracture studies). Sampling the inputs and splay faults at several depths, and the plate interface at great depth, will provide key data on the evolution of fault zone composition, fabric development, and lithification state as a function of pressure, temperature, and cumulative slip. Finally, long-term monitoring through downhole instrumentation will yield time-series datasets after the drilling disturbance signals have subsided, possibly including the pre-seismic near term for a future great earthquake. Ideally, thermal signals, fluid pressure, geochemical tracers, tilt and volumetric strain, microseismicity, and time-varying seismic structure will be monitored.

Getting There: Plans for Implementation

The NanTroSEIZE project will span a number of years and many individual expeditions to achieve all of the proposed scientific objectives, with onboard and shore-based scientific

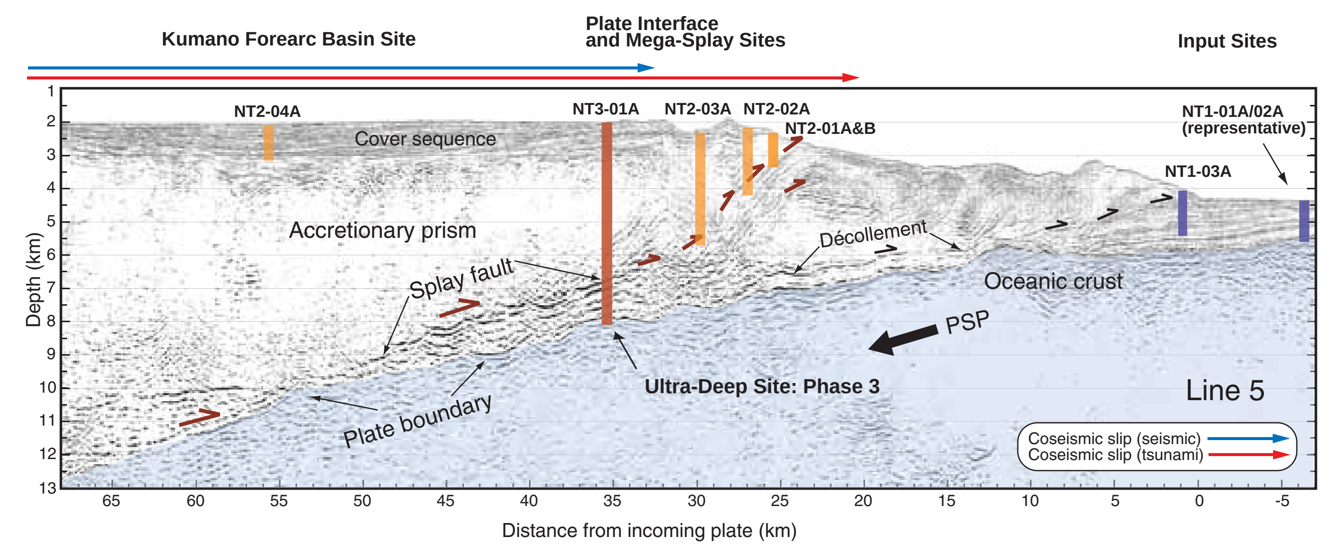


Figure 2. Pre-stack depth migrated seismic line of Park et al. (2002), with locations of planned drill sites.

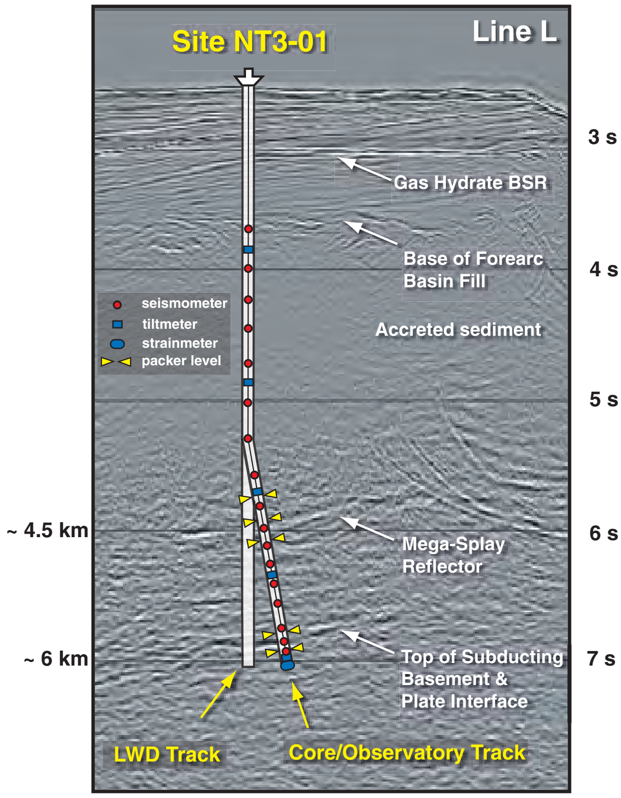


Figure 3. Conceptual drilling and long-term observatory plan for the deepest site, NT3-01. Drilling is planned to proceed with a mix of LWD and coring with casing to total depth, followed by sidetracking to core the prime fault targets and install monitoring instrumentation. Sensors shown here are positioned schematically. A number of sensor elements are not shown for clarity, including temperature arrays, and fluid pressure sensors. Packers isolate perforated zones for fluid communication to the formation above, below, and inside each of the 2 target fault zones. Depths are based on Line 5 in Fig. 2. The borehole deviation is shown conceptually and is not meant to represent true angle or scale.

teams matched to the goals of each sub-expedition. A project management team (PMT) with two co-chief project scientists (the authors), several additional lead scientists, representatives of the drillship operators, and IODP management has been formed and charged with coordinating all scientific and logistical planning.

Volumes of site-survey data have been collected in the drilling area over many years, including multiple generations of 2-D seismic reflection, wide-angle refraction, natural seismicity, heat flow, side-scan sonar and swath bathymetry, and submersible and ROV dive studies. In 2006, Japan and the United States will conduct a joint, 3-D seismic reflection survey over a 14 × 60 km area. The 3-D survey will be used to refine selection of drill sites and targets in the complex mega-splay fault region, to analyze physical properties of the subsurface through seismic attribute studies, to expand findings in the boreholes to wider areas, and to assess drilling safety.

Drilling activities are organized into four stages, each of which will include multiple individual expeditions. Stage 1 calls for drilling and sampling at six of the sites: (a) the incoming sediment of the Shikoku Basin and underlying oceanic crust (two sites), (b) the frontal thrust system at the toe of the accretionary wedge, (c) the mid-wedge mega-splay fault system, and (d) approximately 1000-m-deep pilot holes at the two sites planned for later deep penetrations of the seismogenic zone faults (two sites). Comprehensive coring and logging of the boreholes is planned, including extensive use of logging-while-drilling (LWD) technology to obtain high quality logs. One borehole observatory installation is planned for a pilot hole at Site NT3-01 to monitor pore-fluid pressure, strain, temperature, and seismicity above the plate boundary. This observatory deployment (Becker and Davis, 2005) will serve as a prototype and test-bed for technologies to be used in future deeper borehole observatories. The IODP currently plans to allocate approximately eight months of ship time, divided between the new U.S. SODV and the *Chikyu*, for NanTroSEIZE Stage 1 drilling to take place from September 2007 through January 2008.

Stage 2 will involve drilling the first of the two planned ultra-deep riser holes using the *Chikyu*, targeting the mega-splay fault zone at ~3000 m below the sea floor at Site NT2-03. Extensive coring, use of LWD, downhole experiments to measure pore pressure and seismic properties, and an initial, retrievable, long-term monitoring package are all planned for this site. Additional Stage 2 operations will include deepening and installing borehole observatory systems in several of the shallower boreholes from Stage 1. Stage 2 is likely to begin in mid- to late-2008 and extend into 2009.

Stage 3 is focused on 5500–6000-m-deep drilling into the seismogenic zone and across the plate interface into subducting crust at Site NT3-01. This unprecedented deep ocean borehole will be accomplished through a program of riser-based drilling and a carefully planned casing program. The results of pilot-hole operations, 3-D seismic data, and real-time LWD and MWD monitoring will guide the borehole design. Given the frontier nature of this drilling, it is uncertain how long it will take to complete the borehole, but it may well exceed a full year of drilling. Once drilling is complete, an initial monitoring system will be deployed in the borehole, components of which remain to be designed. We intend for this monitoring system to remain in place for a period of one to two years, while the "final" long-term monitoring package is readied.

Stage 4, will be concerned with installing the final long-term observatory systems into the two ultra-deep boreholes (Figure 3). This monitoring installation will be planned as much as possible for robust, long-duration deployment, such that data pertinent to the behavior and evolution of the plate interface fault system during a significant portion of the seismic cycle can be recorded. In Japan, a system is proposed to deploy a seafloor fiber-optic network for seismic monitoring and other applications in the Kumano Basin region. One exciting possibility is that the NanTroSEIZE boreholes ultimately could be connected to this network in Stage 4, allowing for real time access to the data. We envision that Stage 4 installations will be completed sometime in 2012 or 2013.

Opportunities for Scientific Participation

Detailed plans for how to organize the NanTroSEIZE scientific teams are still being worked out, but there is clearly a need for involving a large number and range of scientists. Shipboard and shore-based opportunities will exist across all stages for interested researchers. Besides the central fault-zone objectives, diverse geological environments will be sampled, including the deep interior of an actively developing accretionary wedge, gas hydrates, partially subducted oceanic crust, abyssal plain turbidite systems, and a major forearc basin sequence. Opportunities will be plentiful in sedimentology, structural geology, physical properties, geochemistry, rock magnetism, borehole geophysics, seismology, microbiology, hydrogeology, crustal deformation, and other disciplines.

The first call for applications to participate in the NanTroSEIZE effort will be forthcoming and widely advertised in 2006. Individual scientists from participating countries should apply according to normal IODP practice. Stage 1 operations in 2007–2008 alone will require the efforts of 50–100 scientists in this massive and challenging undertaking.

Acknowledgements

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