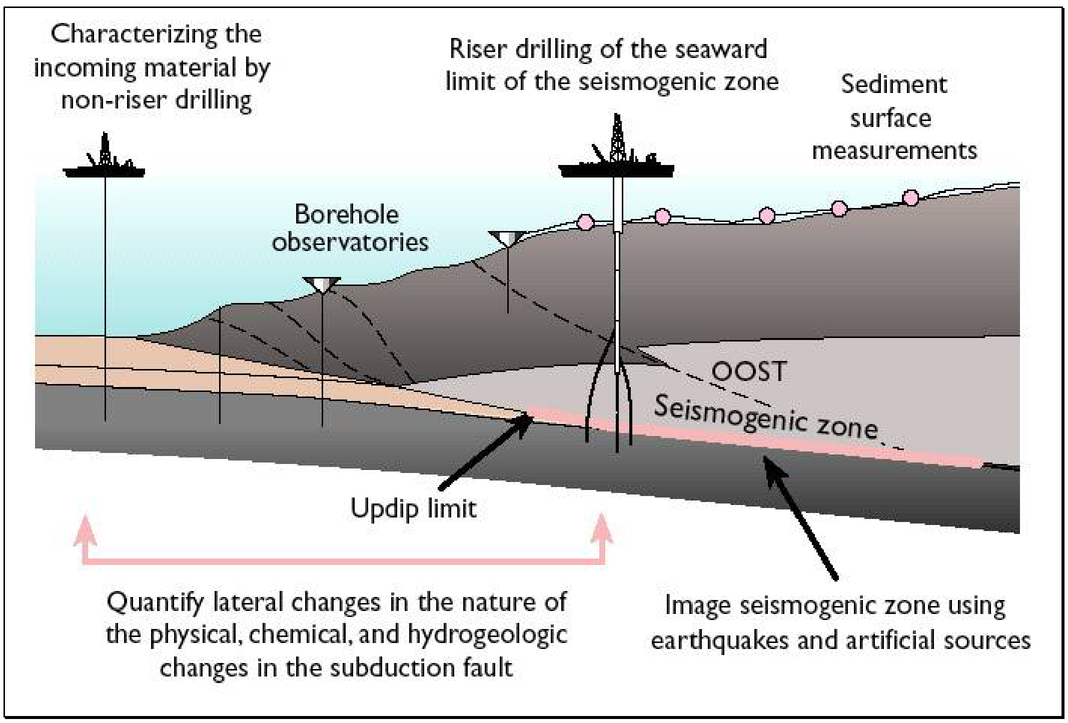
NanTroSEIZE

Sampling and Instrumenting the Nankai Trough Seismogenic Zone



July 21 – 23, 2002
Boulder, Colorado USA

A JOI–USSSP and ODP-Japan Sponsored Workshop

NanTroSEIZE Agenda

Saturday, July 20

6:30 pm	*Icebreaker at Marriott Hotel (cash bar)*	

Sunday, July 21: Plenary Session in Main Seminar Room, Mesa Lab

	Morning Session: Background on Nankai Margin and NanTroSEIZE developments	
8:45 am	Convene and introduce goals and agenda	Tobin, Mikada
9:00 am	SEIZE history and 2001 Pre-proposal	Tobin
9:25 am	iSAS guidelines for complex drilling projects	Suyehiro
9:50 am	Geophysical framework at Nankai Trough	Kodaira
10:15 am	*Coffee Break*	
10:35 am	Nankai great earthquakes and tsunamis	Ando
11:00 am	Nankai ODP drilling results	C. Moore
11:25 am	Other current/planned fault drilling projects	Ito
11:50 am	Costa Rica Drilling proposal	von Huene
12:00 noon	*Lunch Buffet at NCAR cafeteria*	
	Afternoon Session: Overviews on Scientific and Technological Themes	
1:00 pm	Rupture processes of great and tsunamigenic earthquakes	Schwartz/Rice
1:30 pm	Seismogenic fault structure and mechanics	Chester/Kimura
2:00 pm	Fault friction and rheology	Marone
2:30 pm	Hydrogeology and faults	Henry
3:00 pm	*Break for Refreshments*	
3:30 pm	Critical technologies for borehole observatory and logging	Mikada
4:00 pm	*Chikyu* Riser technology and capabilities	Kuroki
4:30 pm	Key seismogenic zone processes/important questions for drilling project	Tobin
4:45 pm	Working Group Introductions	
5:15 pm	Discussion of workshop goals	
6:00 pm	*Bus departure for hotels, downtown*	

Monday, July 22: Working Group Meetings (locations TBA)

	Morning Session
8:45 am	Working Group Sessions
10:00 am	*Coffee Break*
10:30 am	Working Group Sessions continued
12:00 noon	*Lunch at NCAR cafeteria*
	Afternoon Session
1:00 pm	Working Group Sessions continued
3:00 pm	*Refreshment Break*
3:30 pm	Working Group Sessions continued
6:00 pm	*Departure for hotels*

Tuesday, July 23: Plenary Session in Main Seminar Room

	Morning Session
8:45 am	Working Group reports
10:00 am	General discussion and synthesis of reports
10:30 am	*Coffee Break*
11:00 am	Straw proposal outline discussion
11:30 am	Road map to proposal submission discussion, task assignments
12:00 noon	*Lunch at NCAR cafeteria*
1:00 pm	*First bus departure for hotels*
	Afternoon Session
1:00 pm	**Working Group leaders and main proponents remain** to finalize assignments for workshop report and plans for proposal submission
5:00 pm	*Second bus departure (subject to change)*

Working Groups	Initial Group Organizers
Geophysical Framework	S. Kodaira, G. Moore
Hydrology/Geochemistry/Modeling	P. Henry, D. Saffer
Fault Physics/Rupture Dynamics/Seismology	H. Ito, C. Marone, S. Schwartz
Structural and Fluid Evolution	C. Moore, G. Kimura, F. Chester
Instrumentation/Drilling Strategy	H. Mikada, K. Brown
Inputs/Reference Sites	M. Underwood, J. Ashi

Workshop Participants

Name	Email	Institute	Country
Ando, Masataka	ando@seis.nagoya-u.ac.jp	Nagoya University	Japan
Aochi, Hideo	aochi@geologie.ens.fr	Ecole Normale Superieure de Paris	France
Ashi, Juichiro	ashi@ori.u-toyko.ac.jp	Univ. of Toyko ORI	Japan
Becker, Keir	kbecker@rsmas.miami.edu	Miami University	USA
Beeler, Nicholas	mbeeler@gscamnlm04.wr.usgs.gov	US Geological Survey	US
Bilek, Sue	sbilek@umich.edu	Univ. of Michigan	USA
Brown, Kevin	kmbrown@ucsd.edu	Scripps Inst of Oceanography	USA
Bruce, Robert	Bob.Bruce@BHPBilliton.com		USA
Bruhn, Ron	rlbruhn@mines.utah.edu	Utah State University	USA
Chester, Fred	chester@geo.tamu.edu	Texas A&M University	USA
Davis, Earl	davis@pgc.nrcan.gc.ca	Geological Survey of Canada	CA
Evans, Jim	jpevans@cc.usa.edu	Utah State University	USA
Evensen, Joseph	joey.evensen@exxonmobil.com	ExxonMobil Upstream Research	USA
Farrell, John	jfarrell@joiscience.org	Joint Oceanographic Institutes	USA
Fukuyama, Eiichi	fuku@bosai.go.jp	Nat. Research Inst. Earth Sc.	Japan
Garven, Grant	garven@jhu.edu	John Hopkins University	USA
Ge, Shemin	ges@spot.colorado.edu	Univ. of Colorado	USA
Goodwin, Laurel	lgoodwin@nmt.edu	New Mexico Tech	USA
Gulick, Sean P	sean@ig.utexas.edu	Un. of Texas Institute for Geophysics	USA
Henry, Pierre	henry@mailhost.geologie.ens.fr	Ecole Normale Superieure de Paris	France
Hino, Ryota	hino@aob.geophys.tohoku.ac.jp	Tohoku University	Japan
Horseman, Stephen	stho@bgs.ac.uk	British Geological Survey	UK
Ito, Hisao	hisao.itou@aist.go.jp	AIST Japan	Japan
Mikada, Hitoshi	mikada@jamstec.go.jp	JAMSTEC	Japan
Ide, Satoshi	ide@eri.u-toyko.ac.jp	Univ. Toyko ERI	Japan
Ikehara, Ken	k-ikehara@aist.go.jp	AIST Japan	Japan

Name	Email	Institute	Country
Iturrino, Geraldo	iturrino@ideo.columbia.edu	LDEO Borehole Research Group	USA
Obana, Koichiro	obanak@jamstec.go.jp	JAMSTEC	Japan
Kameyama, Masanori	kameyama@jamstec.go.jp	JAMSTEC	Japan
Kastner, Miriam	mkastner@ucsd.edu	Scripps Inst of Oceanography	USA
Kato, Aitaro	aitaro@jamstec.go.jp	JAMSTEC	Japan
Kimura, Gaku	gaku@eps.s.u-toyko.ac.jp	Univ. of Toyko	Japan
Kinoshita, Masataka	masa@jamstec.go.jp	JAMSTEC	Japan
Kodaira, Shuichi	kodaira@jamstec.go.jp	JAMSTEC	Japan
Kopf, Achim	akopf@ucsd.edu	Scripps Inst of Oceanography	USA
Kuroki, Kazushi	kurokik@jamstec.go.jp	JAMSTEC	Japan
Kuwahara,Yasuto	y-kuwahara@aist.go.jp	AIST Japan	Japan
Lallemant, Siegfried	siegfried.Lallemant@geol.u-cergy.fr	Univ de Cergy Pontoise	France
Lewis, Jon	lewis@geo.umass.edu	Univ of Massachusetts	USA
Lockner, David	dlockner@usgs.gov	US Geological Survey	USA
Ma, Kuo-Fong	kuofongm@yahoo.com.tw	National Central University	Taiwan
Marone, Chris	cjm@essc.psu.edu	Penn State University	USA
Shinohara, Masanao	mshino@eri.u-toyko.ac.jp	Univ. Toyko ERI	Japan
Matsumoto, Takeshi	takeshi@jamstec.go.jp	Nippon Marine Enterprises Japan	Japan
Moore, Casey	cmoore@emerald.ucsc.edu	U.C. Santa Cruz	USA
Moore, Greg	gmoore@hawaii.edu	Un. of Hawaii	USA
Morgan, Julia	morganj@esci.rice.edu	Rice University	USA
Nadeau,Robert	nadeau@seismo.berkeley.edu	U. C. Berkeley	USA
Nakamura, Yasuyuki	saru@ori.u-toyko.ac.jp	Univ Toyko ORI	Japan
Neuzil, Chris	ceneuzil@usgs.gov	US Geological Survey	USA
Nishigaki, Makoto	gel94@cc.okayama-u.ac.jp	Okayama University	Japan
Okamura, Yukinoba	okamura-y@aist.go.jp	AIST Japan	Japan
Park, Jin-Oh	jopark@jamstec.go.jp	JAMSTEC	Japan
Peacock, Sheila	peacocks@es4.ers.bham.ac.uk	Univ. of Birmingham	UK
Pujol, Jose	pujol@ceri.memphis.edu	Univ. of Memphis	USA
Rice, James	rice@esag.deas.harvard.edu	Harvard University	USA
Sacks, Selwyn	sacks@pop.dtm.ciw.edu	Carnegie Institute	USA
Saffer, Demian	dsaffer@uwyo.edu	Univ. of Wyoming	USA
Saito, Saneatsu	saito@jamstec.go.jp	JAMSTEC	Japan
Sasagawa, Glenn	gsasagawa@ucsd.edu	Scripps inst. Of Oceanography	USA
Schwartz, Susan	susan@emerald.ucsc.edu	U. C. Santa Cruz	USA
Screaton, Elizabeth	screaton@ufl.edu	Univ. of Florida	USA
Spivak, Arthur	spivak@gso.uri.edu	Univ. of Rhode Island	USA
Stanislavsky, Eyal	estanis1@jhu.edu	John Hopkins University	USA
Stephen, Ralph A	rstephen@whoi.edu	Woods Hole Oceanographic Inst.	USA

Name	Email	Institute	Country
Suyehiro, Kiyoshi	suyehiro@jamstec.go.jp	JAMSTEC	Japan
Thurber, Cliff	cliff@geology.wisc.edu	Univ of Wisconsin	USA
Tobin, Harold	tobin@nmt.edu	New Mexico Tech	USA
Tokunaga, Tomo	tokunaga@geosys.t.u-tokyo.ac.jp		Japan
Tsunogai, Urumu	urumu@ep.sci.hokudai.ac.jp	Hokkaido Univ.	Japan
Ujiie, Kohtaro	ujiiek@jamstec.go.jp	JAMSTEC	Japan
Underwood, Michael	underwood@missouri.edu	Univ. of Missouri	USA
van der Pluijm, Ben	vdpluijm@umich.edu	Univ of Michigan	USA
von Huene, Roland	rhuene@mindspring.com	U. C. Davis	USA
Wada, Taigo	wadat@jamstec.go.jp	JAMSTEC	Japan
Wang, Kelin	wang@pgc.nrcan.gc.ca	Geological Survey of Canada	CA
Wells, Ray	rwells@usgs.gov	U.S. Geological Survey	USA
Yasuo, Yabe	yabe@aob.geophys.tohoku.ac.jp	Tohoku Univ.	Japan

iSAS/IODP Proposal Cover Sheet

☐ **New** ☐ **Revised** ☐ **Addendum**

Above For Official Use Only

Please fill out information in all gray boxes

Title:	**Nankai Trough Seismogenic Zone Drilling and Observatory**
Proponent(s):	**Gaku Kimura, Harold Tobin, Pierre Henry, Hitoshi Mikada, Shuichi Kodaira, and Nankai Trough Seismogenic Zone Research Group (35 others)**
Keywords: *(5 or less)*	Seismogenic zone, fault mechanics, tsunami, subduction, riser drilling
Area:	Southwestern Japan margin

Contact Information:

Contact Person:	Harold J. Tobin		
Department:	Earth and Environmental Science Department		
Organization:	New Mexico Tech		
Address	Socorro, NM 87801 USA		
Tel.:	1-505-835-5920	Fax.:	1-505-835-6436
E-mail:	tobin@nmt.edu		

Permission to post abstract on iSAS Web site: **X** **Yes** ☐ No

Abstract: (*400 words or less)*

Drilling and installation of a deep borehole observatory into a subduction megathrust seismogenic zone is a stated major objective of IODP. The Nankai Trough off densely-populated southwestern Japan is one of the most active great-earthquake generating regions on earth. Nankai has long been treated as a focused study area in DSDP and ODP, representing a type locality for forearcs with well-developed accretionary prisms. The Nankai Trough area is considered one of the prime locations to carry out the first riser drilling program of IODP because seismic images show clear drilling targets, the subduction zone is well characterized geophysically, and monitoring systems can be supported from the nearby Japanese Islands.

We propose a drilling and instrumentation program integrating non-riser drilling at reference and shallow thrust sites with riser-based deep drilling and borehole observatory installation near the up-dip limit of the seismogenic portion of the plate interface. The proposed program will test models for the onset of seismogenesis, the degree of fault locking, and the causes of fault "weakness" in subduction zone thrusts. It will also determine the rheology of the fault zones and whether the properties of the fault zone change through time. This will require 4.5 to 6 km sub-seafloor penetration in 2 to 2.5 km water depth, well within the design parameters of Phase I riser implementation. Both splay thrusts and the master decollement are targets for drilling, and both can potentially be accessed in the same riser hole. Well-studied areas off the Kii Peninsula, Cape Muroto, and Tokai are all currently under consideration as candidate locations for this proposed program. Continued analysis of existing and new site survey data will lead to final selection of specific drilling targets.

Scientific Objectives: (*250 words or less*)

The principal scientific objective of the proposed drilling is to acquire data bearing on and testing the following key hypotheses:

Hypothesis #1: Systematic, progressive material and state changes control the onset of seismogenic behavior and locking of subduction thrusts.

Hypothesis #2: Subduction zone megathrusts are weak faults; i.e., they slip under conditions of low resolved shear stress.

Hypothesis #3: Within the seismogenic zone, relative plate motion is primarily accommodated by coseismic, frictional slip.

Hypothesis #4: Physical properties, chemistry and state of the fault zone change with time throughout the earthquake cycle (interseismic and coseismic).

Testing of these hypotheses will be accomplished through the drilling of a transect including one or more non-riser trench reference sites, one or more non-riser sites into the shallow decollement or splay thrust faults, and one riser site to ~5 km sub-seafloor across the active plate boundary. Observations brought to bear on the hypotheses will include core, log, and seismological information, and long-term borehole observatory data.

Proposed Sites:

Site Name	Position	Water Depth (m)	Penetration (m)			Brief Site-specific Objectives
			Sed	Bsm	Total	

Preliminary IODP Proposal

Nankai Trough Seismogenic Zone Drilling and Observatory

Nankai Trough Seismogenic Zone Research Group:

Gaku Kimura *	University of Tokyo	Japan
Harold J. Tobin *†	New Mexico Tech	USA
Pierre Henry *	École Normale Supérieure	France
Hitoshi Mikada *	JAMSTEC	Japan
Shuichi Kodaira *	JAMSTEC	Japan

and (in alphabetical order):

Juichiro Ashi
Nathan Bangs
Kevin Brown
Warner Brueckmann
Phil R. Cummins
Toshitaka Gamo
Sean S. Gulick
Ryota Hino
Takane Hori
Hisao Ito
Masanori Kameyama
Yoshiyuki Kaneda
Masataka Kinoshita
Achim J. Kopf
Shin'ichi Kuramoto
Siegfried Lallemant
Kimihiro Mochizuki
Gregory F. Moore
J. Casey Moore
Yasuyuki Nakamura
Jin-Oh Park
Sheila Peacock
Andreas Rietbrock
Demian Saffer
Saneatsu Saito
Keizo Sayanagi
Tom Shipley
Kiyoshi Suyehiro
Asahiko Taira
Hidemi Tanaka
Hidekazu Tokuyama
Kohtaro Ujiie
Mike Underwood
Kelin Wang
Makoto Yamano

* Main proponents
† Contact person

October 1, 2001

Introduction

Subduction zone earthquakes account for ~90% of global seismic moment release, producing devastating earthquakes and tsunamis near heavily populated coastal areas. Significant progress in understanding earthquake rupture propagation has been achieved in the last decade through instrumentation, laboratory experiment, and theory. However, the factors controlling stable vs. unstable slip on faults remain poorly understood, impairing our ability to evaluate those earthquake and tsunami hazards. Our understanding of the mechanics and dynamics of plate boundary faulting is limited in particular by a lack of information on ambient conditions and mechanical properties of these faults at depth. A major present goal in earthquake mechanics research is thus direct *in situ* sampling and instrumentation by drilling into the seismogenic zone of an active plate boundary fault system. Subduction megathrust systems present clear advantages in the analysis of seismogenesis because they are shallowly dipping, amenable to imaging and drilling, and can be sampled in multiple locations from the incoming plate to depths where earthquakes occur, in order to document evolution of fault properties.

The IODP Initial Science Plan states (pg. 68): *"As one of its inaugural activities, IODP will drill through a seismogenic fault zone to characterize the composition, deformation microstructures and physical properties of the rocks at* in situ *conditions."* In documents produced through the ODP/IODP planning process (CONCORD, COMPLEX, and the Seismogenic Zone DPG; Hyndman, 1999), and the MARGINS Seismogenic Zone Initiative [MARGINS, 1999], the rationale for this objective has been exhaustively laid out; we do not further justify it here. Rather, we focus on the reasons to carry it out at the Nankai Trough, present specific hypotheses and objectives, and outline an integrated program plan of non-riser and riser drilling designed to investigate the aseismic to seismic transition of the megathrust system. We show several candidate sites demonstrating that the objectives are achievable within the designed operational limits of the riser ship, but emphasize that specific sites for drilling will not be selected until further site survey data collection and analysis is complete.

Why the Nankai Trough?

The Nankai Trough region is among the best-studied subduction zones in the world. It has become a focus for investigation of the seismogenic zone because it has a 1300-year historical record of recurring great earthquakes (M_w ~8.0), typically tsunamigenic [MARGINS, 1999], including the 1944 Tonankai (M_w=8.2) and 1946 Nankaido earthquakes [Ando, 1975; Fig. 1].

With great earthquakes recurring at ~120 year intervals, Nankai contrasts with the other SEIZE focus area in Central America, which is characterized by smaller though more frequent earthquakes [Protti et al., 1994]. Recent onland 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 updip limits of the 1946 earthquake [Obana et al., 2001] implies significant interseismic strain accumulation on the megathrust.

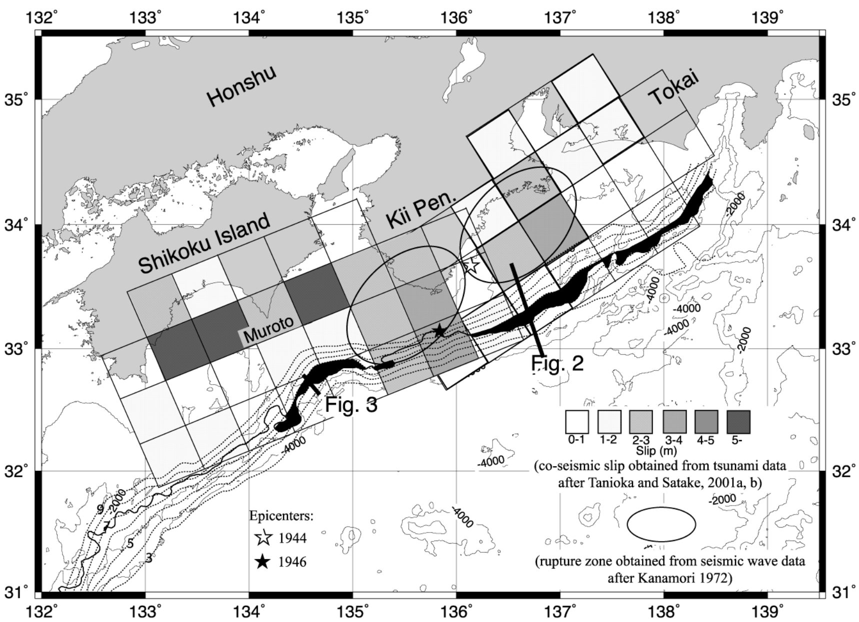


Figure 1. Location map of Nankai margin, illustrating the coseismic slip areas of the 1944 and 1946 earthquakes. Areas marked in black represent locations with ≤2.5 km water depth and ≤6 km sub-bottom depth to the plate interface. Areas under consideration for proposed drilling include the Cape Muroto, Kii Peninsula, and Tokai regions.

Nankai is an analog for other sediment-rich subduction zones such as Cascadia or the Eastern Aleutian Trench, that also have generated great earthquakes. Unlike those examples, Nankai has relatively shallow water depths and a plate boundary thrust located within the designed drilling capabilities of the riser vessel. Seismic imaging of the décollement zone and accretionary prism in multiple survey areas is excellent, providing clearly-defined targets for deep drilling (Figs. 2 & 3). Much background information is available from decades of drilling and regional geophysical/geological studies. A relatively high thermal gradient places many diagenetic-metamorphic reactions, implicated in the onset of seismogenesis, within the riser hole depth range. On-land analogs of the seismogenic zone rocks are exposed in the nearby Shimanto complex [Taira et al., 1988], accreted under conditions similar to those extant offshore today. Thrusts splaying from the main décollement through the prism to the surface are commonly imaged, and have been identified as participating in co-seismic tsunami generation (Fig. 2).

These splays offer additional potentially seismogenic target fault zones drillable at the same site as the main plate interface.

For all of these reasons, the Nankai Trough region presents the best confluence anywhere in the world of seismogenic history and characteristics, imaging of multiple clearly-defined targets, pre-existing data, and feasibility of drilling.

Scientific Hypotheses and Questions

The drilling plan proposed here is framed around a set of specific hypotheses, derived from major outstanding questions in fault mechanics and earthquake physics through the criterion of being realistic to address by drilling. It will provide data bearing on each hypothesis and, whatever the results, will undoubtedly contribute a large step forward in fault zone studies.

Hypothesis #1: Systematic, progressive material and state changes control the onset of seismogenic behavior and locking of subduction thrusts.

Several possible mechanisms controlling the onset of slip instability (and thus seismic behavior) have been proposed, particularly: (a) thermally-controlled diagenetic and metamorphic changes in fault composition, such as clay transformations, deposition of cementing phases, and/or onset of pressure solution; and/or (b) increasing effective stress mediated by declining fluid overpressure. Drilling of the fault and emplacement of borehole instrumentation near the up-dip limit of seismogenic behavior (as variously defined by microseismicity, co-seismic slip, and geodetic strain) will constrain state variables (stress, pore pressure, temperature) and document parameters such as mineral composition, fault architecture, strain rate and microseismic activity. For example, if cementing mineral phases have healed and locked the fault zone, it will be apparent in the nature of the fault rock as determined by cores and/or logs.

Hypothesis #2: Subduction zone megathrusts are weak faults; i.e., they slip under conditions of low resolved shear stress.

While controversial, diverse mounting evidence from plate boundary faults in all tectonic settings suggests they are weak, both relative to the surrounding rock volumes, and in an absolute sense based on theoretical and laboratory-based understanding of friction-controlled brittle failure (e.g., Hickman, 1991). Perhaps the strongest case in this regard can be made for low-angle subduction thrusting. Potential causes of this apparent weakness include: (a) intrinsically weak materials present in the fault zone, (b) elevated fluid pressure resulting in low effective stress conditions, and/or (c) dynamic weakness generated during rapid slip events. Sampling of the fault materials and in situ measurement of state variables will address this hypothesis.

Hypothesis #3: Within the seismogenic zone, relative plate motion is primarily accommodated by coseismic, frictional slip.

This hypothesis implies that the plate boundary fault within the seismogenic zone is locked, as implied by GPS observations (Miyazaki and Heki, 2001), and little strain is accommodated elsewhere. Material sampling on and off the fault will reveal deformation recorded in the rocks, while monitoring and laboratory experiments will document present conditions such as strain rate, allowing us to test consistency between the two. Furthermore, drilling of one or more splay faults will help constrain how much interplate motion is accommodated by aseismic or seismic slip on such faults, with implications for strain accumulation on the megathrust.

Hypothesis #4: Physical properties, chemistry, and state of the fault zone change with time throughout the earthquake cycle (interseismic and coseismic).

Many temporal changes, related to the earthquake cycle, in measurable properties (fluid pressure, stress, temperature, fluid chemistry, seismic velocity, permeability, etc.) have been proposed. If real, these changes and the time scales over which they occur will be addressed by the long-term monitoring component of the proposed drilling. Instrumentation now will provide a platform for observation for decades to come.

Key Observations and Technology

The critical *in situ* data and approaches which will test the above hypotheses include:

- Fault zone composition and architecture
- Fluid pressure
- Stress state
- Temperature
- Fluid chemistry
- Permeability
- Borehole strain measurements
- Microseismicity
- Seismic velocities (v_p and v_s)
- Experimental studies and modeling
- Theoretical studies
- Reference site observations (inputs)

We envision a combination of observations made during drilling (LWD/MWD, core- and cuttings-based, and downhole measurements such as temperature, pressure, and stress), and measurements made over the long term in the borehole observatory (fluid pressure, strain, microseismicity, etc.) will be applied to address the hypotheses. Information from non-riser drilling sites will be critical toward answering some of these questions. Associated experimental and theoretical efforts (e.g., laboratory friction experiments, hydrological, thermal, and mechanical modeling, and reaction kinetics experiments) will be an important component of hypothesis testing constrained by drilling results.

We anticipate a very detailed planning process to coordinate all of these operational goals, including development of new technology. Successful achievement of our scientific goals will require a comprehensive suite of cutting-edge drilling and borehole instrumentation technologies, planned in detail by an expert team, with substantial industry input. Long-term monitoring will be designed to address potential temporal changes during inter-, pre-, co-, and post-seismic phases, and will include as many of the following approaches as are mutually compatible in the boreholes: temperature, fluid pressure, stress, electromagnetic properties, seismometry, tilt/strain, and fluid chemistry.

Proposed Program and Site Selection Criteria

In this preliminary stage, we have three regions under consideration as candidate locations for an IODP transect (Fig. 1). All three areas share the general Nankai advantages described above, but exhibit various specific characteristics useful to address our objectives. Geophysical surveys and potential site characterization are ongoing, and final transect selection will be based on the best available data when a decision point is reached.

A basic constraint is that a deep site must be chosen which both fulfills the scientific objectives and is within the operational capability of the riser ship, currently planned to be 2.5 km water depth (riser length limit) and 10 km total drill string length. Drilling time estimates increase exponentially as a function of total depth drilled, so it will be important to minimize the sub-bottom depth needed to reach the subduction interface (Hyndman, 1999). Black filled areas in Fig. 1 represent locations where the water depth is ≤2.5 km, *and* seismic data indicate the downgoing plate can be reached in ≤6 km below seafloor (bsf).

The chosen riser site must be part of a transect including non-riser sites to place the deep hole in its regional context and to test models for downdip evolution of material properties of sediments and basement. The sedimentary and thermal regimes of the subducting Shikoku Basin section change considerably across the strike of the Nankai deformation front, as does basement structure (Moore et al., 2001), potentially influencing seismic segmentation of the plate boundary, so it will be important to drill local *reference sites*. We also propose one or more *non-riser prism sites* to access an imaged splay fault at 1-2 km bsf. Such a site will permit comparison between faults at differing P-T-stress conditions, potentially access fluids derived from the seismogenic zone, and provide valuable experience in drilling conditions in the interior of the prism, prior to riser drilling. We anticipate that this program requires about one ODP-length leg of non-riser drilling.

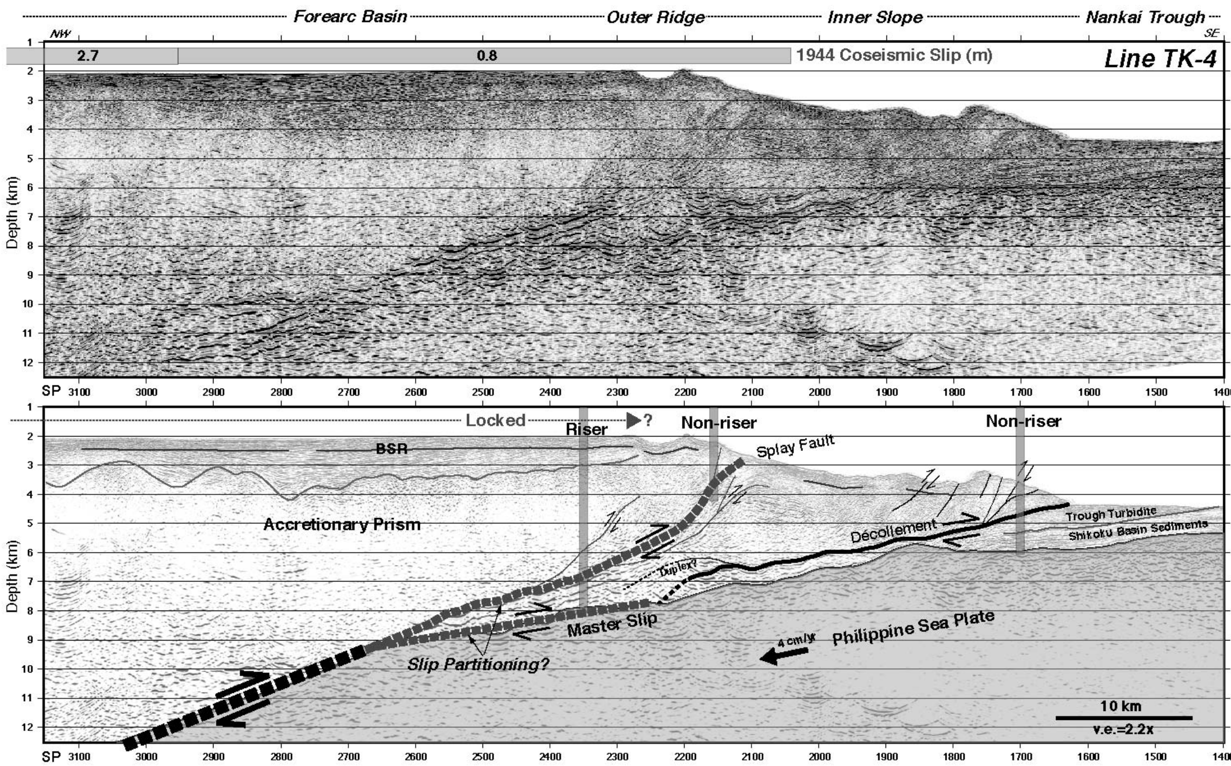


Figure 2. A depth migrated MCS profile (top) of line TK-4 across the central Nankai Trough off east Kii Peninsula and (bottom) its line-drawing interpretation. Location of this line is shown in Fig. 1. The 1944 Nankai coseismic slip was estimated from tsunami waveforms inversion [Tanioka and Satake, 2001a]. Possible riser and non-riser sites are shown.

Kii Peninsula Transect

One candidate location for the proposed transect is east of the Kii Peninsula (Fig. 1). Crustal structure is well imaged at potential riser and non-riser sites on this transect (Fig. 2), including the top of the downgoing oceanic crust and internal structure in the accretionary prism. The bottom-simulating reflector (BSR) -derived thermal gradient predicts temperature on the top of the oceanic basement under the outer ridge to be approximately 180-200˚ [Park, unpub. data], greater than the 150˚ threshold recently hypothesized as the onset of stick-slip, seismogenic behavior [Hyndman et al., 1995].

A high-amplitude reflector interpreted as an active thrust fault splays upward from the master slip plane of the megathrust to the surface. This splay fault is observed on four MCS profiles east of Kii Peninsula, and a seafloor scarp of this splay is continuously recognized along strike in swath-bathymetric data over the entire central Nankai Trough margin. Tsunami waveform inversion [Tanioka and Satake, 2001a] indicates that the forearc basin, including the outer ridge, was entirely within the coseismic slip area of the 1944 earthquake in this location, suggesting there was surface displacement of the splay fault.

The plate interface can be reached at ~6 km bsf in ~2 km water depth. A riser site here would also penetrate the splay fault reflector at 4-5 km bsf, where it is likely to be at a temperature of ≥150˚, permitting penetration of two thrust faults under different P-T-stress conditions, both within the hypothesized seismogenic window. A further non-riser site located up-dip to penetrate this splay will provide a non-seismogenic zone sampling point, and likely will tap fluids sourced in the megathrust system, revealing thermal and geochemical fingerprints of processes at depth. Non-riser sites located both seaward and landward of the deformation front near the prism toe would define the poorly known solid, fluid, and thermal inputs to the seismogenic zone off Kii.

Cape Muroto Transect

3D seismic imaging (Fig. 3) of the Muroto region off Shikoku reveals structure from the trench 60 km down-dip, into regions of the megathrust thrust shown to be seismically active (Obana et al., 2001). The décollement is imaged continuously within the lower Shikoku sequence ~300m above basement, to a depth of ~7 km. Like Kii, probable splay fault reflectors are imaged. Potential drilling targets are within the coseismic slip zone of the 1946 earthquake (Tanioka and Satake, 2001b).This transect has the advantage that inputs to the megathrust system are well-documented, and that seismic interpretation suggests that the physical properties of the décollement evolve progressively within the single lithology of the lower Shikoku section. The Muroto transect is in an area of especially high heat flow, placing thermally-controlled boundaries at shallow, accessible depths (Moore et al., 2001). Muroto candidate riser sites would involve drilling to only ≤5 km bsf to reach the plate interface (Fig. 3). A non-riser site could also access the splay fault at lower P-T conditions. Reference and up-dip décollement sites already exist at ODP Sites 808, 1173–1176, and 1178.

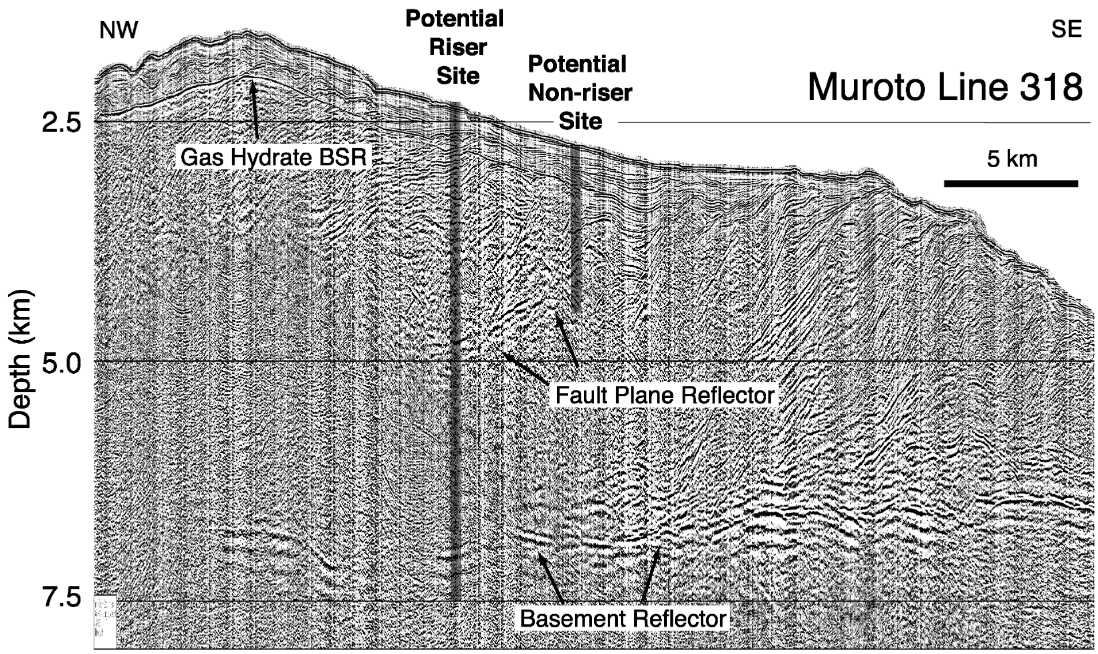


Figure 3. Depth-converted time migration section extracted from the Muroto transect 3-D reflection data. The potential riser site is chosen to cross the BSR and splay fault, and reach the plate interface reflection at ~7 km total depth (~5 km below sea floor).

Tokai Transect

The Tokai area has a wide forearc basin domain and relatively small active accretionary wedge, and is strongly affected by the subduction of basement ridges, causing uplift of the forearc basin by a dominantly compressive fault system [Le Pichon et al., 1996]. The prism in this area has been intensively studied with OBS surveys, 2-D and 3-D (acquired in 2000; currently being processed) seismic reflection and submersible dives; however, the trench and basin inputs are poorly known. A connection between the main active surface faults and the subduction megathrust has been proposed [Mazzotti et al., in press], similar to imaged splay faults in the other two regions. This fault segment did not rupture during the 1944/1946 events and likely is later in the interseismic cycle than adjacent regions. The Tokai area therefore presents an opportunity to drill at moderate depths to the plate interface through active splay thrusts that may participate in a relatively near-term large seismic/tsunamigenic event.

Integrated Drilling Strategy

Successful achievement of these ambitious objectives at the Nankai Trough will require a comprehensive, carefully-coordinated program to maximize the value of the culminating deep borehole. We envision a series of specific milestones to be reached over the next ~6-7 years:

1. **Geophysical Site Characterization:** Although the Nankai Trough is among the world's most-intensively studied continental margins, further geophysical data are still required, especially including 3D seismic off Kii, new wide-angle surveys to define the velocity structure for accuracy in depth imaging and earthquake location, and additional heat flow data.
2. **Non-Riser Reference and Up-Dip Sites:** Several non-riser reference sites in the incoming Shikoku Basin section and décollement toe should be drilled early in the IODP program. Such sites have been drilled to date only off Shikoku. We further propose one non-riser splay fault site to a depth of 1-2 km. This will require about one ODP-length leg of non-riser drilling.
3. **Non-Riser 1 to 1.5 km Hole(s) at Candidate Site(s):** To characterize the drilling environment at the final candidate site(s) for riser drilling, it will be necessary to drill one or more pilot holes in non-riser mode, albeit perhaps using the riser ship (Hyndman, 1999).
4. **Riser Stage 1: Penetration to Splay Fault:** The first riser drilling objective will be to complete drilling and downhole observations to the depth of the splay fault at ~3-5 km bsf. This *in itself* will access an active prism thrust fault at never-before-sampled P-T conditions, test models for tsunamigenic slip, and will develop experience with riser drilling operations before extending operations down to the main plate boundary fault.
5. **Riser Stage 2: Drill to Décollement with LWD/MWD and Coring:** After stage 1, drilling operations will be extended to depth across the principal plate boundary objective using LWD/MWD technology supported by coring as possible. Penetration and geophysical/material sampling across the main plate boundary would constitute an unprecedented achievement.
6. **Riser Stage 3: Install Deep Borehole Observatory:** The final and most ambitious portion of the program plan will be installation of the borehole observatory into the plate boundary hole. This will require extensive completion operations and installation of the instrumentation detailed above for long-term monitoring and active testing of in situ conditions. It may include multiple kick-off holes crossing the fault.

References Cited

Ando, M., 1975. Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. Tectonophysics, 27: 119-140.

Hickman, S., 1991. Stress in the lithosphere and the strength of active faults, U.S. Nat. Rept. Int. Union Geod. Geophys. 1987-1990, Rev. Geophysics, 29: 759-775.

Hyndman, R., 1999. Seismogenic Zone Deep Drilling and Measurement: Report of Detailed Planning Group, http://joides.rsmas.miami.edu/files/seizerept.pdf.

Hyndman, R., Wang, K, Yamano, M., 1995. Thermal constraints on the seismogenic portion of the southwestern Japan subduction thrust. JGR, 100: 15373-15392.

Le Pichon, X., Lallemant, S.J., Tokuyama, H., Thoue, F., Henry, P., 1996. Structure and evolution of the backstop in the Eastern Nankai trough area (Japan): implications for the soon to come Tokai earthquake. Island Arc, 5: 440-454.

MARGINS, 1999. The Seismogenic Zone Experiment (SEIZE) Science plan: http://www.ldeo.columbia.edu/margins/SEIZE_sci_plan.html.

Mazzotti, S; Lallemant, S J; Henry, P; PIchon, X Le; Tokuyama, H; Takahashi, N., 2001. Lithospheric scale tectonics of the Eastern Nankai subduction: intraplate shortening and undethrusting of a large basement ridge. Marine Geology, in press.

Miyazaki, S., and Heki, K., 2001. Crustal velocity field of southwest Japan: Subduction and arc-arc collision, JGR, 106: 4305-4326.

Moore, G.F., Taira, A., Klaus, A., et al., 2001, New Insights into Deformation and Fluid Flow Processes In the Nankai Trough Accretionary Prism: Results of Ocean Drilling Program Leg 190. Geophysics, Geochemistry, Geosystems, in press.

Obana, K., Kodaira, S., Mochizuki, K. and Shinohara, M., 2001. Micro-seismicity around the seaward updip limit of the 1946 Nankai earthquake dislocation area. GRL, 28: 2333-2336.

Protti M., Guendel, F., McNally, K., 1995. Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, *in* GSA Special Paper 295, 309-326.

Taira, A., Katto, J., Tashiro, M., Okamura, M. and Kodama, K., 1988. The Shimanto Belt in Shikoku, Japan: Evolution of a Cretaceous to Miocene accretionary prism. Mod. Geol., 12: 5-46.

Tanioka, Y., and Satake, K., 2001a. Detailed coseismic slip distribution of the 1944 Tonankai earthquake estimated from tsunami waveforms. GRL, 28: 1075-1078.

Tanioka, Y., and Satake, K., 2001b, Coseismic slip distribution of the 1946 Nankai earthquake and aseismic slips caused by the earthquake. Earth, Planets, and Space, 53: 235-241.

Map of Boulder, Colorado