LEG 186

WEST PACIFIC SEISMIC NETWORK

Modified by K. Suyehiro from Proposal 431 Submitted by:

K. Suyehiro, H. Fujimoto, T. Kanazawa, J. Kasahara, Y. Fukao, H. Momma, K. Fujioka, T. Matsumoto, J. Kinoshita, S. Sacks, A. Linde, R. Hino, A. Hasegawa, M. Shinohara, and I. Kawasaki

Staff Scientist: Gary Acton **Co-Chief Scientists: TBN**

ABSTRACT

During Leg 186, we will drill two sites from the deep-sea terrace on the landward side of the Japan Trench off northeast Japan to monitor crustal response to stable (aseismic) or unstable (seismic) sliding of the subducting Pacific Plate. This will be the first attempt to establish such a long-term seafloor borehole observatory in one of the world's most active and most studied subduction zones. Near-field data from an active plate boundary are crucial in quantifying the plate's elastic and anelastic behaviors in relation to earthquakes. Borehole strainmeters and broadband seismometers will be installed at the bottom of the two holes to continuously monitor strain changes and seismic activities associated with episodic plate motions. Secondary objectives include (1) determining the forearc subsidence history and placing constraints on the subduction mass balance at this tectonic erosional environment and (2) obtaining arc volcanism reference since 3 Ma.

INTRODUCTION

During Leg 186, we will drill two sites from the deep-sea terrace on the landward side of the Japan Trench off northeast Japan to monitor crustal response to stable (aseismic) or unstable (seismic) sliding of the subducting Pacific Plate. The western Pacific area, where the plate-consuming boundaries are concentrated, is the best suited region on Earth to address the dynamics of the subducting plates, formation and evolution of island arcs and marginal seas, and their relation to mantle convection (e.g., Fukao, 1992; Fig. 1). In particular, the Japan Trench region has both high seismicity and plate convergence rates compared to other trenches. Dense regional geophysical networks have been expanded in the land area across Japan over the years. Such data accumulation has made it possible to precisely locate the two proposed sites in seismically active (JT-1) and inactive (JT-2) areas about 10 km immediately above the interplate seismogenic zone (Fig. 2).

The Japan Trench subduction zone is the world's best studied area, but it lacks near-field data that are crucial in quantifying the plate's elastic and anelastic behaviors at an active plate boundary in relation to earthquakes. Borehole strainmeters and broadband seismometers will be installed at the bottom of the holes to continuously monitor strain changes and seismic activities associated with episodic plate motions.

Secondary, but important, geological objectives include (1) determining the forearc subsidence history and placing constraints on the subduction mass balance at this tectonic erosional environment and (2) obtaining arc volcanism reference since 3 Ma.

BACKGROUND

The scientific importance of establishing long-term geophysical stations in deep oceans has been acknowledged by earth sciences and Ocean Drilling Program (ODP) communities and is expressed in various articles (COSOD II, 1987; Purdy and Dziewonski, 1988; BOREHOLE, 1995; Montagner and Lancelot, 1995; Ocean Drilling Program-Long Range Plan, 1996). In essence, we want to understand active processes driving Earth's dynamics from a global to a regional scale, but 71% of Earth's surface is covered by oceans that can only be probed by utilizing state-of-the-art digital sensors linked with land-based stations. Many sensors, whose locations will be carefully selected to maximize results, are needed around the world to obtain the goals of the international geoscience programs. We have selected the western Pacific area for installation of ocean-bottom sensors because it is ideal for addressing problems related to plate subduction.

In the Japan Trench area, seven large (magnitude [M] > 7) interplate events occurred in the last 30 yr between 38° and 41°N. Recent large events are the 1968 Tokachi-Oki earthquake (~41°N moment magnitude [Mw] 7.9) and the 28 December 1994 Far-off Sanriku earthquake (~40°N Mw 7.7). These events, however, are not sufficient to account for the subducting rate of about 10 cm/yr. Thus, the seismic coupling seems much smaller along the Japan Trench (35°-41°N) as compared with the Kurile Trench or Nankai Trough regions, which have a higher seismic energy release rate. Subduction at the Japan Trench may be proceeding by stable sliding either only with relatively small (surface-wave magnitude [Ms] < 8) events or with occasional large events.

There is a third important category whereby the subduction rate is accommodated by episodic aseismic events of time constants on the order of 10 min to several days (slow earthquakes). Such events, if they exist, are presently extremely difficult to detect. Kawasaki et al. (1995) reported that an ultra-slow earthquake estimated to be Mw 7.3-7.7 accompanied the 1992 Off-Sanriku (39.42°N, 143.33°E, Mw 6.9) earthquake based on strain records observed ~120-170 km away from the source. A postseismic strain change of 10^{-7} to 10^{-8} of a time constant of about a day were observed by quartz-tube extensometers (devices that measure absolute strain). Historically, in the same area, the 1896 Sanriku tsunami earthquake (Mw ~8.5 but body-wave magnitude [Mb] ~7) killed about 22,000 people. Tsunami earthquakes rupture in a much longer time constant of minutes compared to normal type (Tanioka and Satake, 1996).

More recently, the Japanese global positioning system (GPS) network has revealed a postseismic motion of northern Japan after the 1995 Far-off Sanriku earthquake (M 7.2) that can be explained by a stress diffusion model assuming slow slip on the earthquake fault (Heki et al., 1997). A different, but previously more prevailing interpretation, is that the postseismic deformation is due to aseismic slip at a depth extended deeper down from the seismogenic zone. If such a slow slip really occurred in the vicinity of the normal seismogenic zone, then strainmeters in the proximity would have recorded signals not only much larger in magnitude but also would have resolved how and where the slip initiated relative to a normal earthquake and how it proceeded. Furthermore, one can test if aseismic and episodic slips occur irrespective of normal earthquakes.

The strain waveforms of slow earthquakes are of a ramp type. The amplitudes of strain steps decay reversely proportional to the distance cubed, much more rapidly than seismic waves. It is essential, therefore, to measure the strain signatures as near to these events as possible (within 20 km for an event equivalent to Mw 7.0; e.g., Johnston et al., 1990) to estimate how the regional tectonic stress affects earthquake occurrences.

Because the primary objective is the establishment of long-term borehole observatories, once the instruments are installed, they must be serviced for data analyses, distribution, and archiving. There is an ongoing national program within Japan to achieve this (Ocean Hemisphere Project). A new fiber optic cable owned by the University of Tokyo already exists and currently terminates near Site JT-1. Once Site JT-1 proves to be useful, connections will be made to supply power, send commands, and retrieve data in real-time on land. Furthermore, a 50-km cable extension is planned to connect Site JT-2 as well. These stations will make invaluable additions to the existing geophysical network over the western Pacific. The data will eventually become accessible worldwide through the Internet.

SCIENTIFIC OBJECTIVES

Dynamic Sliding of the Subducting Plate and Earthquake Process

The seismic coupling efficiency of the subduction zone off Tohoku appears to be as low as 25%. This means that of the total Pacific plate motion expected, only one-quarter is seen as strike-slip motion leading to thrust-type earthquakes. One possibility is that three-quarters of the motion is released as slow earthquakes, which are not recorded on normal seismographs. In the past, sparse observations suggest that the slow strain release may consist of multiple episodes in which each event is rather small. For this reason, installation of an instrument of the highest achievable sensitivity is required. Any data leading to better understanding of the partitioning of strain release into damaging "fast" events and slower events will be extremely valuable and may lend further insight into the whole earthquake process.

The plate boundary off northeast Japan fulfills three important conditions for a long-term geophysical observatory:

1. Dense geophysical networks to which our proposed observatories can be optimally linked already exist on land.
2. Moderately large (M ~7) seismic events occur frequently, and aseismic slips (slow earthquakes) with comparable or larger magnitude are expected to occur even more frequently.
3. Crustal and uppermost mantle structures have been well studied by reflection-refraction seismic surveys and tomographic inversions (Suyehiro et al., 1985a, 1985b, 1990; Suyehiro and Nishizawa, 1994; Ito, 1996).

Earthquake Source Studies

Stations at proposed Sites JT-1 and JT-2 will greatly improve source location (particularly depth), focal mechanism, and rupture process determinations of the earthquakes near the Japan Trench (Nishizawa et al., 1990, 1992; Suyehiro and Nishizawa, 1994; Hino et al., 1996). Near-field data obtained from the stations at Sites JT-1 and JT-2 will particularly improve the resolution of the source mechanisms of very slow rupture events such as tsunami earthquakes.

High-Resolution Geometry of the Plate Boundary

The two stations at proposed Sites JT-1 and JT-2 will be linked to the network of the broadband and/or very broadband seismometers on the main Japanese islands and will make a dense seismic network of 50-km in scale. The observations of various phases of body waves from many shallow to deep earthquakes within the network will provide sufficient data to improve the structural image of the plate boundary, particularly, the changes in physical properties associated with tectonic erosion and seismogenesis.

Miocene and Younger Volcanic Ash Stratigraphy in the Western Pacific (Site JT-1)

The cores will represent an important reference section near Japan to compare to the remote ash deposits already cored to the east. They will also provide important information about eruptive processes, volcanic hazards, and aspects of climate such as response to wind, sand, and volcanogenic input of greenhouse and related gases (J. Natland, pers. comm., 1997).

During Leg 132, a number of rhyolitic to dacitic volcanic ash beds on Shatsky Rise, east of Japan were recovered (Fig. 1). Comparison with ash stratigraphy at Deep Sea Drilling Project (DSDP) Sites 578-580, about halfway between Shatsky Rise and Japan, indicates that the Shatsky ash beds were derived either from Japan or the Kurile-Kamchatka arc systems and that they were carried far to the east on the high-speed polar and sub-tropical jet streams (Natland, 1993). A summary appraisal is that 25-40 eruptions produced ash that reached one or more of those sites in each of the past 3 m.y., with ~10% of these reaching Shatsky Rise in the form of discrete ash beds or pumice drops. Some of the eruptions were extremely large, resulting in deposits 5 to 15 cm thick, even on Shatsky Rise. The last drilling in this region was during DSDP Legs 56 and 57, before the advent of hydraulic piston coring. An important, but seriously incomplete and at times highly disturbed, ash record was recovered in Holes 438A and 440B (e.g., Cadet and Fujioka, 1980). Fluctuations in accumulated ash thickness through time over the 15° of latitude represented by the proposed Leg 186 sites indicates that both the position and velocity of the jets have changed during the past 3 m.y., during the period of pronounced climatic deterioration since the early Pliocene.

Age and Nature of the Cretaceous Basement

Only one hole (Hole 439) touched the Cretaceous basement during Legs 56 and 57 (Shipboard Scientific Party, 1980). This Cretaceous unit is unconformably underlain at the drill site by a 48-m-thick breccia conglomerate, which contains 24-m.y.-old hypabyssal dacitic to rhyolitic boulders (von Huene et al., 1994).

Subsidence History Across the Continental Slope to Constrain the Processes of Tectonic Erosion

Quantitative estimates of the tectonic erosion process were made for the Neogene history of the Japan Trench region based on drilling and seismic records (Fig. 3; von Huene and Lallemand, 1990; von Huene et al., 1994). Key evidence came from Site 439. Evidence collected from additional drilling will further constrain the timing and erosion volumes in relation to backarc opening and the style of convergence.

Subduction Rate

It is planned that proposed Sites JT-1 and JT-2 will be used as a benchmark for geodetic measurements in the future. Repetitive measurements of the positions of Sites JT-1 and JT-2 using an acoustic technique and differential GPS positioning will provide information on the subducting rate of the western Pacific Plate at the Japan Trench.

DRILLING STRATEGY

The two proposed sites are to become legacy holes, thus requiring them to be equipped with reentry cones and casing through unstable sections. Because the instrument must match the rigidity of the surrounding rock, we need to drill into the Cretaceous basement. Installation of borehole sensors are to be made by the drillship. The sensor package is about 8" in diameter and is to be attached at the end of the drill string and to be disconnected at the seafloor level after cementing the package section about 30 m from the bottom (Fig. 4).

To obtain volcanic ash records, piston coring to refusal is required, ideally at least twice, to ensure complete recovery in the Pliocene and younger section, and single extended core barrel (XCB) coring into the Miocene section below that (from ~250 to 450 mbsf).

LOGGING PLAN

The logging program for the two holes is designed to measure physical properties, anisotropy, and hole shape. These objectives are quite similar to the objectives at the pilot site OSN-1 during Leg 136. The anazimuthal resistivity tool (ARI) could be used in place of the laterolog to measure electrical anisotropy at ~1-m resolution, complementing the high-resolution formation microscanner (FMS) images. Standard geophysical logs can be used to measure physical properties, and hole volume can be estimated with high accuracy using a borehole televiewer (BHTV) log in the basement intervals. This will significantly improve grouting procedures for the strain sensors and emplacement for the seismometers. High-resolution temperature logs should be emphasized to identify permeable zones and inflow/outflow from both drilling-induced and natural fractures in the holes.

All sites should be logged with (1) the standard triple-combo tool with ARI or dual laterolog (DLL); (2) the FMS/Sonic/Temperature tool; and (3) the BHTV (logging speed is ~1 m/min).

PROPOSED SITES/OBSERVATORIES

Site JT-1B

Proposed Site JT-1B is located at the deep-sea terrace for observatory installation within a seismically active zone (Fig. 2). This zone is known to be capable of generating from micro- to large (M 7) earthquakes.

Site JT-2B

Proposed Site JT-2B is located at the deep-sea terrace south of Site JT-1B for observatory installation within a seismically inactive zone (Fig. 2). Slip within this zone has not been accompanied by detectable earthquakes for more than a decade. No clear historical record is available that indicate seismic slips in this zone except possibly in 1678 or 1915.

Observatory Design

All the instruments will be third-party tools. Both sites are to be equipped with (1) a high-resolution volumetric strainmeter (Carnegie Institution of Washington/University of Tokyo joint development), (2) broadband seismometers (Guralp CMG-1) and back-up sensors (PMD2023), (3) a temperature sensor, (4) a pressure gauge, and (5) a tilt sensor. Any heat generating instrument will be separated from the strainmeter.

(1) *Strainmeter*

The Sacks-Evertson borehole volumetric strainmeter has proven to have resolution of better than 10-11 at various locations on land, including San Andreas, California, Iceland, and Japan (Sacks et al., 1978; Linde et al., 1988, 1993, 1996). The instrument must be buried and cemented in solid contact within a competent rock section. The deepest installation so far has been at ~500 m. The high dynamic range and very broad frequency response (up to some tens of Hertz) of the borehole strainmeter will result in an ocean-bottom installation providing valuable data for subduction zone earthquakes. For example, on-land borehole strainmeters have proven to be effective in detecting the slow initial stage of large earthquakes.

(2) *Seismic Sensor*

In September 1989, a feed-back type accelerometer capsule was installed in Hole 794D in the Japan Sea during Leg 128 (Ingle et al., 1990; Suyehiro et al., 1992, 1995). The instrument recorded a teleseismic event (Mb 5.4 at ~4000 km epicentral distance) clearly showing a surface wave dispersion train (Kanazawa et al., 1992). In May 1992, a comparison of seafloor and borehole (Hole 396B) sensors was made using a deep-sea submersible for installation and recovery (Montagner et al., 1994). Although at this stage, there is no clear conclusion as to how we should establish seafloor seismic observatories, it is becoming clear that oceans can provide low-noise environments. For this particular case, where seismic sensors are to be installed as near to the source as possible, borehole installation should give better constraints on hypocenter depths. It is imperative that no fluid motion occur around the sensor; therefore, the seismometer and the strainmeter must be cemented at the same location in the same operation.

(3) *Pressure*

Two sensors will be equipped to measure pressure at the sea bottom and at the bottom of the hole.

(4) *Tilt*

Tiltmeters (two component) will be included to measure crustal deformation.

(5) *Temperature*

The vertical profile of temperature in the hole will be measured by placing temperature sensors at the top of the hole and at the top and the bottom of the bottom housing. Temperature inside the bottom housing will be measured to compensate for temperature variations and the sensitivity of the sensor.

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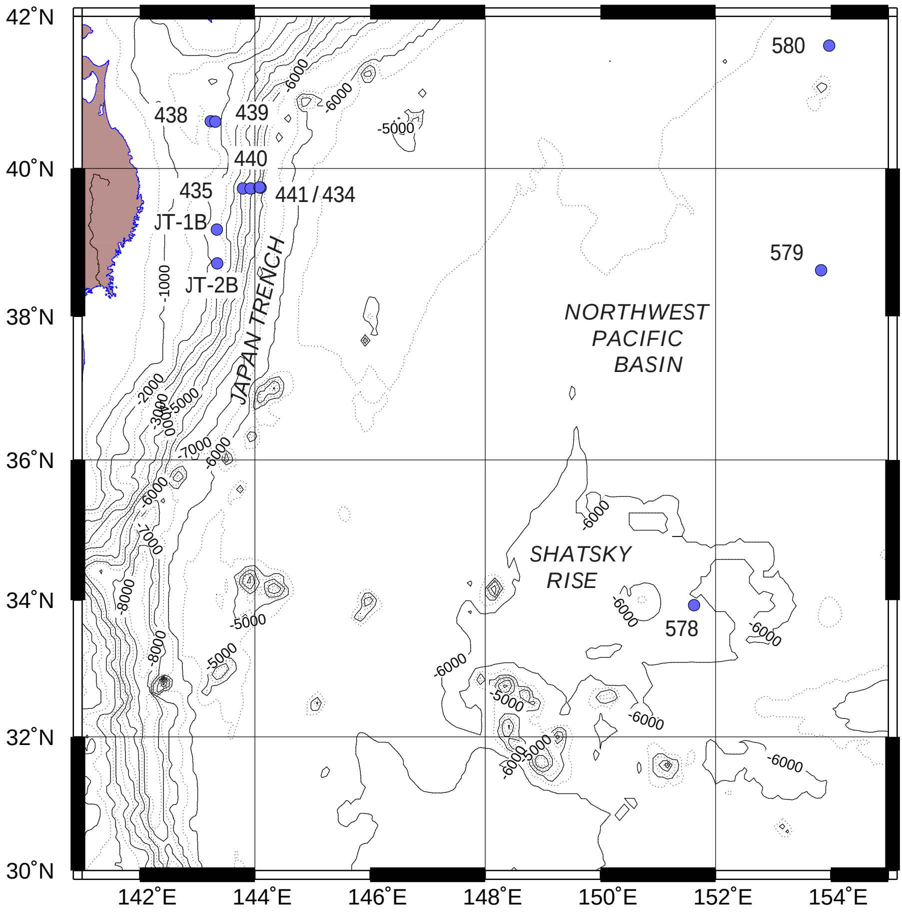
FIGURE CAPTIONS

Figure 1. Map of western Pacific area where at least five major plates with consuming boundaries interact. Gray dots are DSDP sites. Bathmetry is in meters.

Figure 2. Map of Japan Trench area with seismicity. The locations of proposed Sites JT-1 and JT-2 are shown. Focal depth symbols: open circle = 0-10 km, open square = 10-20 km, open triangle = 20-30 km, closed circle = 30-40 km, closed square = 40-50 km, closed triangle = 50+ km.

Figure 3. Tectonic subsidence history (from von Huene and Lallemand, 1990).

Figure 4. Schematic configuration of the instrument package with multisensors for crustal strain and broadband seismometry.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JT-1B
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-7000
-8000

Figure 1

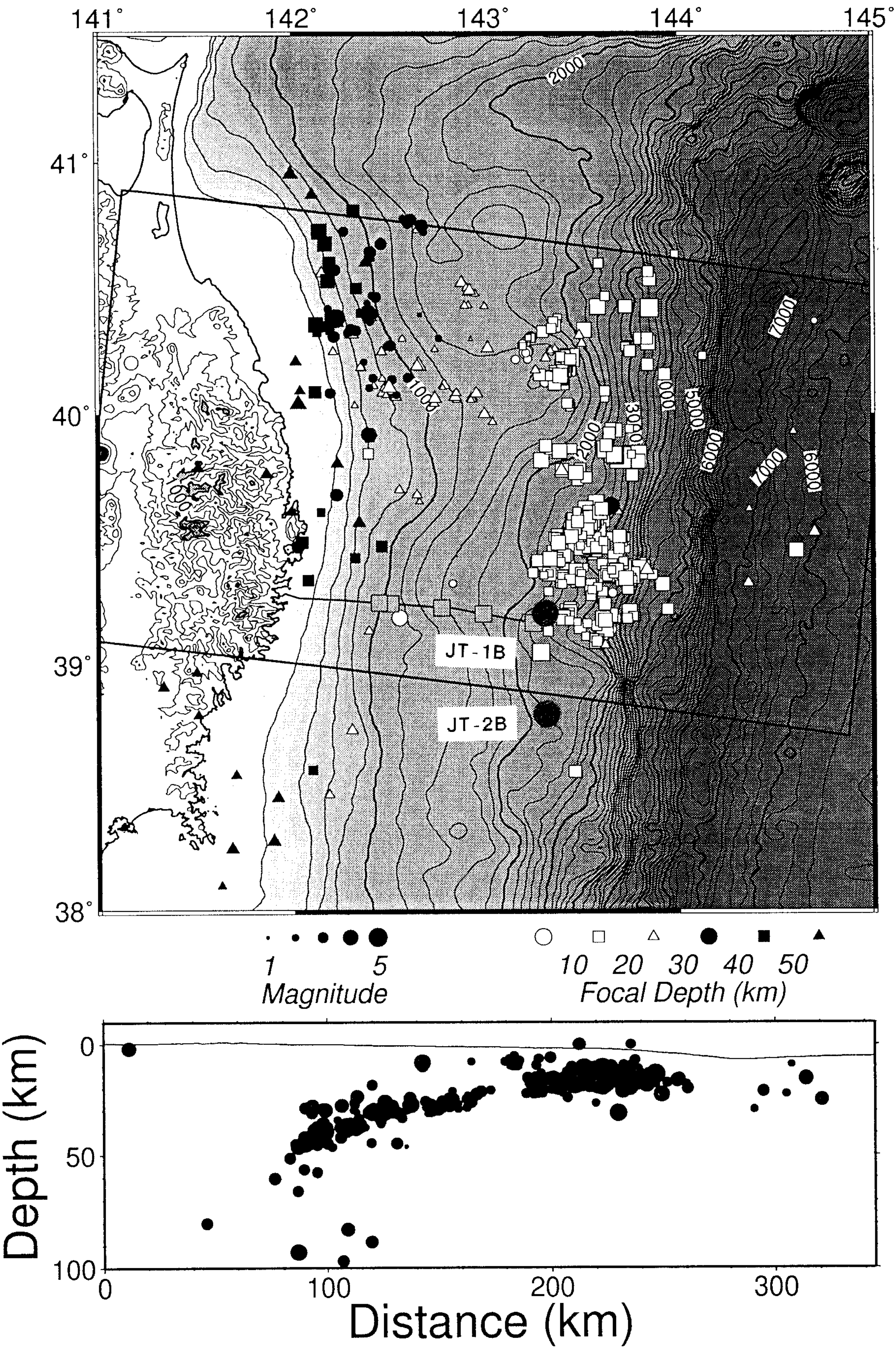
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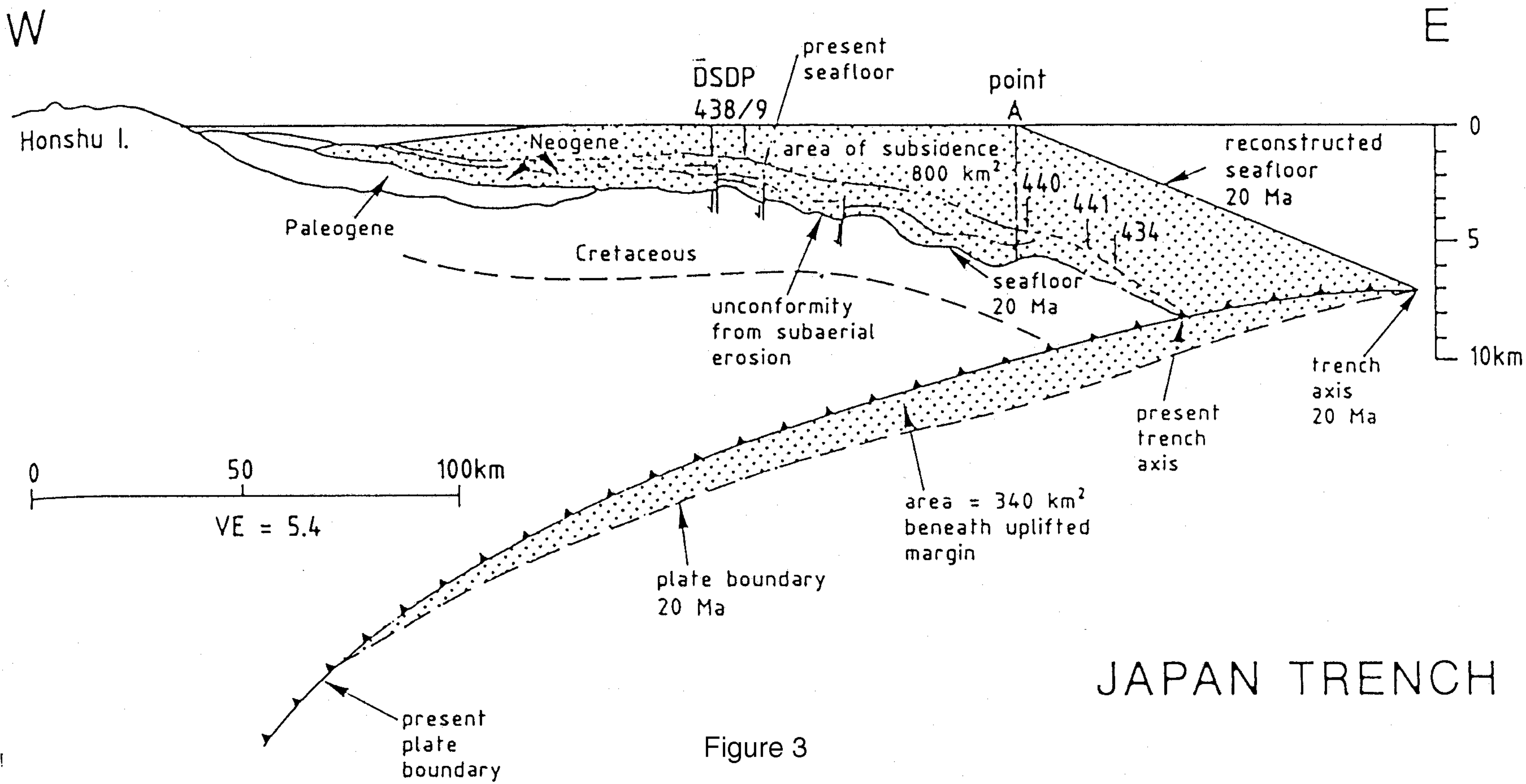
Figure 2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20 Ma
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present
trench
axis
0
50
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beneath uplifted
margin
plate boundary
20 Ma
JAPAN TRENCH
present
plate
boundary

Figure 3

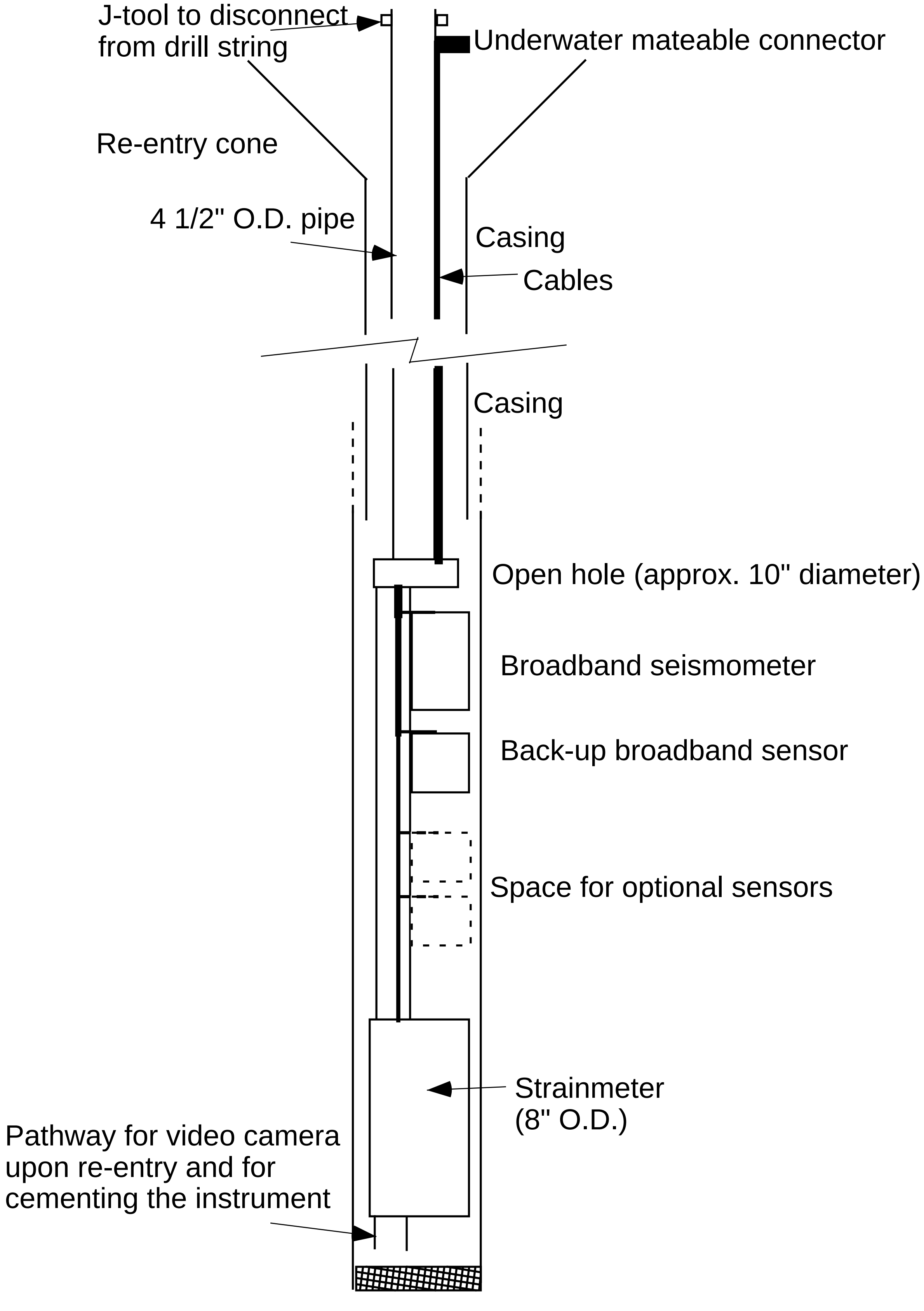
J-tool to disconnect
from drill string
Underwater mateable connector
Re-entry cone
4 1/2" O.D. pipe
Casing
Cables
Casing
Open hole (approx. 10" diameter)
Broadband seismometer
Back-up broadband sensor
Space for optional sensors
Strainmeter
(8" O.D.)
Pathway for video camera
upon re-entry and for
cementing the instrument

Figure 4

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: JT-1B	**PRIORITY**: 1	**POSITION:** 39°10.878´N, 143°20.095´W
WATER DEPTH: 2700 m	**SED. THICKNESS**: ~1300 m	**TOTAL PENETRATION**: 1400 m
SEISMIC COVERAGE: Intersection of KH96-3, Lines Leg 2-1 and Leg 2-4		

Objectives: (1) Install long-term geophysical borehole observatory to monitor changes in strain, seismic signals, tilt, pressure, and temperature. Quantify episodic plate motions within seismically active part of the interplate seismogenic zone. (2) Recover past 3 m.y. volcanic ash stratigraphy for comparison with other western Pacific ash deposits in relation to eruptive processes and transport mechanisms. (3) Constrain subsidence history of the Japan Trench forearc. (4) Determine nature of Cretaceous basement.

Drilling Program: Double APC to 250 m, XCB to 450 m, RCB to 1400 m, reentry cone. Case through unstable section

Logging and Downhole Operations: Triple combo, FMS/Sonic/Temp, BHTV; install long-term sensor package and cement at the bottom

Nature of Rock Anticipated: Sandy, silty, pebbly clay with ash layers (50 m); clayey diatom ooze, diatomaceous clay, ash layers (~350 m); diatomaceous claystone, clayey diatomite (~250 m); claystone, diatomaceous claystone, calcareous claystone (~200 m); sandy claystone, diatomaceous claystone (~200 m); turbidite sand silty claystone (~100 m), sandstone and siltstone (~100 m), boulder to pebble conglomerate and breccia, dacite and mudstone clasts (~50 m); silicified claystone (~100 m)

SITE: JT-2C	**PRIORITY**: 1	**POSITION**: 38°42.151´N, 143°20.506´E
WATER DEPTH: 2143 m	**SED. THICKNESS**: ~1300 m	**TOTAL PENETRATION**: 1600 m
SEISMIC COVERAGE: Near intersection of KH96-3,Lines Leg 2-2 and KH90-1 Line JT90		

Objectives: (1) Install long-term geophysical borehole observatory to monitor changes in strain, seismic signals, tilt, pressure, and temperature. Quantify episodic plate motions within seismically inactive part of the interplate seismogenic zone. (2) Constrain subsidence history of the Japan Trench forearc. (3) Determine nature of Cretaceous basement.

Drilling Program: APC, RCB to 1400 m; reentry cone; case through unstable section

Logging and Downhole Operations: Triple combo, FMS/Sonic/Temp, BHTV; install long-term sensor package and cement at the bottom

Nature of Rock Anticipated: Sandy, silty, pebbly clay with ash layers (50 m); clayey diatom ooze, diatomaceous clay, ash layers (~350 m); diatomaceous claystone, clayey diatomite (~250 m); claystone, diatomaceous claystone, calcareous claystone (~200 m); sandy claystone, diatomaceous claystone (~200 m); turbidites and silty claystone (~100 m), sandstone and siltstone (~100 m), boulder to pebble conglomerate and breccia, dacite and mudstone clasts (~50 m); silicified claystone (~100 m)