Special Issues: The results from the first five-year 's term (2004-2008) of JAMSTEC

– Review –

Chikyu: The First Three Years of Operation

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Three years have passed since the completion of the *Chikyu*, a state-of-the-art scientific drilling vessel. As the main platform of the Integrated Ocean Drilling Program (IODP), the *Chikyu* explores the mysteries of planet Earth. The *Chikyu* aims to achieve scientific breakthroughs in the mechanism of great earthquakes, the origins of life, the past and future of the Earth's global climate, and drilling into the mantle. The *Chikyu* is the first science research vessel to be equipped with the Riser Drilling System, and she also has shipboard research laboratories on four dedicated decks with a total area of 2,300 m^2. These laboratories have an extensive array of cutting-edge equipment used to conduct physical, chemical and biological analyses of recovered cores, pore water and boreholes. After the first dry-docking from March to May 2006, the *Chikyu* successfully performed shakedown drilling operations off Japan's Shimokita Peninsula, and then again off Kenya and the Northwest Australian Continental Shelf. The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), a complex multiyear ocean drilling project implemented as part of the Integrated Ocean Drilling Program, began the *Chikyu*'s involvement with IODP drilling. NanTroSEIZE is a multiple-expedition project involving teams of some of the top scientists from all around the world. NanTroSEIZE attempts for the first time to drill, sample, and instrument the earthquake-causing, or seismogenic, portion of a plate subduction zone. The *Chikyu* successfully completed the first three Stage 1 NanTroSEIZE expeditions in 2007 and 2008. This paper describes the *Chikyu*'s operations over the past three years.

Keywords : *Chikyu*, NanTroSEIZE, IODP, riser drilling, dynamic positioning system

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1. Introduction

Three years have passed since the completion of the *Chikyu* (which means “the planet Earth” in Japanese), a state-of-the-art scientific drilling vessel with the world's most advanced drilling capability (7,000 m below the seafloor in water depths of 2,500 m), designed to recover ocean sediment cores or geological samples (Fig. 1). This paper summarizes the operational capabilities and history of the *Chikyu*, including a brief documentation of the first scientific expeditions, NanTroSEIZE Stage 1.

1.1. The birth of the *Chikyu*

The construction of the *Chikyu* began in April 2001 and was completed in July 2005. The world's largest scientific drilling vessel was born; her overall length is 210 meters, her gross tonnage is 57,087 tons, and the vessel has a drilling derrick standing 121 meters above the ocean surface, towering at the center of her main deck. The *Chikyu* is outstanding not only for her size but also for her integrated capability of deep drilling, accurate positioning, and scientific equipment. Examples of this integrated technology include the Dynamic Positioning System (DPS) and the Riser Drilling System. The *Chikyu* is the world's first scientific drilling vessel equipped with a riser drilling system. In addition, the *Chikyu* has a fully-equipped laboratory space comprising four decks (a total floor area of approximately 2,300 m^2) with many of the latest analytical instruments installed. The *Chikyu* has been opened to the public many times at several ports around Japan since her completion.

1.2. IODP, JAMSTEC and CDEX

The *Chikyu* explores the planet Earth as the main platform of the Integrated Ocean Drilling Program (IODP). The IODP is an international marine research drilling program dedicated to advancing scientific understanding of the Earth by monitoring and sampling subseafloor environments. Through multiple platforms, preeminent scientists explore the IODP's principal themes:

- The deep biosphere and the subseafloor ocean,
- Environmental change, processes, and effects, and
- Solid earth cycles and geodynamics.

The IODP has operated since October 2003 and is funded jointly by the Ministry of Education, Culture, Sports, Science and Technology of Japan and the U.S. National Science Foundation, with additional support provided by the European Consortium of Ocean Research Drilling, the Ministry of Science and Technology of the People's Republic of China, and the Republic of Korea through the Korea Institute of Geoscience and Mineral Resources. The IODP now has 21 member countries (Fig. 2).

IODP vessels include a riser drilling vessel, the *Chikyu*, a riserless drilling vessel, the JOIDES Resolution, and mission-specific platforms. Three Implementing Organizations (IOs), in Japan, the United States, and Europe, serve as science operators of the various ships and platforms.

On 18 November 2004, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and IODP Management International Inc. (IODP-MI) signed a Memorandum of Understanding. With this agreement the IODP-MI, which is the

Fig 1. *Chikyu*.

central management office of the whole program, and JAMSTEC, the management agency of the *Chikyu*, officially established a formal framework of cooperation concerning the IODP. JAMSTEC established the Center for Deep Earth Science Exploration (CDEX) within the organization in October 2002. CDEX has been responsible for the overall management of the *Chikyu* as Japan's Implementing Organization in the IODP and has been dedicated to creating new frontiers in science and technology.

1.3. Why the *Chikyu*?

We all know that the planet Earth is an oasis full of water and life. But the Earth has gone through many transitions in the past 4.6 billion years, such as meteor showers, earthquakes, intense volcanic activity, tsunamis, extreme environmental changes and so forth. These events have exerted a considerable influence upon life on the Earth. The footprints of these events, past activities of creatures and diastrophism are left deep inside the planet.

To be more specific, a unique global historical record of Earth's changing tectonics, climate, ocean circulation, and biota is preserved in marine sedimentary deposits and underlying basement rocks. Detailed and complete records of this history are accessible only through ocean drilling because many of these critical processes (e.g., subduction-related earthquakes, formation of massive sulfides and extensive sequestration of carbon in sediments) are active only in submarine environments. Only through understanding the past history of the Earth's systems will we be able to predict its future, a time that may involve far-reaching change on a cultural time scale (Integrated Ocean Drilling Program, 2001).

The *Chikyu* explores the mysteries of the Earth. The *Chikyu* aims to obtain outstanding research results concerning the mechanisms of great earthquakes, the origin of life, the past and future of the Earth, and breaking through to the never-before-accessible frontier, the mantle.

1.3.1. Mechanisms of great earthquakes

Plans call for the *Chikyu* to drill into the fault slip zone of a great subduction earthquake for the first time in the history of scientific ocean drilling. The *Chikyu* is making direct observations and then elucidating why and how earthquakes occur. The installation of observatories in the drilled holes is one phase of the overall plan. This equipment can record and transmit data to land-based stations at the instant an earthquake occurs.

1.3.2. The secret of the origin of life

Primordial life arose on the primitive Earth in high-pressure, high-temperature and anoxic environments. These environments persist deep underground in the Earth. We now know, through scientific ocean drilling over the past 40 years, that the subseafloor hosts an extensive microbial population called the deep biosphere. This fact poses fundamental questions about the evolution and distribution of life. The *Chikyu* will drill deep into the subseafloor in a continuing search for primitive life, and then explore the secrets of the origin of life on Earth.

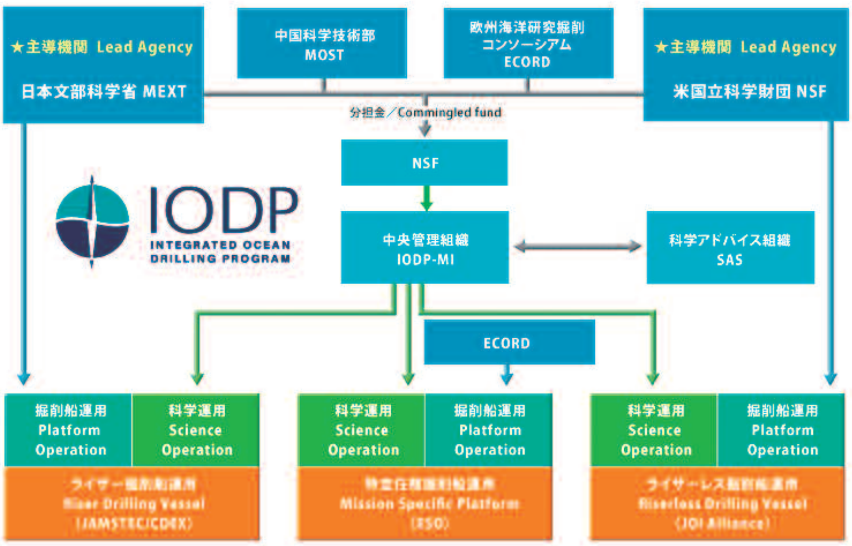


Fig 2. The Integrated Ocean Drilling Program.

1.3.3. The past and future Earth

The *Chikyu* recovers ocean sediment cores or geological samples, which provide a unique record of the history of the Earth. These cores will allow us a more sophisticated analysis of the changes in the Earth's past environments and provide us with a clue towards developing predictions of the Earth's future environment.

1.3.4. Accessing the mantle

The *Chikyu* boasts an outstanding capability to drill through into the mantle and recover samples. Sampling a whole section of oceanic crust down to the mantle will provide a thorough understanding of the entire oceanic crustal section and its history. Continental drift and volcanic activity are said to originate in mantle convection, and by accessing this zone, the *Chikyu* will help us understand how the mantle affects the dynamics of the Earth's interior.

1.4. Events since delivery

A brief chronology of the *Chikyu*'s past three years appears in Table 1.

2. The *Chikyu*'s characteristics and shakedown

2.1. Characteristics of the *Chikyu*

The *Chikyu* is a cutting-edge scientific drilling vessel capable of drilling 7,000 m into the seafloor in deep-sea areas with a water depth of 2,500 m (final target: 4,000 m) (Table 2; Fig. 3). The *Chikyu* is equipped with a system called the Riser Drilling System, which has been used in the oil and gas industry. This is the first time it has been employed for scientific research applications. The shipboard research laboratories are on the four decks, with a total area of 2,300 m^3, and they have abundant equipment to conduct physical, chemical and biological analysis of recovered cores, pore water and boreholes.

2.1.1. Dynamic Positioning System (DPS)

The *Chikyu* needs to maintain her position and heading under such external influences as waves, wind and currents during drilling operations. The Dynamic Positioning System (DPS) is a computer-controlled system that automatically maintains the *Chikyu*'s position and heading by using her thrusters. The *Chikyu*'s propulsion system is diesel-electric and drives her thrusters via electric motors with variable-speed drives. This system allows for a more adaptable setup and better handling of the large changes in power demand. The *Chikyu* has a bow thruster and six azimuth thrusters, each of which rotates through 360 degrees (Figs. 4 and 5). The *Chikyu*'s DPS not only provides feedback control over deviations but also provides a highly accurate feed-forward control over wind. The DPS

Table 1. Events concerning the *Chikyu*, 2005-2009

Date	Event	Remarks
29 July 2005	Delivery	
Aug 2005–Mar 2006	Operational tests and familiarization training	
Mar–May 2006	First dry-docking	
Aug–Oct 2006	Drilling shakedown off the Shimokita Peninsula	First scientific riser drilling (trial drilling)
Nov 2006–Aug 2007	Overseas drilling shakedown	· Offshore of Kenya and Northwest Australian Continental Shelf · Partial damage to riser tensioners
Sep 2007–Feb 2008	Nankai Trough Seismogenic Zone experiment	The *Chikyu*'s first Integrated Ocean Drilling Program
Feb–Apr 2008	Dry-docking inspection (legal inspection)	Damage found on azimuth thrusters
Apr 2008–Mar 2009	Repair work	

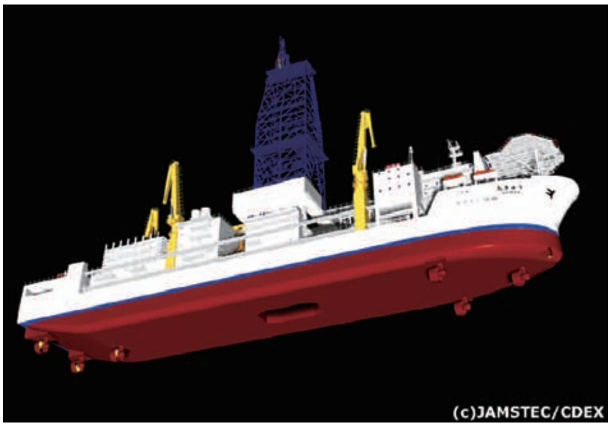


Fig 4. Six azimuth thrusters
Three azimuth thrusters are at the bow and three at the stern.

Fig 5. Azimuth thruster propeller
The propeller diameter is 3.8 m, rotating through 360 degrees.

Table 2. Principal Details of the *Chikyu*

Laid down	31 March 2001
Launched	18 January 2002
Completed	29 July 2005 at the Nagasaki Shipyard of Mitsubishi Heavy Industries Ltd.
Class	NK (Nippon Kaiji Kyokai)
Navigation area	Oceangoing (International Navigation)
Length	210 m
Breadth	38.0 m
Height (from ship bottom)	130 m
Depth	16.2 m
Draft	9.2 m
Gross tonnage	57,087 tons
Cruising range	Approx. 14,800 nautical miles (Full load conditions, 10 knots)
Capacity	150 (100 crew and 50 scientists)
Propulsion system	• Azimuth thruster 4,100 kW (5,710 PS) × 6 Propeller Diameter: 3.8 m • Side thruster 2,550 kW (3,470 PS) × 1
DPS	NK DPS-B Wind speed: 23 meters per second Surface current: 3–4 knots Wave height: 4.5 m
Max cruising speed	12 knots
Generator	5,000 kW × 6 (main generator) 2,500 kW × 2 (auxiliary generator)
Helicopter deck	Capable of receiving any helicopter with a capacity of up to 30 persons
Drilling system	Both riser drilling system and riserless drilling system
Max water depth	2,500 m (riser drilling)
Length of drill string	10,000 m
Blowout preventer	Weight: 380 tons Height: 14.5 m Pressure: 103 MPa
Riser pipe	Length: 27 m Diameter: approx. 50 cm
Drill pipe	Length: 9.5 m Diameter: 13–14 cm
Derrick	Height: 70.1 m Width: 18.3 m Length: 21.9 m Hanging capacity: 1,250 tons
Moon pool	12 m × 22 m
Draw works	Lifting capacity: 1,250 tons (3,728 kW)

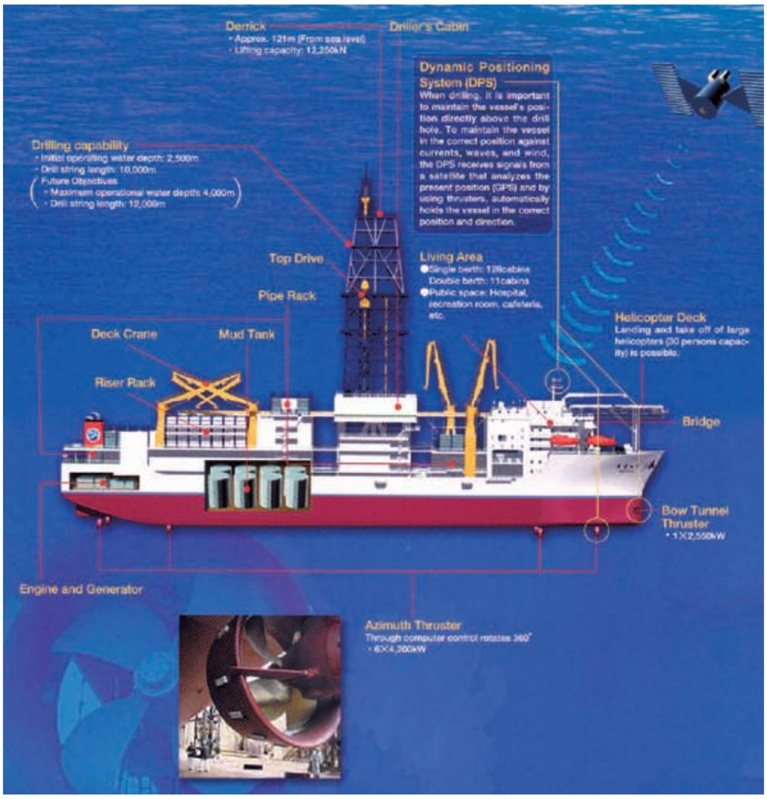


Fig 3. Schematic image of the *Chikyu*.

software includes a mathematical model of the *Chikyu*, which was created through data about wind drag, current drag, and thruster characteristics acquired through tank tests and simulations. With the help of this mathematical model, the DPS controller issues commands to the thrusters.

The *Chikyu* is equipped with two different types of position reference system: the Differential Global Positioning System (DGPS) and the Acoustic Position Reference System (APRS), each of which has redundancy or consists of two sets (Fig. 6). This is because in drilling operations, reliability is extremely critical, and these systems require a high degree of reliability and redundancy.

2.1.2. Riser Drilling System

The riser is a large-diameter pipe that extends from the *Chikyu* down to the seafloor and girdles the drill pipe. The inside space between the riser pipe and the drill pipe allows for the circulation of drilling mud (Figs. 7 and 8). Drilling mud is a viscous and heavy fluid designed to maintain pressure balance within the borehole and lift the cuttings up to the vessel and also to lubricate, cool, and clean the drill bit.

A Blowout Preventer (BOP) is a device placed at the seafloor to provide for unexpected release of high-pressure gas, oil or other fluids into the surrounding seawater or on the drilling rig (Fig. 9). With these devices, safer and deeper drilling can be achieved.

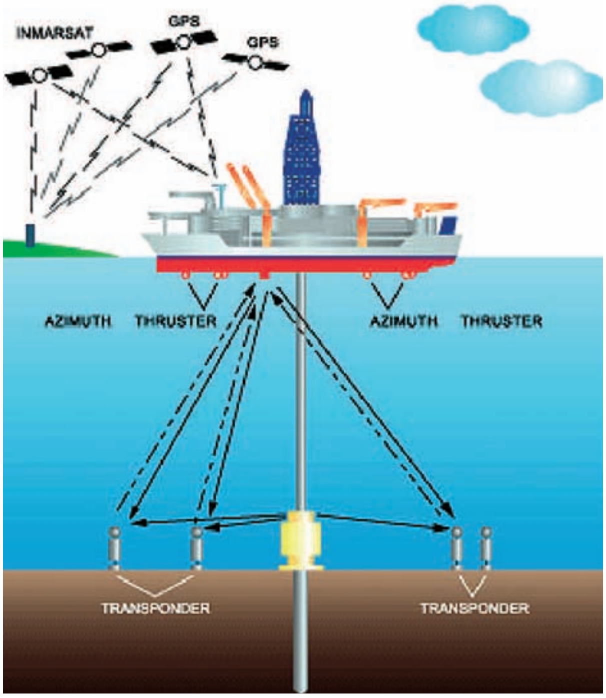


Fig 6. Position reference system
Satellite systems and acoustic systems are used for position reference.

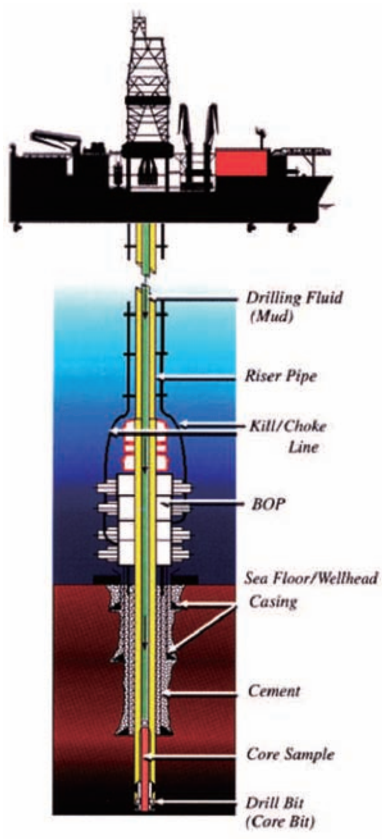


Fig 7. Schematic image of the riser drilling system
The riser extends from the *Chikyu* down to the seafloor, girdling the drill pipe.

Fig 8. Riser pipes
Length: 27 m
Outer diameter: 1.2 m
Inner diameter: 0.5 m
Weight: 27 tons (in the air)

Fig 9. BOP
Height: 14.5 m Width: 5.2 m × 5.9 m Weight: 380 tons

2.2. Drilling shakedown of the *Chikyu*

In July 2005 the *Chikyu* was completed at Nagasaki. After completion, the second half of 2005 was dedicated to familiarization training and System Integration Tests (Phase 1) conducted off Nagasaki, in Suruga Bay, off the Boso Peninsula and at other areas around Japan.

System Integration Tests (Phase 1) included tests for:

- Drill-pipe assembly, hoisting, and lowering,
- Mud system,
- Dynamic Positioning System (DPS),
- Core sample acquisition, and
- Blowout preventer (BOP) lowering.

After the first dry-docking from March to May 2006, the *Chikyu* performed its drilling shakedown off the Shimokita Peninsula, and again off Kenya and on the Northwest Australian Continental Shelf.

2.2.1. Shimokita Peninsula drilling shakedown

The *Chikyu* left the port of Hachinohe on 6 August 2006 and carried out 82 days of System Integration Tests (Phase 2) off the Shimokita Peninsula in water 1,200 m deep (Fig. 10).

System Integration Tests (Phase 2) were conducted for:

- Lowering to the seafloor and installing the riser and BOP,
- Emergency disconnect sequence for the riser and BOP,
- Inserting the casing pipe and cementing,
- The *Chikyu*'s core sampling system, and
- Wireline logging system.

The projected objectives were achieved for the five items above, but some challenges for the future remained, mainly because of the violently rough weather.

(1) System integration tests (Phase 2)

The tests were scheduled for completion by October, as the weather typically begins to worsen by November in this region of northeastern Japan. But the severe weather of Typhoons 12, 13 and 14 as well as rapidly developing low-pressure systems during the test period interrupted the operation and obliged the *Chikyu* to stand by. On 7 October the BOP hydraulic connectors sustained damage during weather-related emergency disconnection of the riser pipes and the upper BOP from the lower BOP (Fig. 11). A malfunction of the cuttings-transfer equipment was found in the Drilling Waste Treatment System. For these reasons, work schedules were delayed from the initial projections. Therefore, the target drilling depth (2,200 m) could not be achieved, and the depth attained was 647 m. However, as mentioned above, the projected overall objectives were achieved for the System Integration Test, and familiarization training was also successful.

Unwittingly, we learned much from the rough weather. For example, the DPS delivered a masterful performance. It was able to hold the *Chikyu* within a 15 m radius during a typhoon with a wind speed of over 30 m per second. Through this drilling shakedown, the *Chikyu*'s basic performance as a deep-sea scientific drilling vessel was proven.

Fig 11. Lowering BOP to be installed on the seafloor

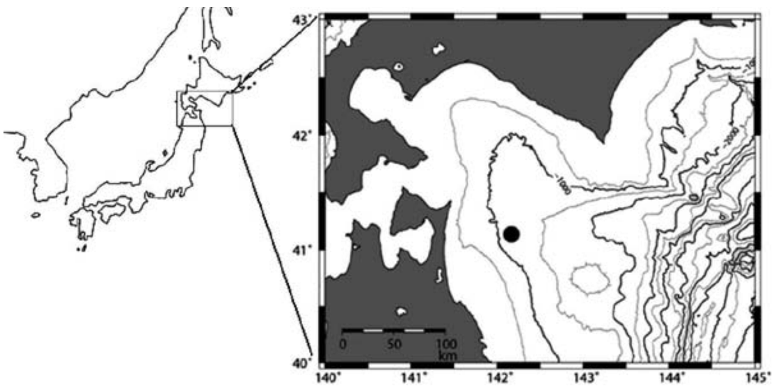


Fig 10. Map of the test site east of the Shimokita Peninsula

(2) Recovered cores

From the analysis of the volcanic ash and microfossils in the deepest cores recovered, it is inferred that these cores include strata that were ocean floor about 650,000 years ago. The main constituent of those strata is material created by the accumulation of terrigenous mud and sand, marine plankton, and volcanic ejecta (Fig. 12). Since the cores acquired during this testing include multiple wide-area volcanic ash layers that can be dated, it should be possible to work from those cores to accurately determine the ages of the cores and decipher historical climate variations in the northeast region of Japan. Most importantly, through the handling of those core samples, the basic functions of the *Chikyu*'s laboratory were tested and reviewed.

2.2.2. Overseas drilling shakedown

The *Chikyu* conducted some drilling work under a contract from Woodside Energy Ltd., an Australian resources developer, through the Norwegian drilling contractor Seadrill Offshore AS. The drilling sites were off Kenya and the Northwest Australian Continental Shelf (Fig. 13). The aim of the contract was to accumulate sufficient drilling-operation experience and to prepare for beginning the Integrated Ocean Drilling Program. This overseas drilling shakedown started in November 2006 and was completed in July 2007.

Fig 12. Recovered core samples in the Core Lab
It is inferred that these cores include strata that were the ocean floor about 650,000 years ago.

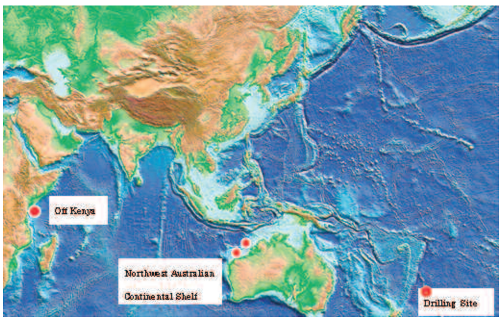


Fig 13. Overseas drilling shakedown area

(1) Off Kenya

Riser drilling operations were conducted at a site in a strong current. The water depth was 2,200 m, and the drilling depth under the seafloor was 2,700 m.

(2) Northwest Australian Continental Shelf

Two riser drilling operations were conducted in water depths (WD) of 500 m and 1,000 m, respectively. Drilling depths under the seafloor were 3,700 and 2,200 m below the seafloor (mbsf), respectively.

Six riserless drilling jobs to install casings and some equipment in boreholes were conducted. The water depths of the sites and the drilling depths under the seafloor were as follows:

- WD 1,340 m, mbsf 1,200 m
- WD 1,440 m, mbsf 1,860 m
- WD 1,400 m, mbsf 560 m
- WD 830 m, mbsf 700 m
- WD 470 m, mbsf 3,200 m
- WD 640 m, mbsf 1,000 m

(3) Outcome

The following items were assured successfully:

- Accumulation of riser drilling skills and techniques
- Installation and operation of BOP at a depth of 2,200 m
- Riser drilling under strong current with an average speed of 2.5 knots (about 4.6 km/h)
- Performance of drilling direction control (slant drilling) required for deeper ocean drilling

Fig 14. Riser tensioner
The six cylindrical rods of the riser tensioner (yellow) support the riser pipe (white) in the center.

- Drilling into the complicated layers comprising alternate layers of sandstone, mudstone, and limestone
- Improvement of crew skills, familiarization, and operating pace

(4) Partial damage to riser tensioners

A riser tensioner is a device installed above the moon pool to keep a positive pulling force on the riser pipe, independent of the vessel's motion due to waves or wind (Fig. 14). The *Chikyu*'s riser tensioners have six cylinder rods, each 16 m long, which makes the length of each riser tensioner 34 m when the rods are fully expanded. Each cylinder weighs 31 tons, with each cylinder rod alone weighing seven tons.

On 19 May 2007, during drilling operations on the Northwest Australian Continental Shelf, peeling of the surface coating was found on the lower part of one of the six cylinder rods of the riser tensioners. On 22 May operations were suspended because the peeling worsened and the same type of peeling and coating abnormality was found on two other cylinder rods (Fig. 15). Thereafter, only nonriser drilling operations, without the riser tensioners, were conducted. Note that the riser tensioners are only used during riser drilling operations. The damage was scheduled to be repaired, details of which will be discussed in Section 5.

3. Laboratory operation

3.1. Laboratories

The *Chikyu*'s laboratories are spread out over four decks: the Lab Roof Deck, the Core Processing Deck, the Lab Street Deck, and the Lab Management Deck.

Fig 15. Peeling of the surface coating
The coating on the upper part of the cylinder rod has peeled off (circled in red).

Each deck consists of a specialized room for a specific purpose. An elevator connects all levels of the lab floors and is used to transport cores and supplies. Laboratory specialists (lab technicians) will assist in the use of all measurement instruments. The Lab Roof Deck at the top of the vessel is where the core comes in through a catwalk. The Core Processing Deck contains a 3-D CT scanner room as well as physical properties and paleomagnetism laboratories with a magnetically shielded chamber that blocks out 99% of the Earth's magnetic field. Also, digital photos are taken to record the appearance of each core when it first arrives in the Core Lab. The Lab Street Deck contains the Geochemistry Lab with ICP-MS and ICP-AES and all other instruments for interstitial water analysis as well as major and trace elements analysis. The electric workshop, gas-bottle storage and chemical storage rooms are also located on this level. Offices, a library and computer room, and a computer center and conference room are located on the Lab Management Deck.

To operate the core within the laboratory, the facility is used for a variety of forms of research during operations. The laboratory is available for use by scientists to conduct a wide array of studies.

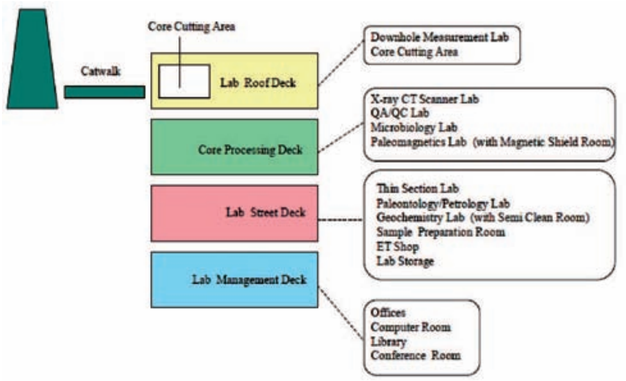


Fig 16. Lab structure spread over four decks.

Fig 17. Core Lab on the Core Processing Deck

3.2. Database

All the data collected during the expeditions are stored in the J-CORES database. J-CORES is a scientific data management system built to store and distribute science data taken during *Chikyu* expeditions. Visual Core Descriptions (VCDs) are also input into J-CORES to edit VCD data in depth. The system is installed both aboard the *Chikyu* and at the onshore CDEX data center. Data from the *Chikyu* are moved to the CDEX data center on a regular basis during the expedition.

3.3. Example of core flow

Figure 18 is a diagram of an example of core flow aboard the *Chikyu*. Sampling and measurement are changeable depending on the sample requests made by scientists.

The core is brought to the Cutting Area (Lab Roof Deck) via the catwalk using a roller conveyor to prevent stressing the core. As soon as the core arrives in the cutting area, head-space and void gases are measured using a plug to acquire high-quality gas for an initial assessment. Methane hydrates or any gases needing to be sampled immediately before evaporating due to extended exposure in the atmosphere are collected here. They are immediately analyzed for safety and to prevent deterioration of fresh gases in the Geochemistry Lab. The sample in the core catcher at the bottom of the core barrel is used for micropaleontology sampling.

Microfossil extraction and age determination are also performed onboard. As soon as all the gases are collected in the Core Cutting Area, the 9-m-long core is cut into 7 sections 1.5 m in length. Each core section is provided an ID barcode (indicating the expedition number, drill-hole number, core number, and section number) by lab technicians. Each 1.5-m-long core is transported by elevator to the Core Processing Deck, one floor below the Lab Roof Deck, to collect CT scans of the whole core and to construct an inner view of the core, and to examine its physical properties and structure with the X-ray CT scanner in the X-ray CT Lab.

All the nondestructive tests are performed at this point. Interstitial water and microbiology sampling are obtained after the X-ray CT scanner and before the core's condition is affected by exposure to air. After the cores have equilibrated to room temperature, they are split in half as working and archive halves. The core holder cuts hard cores with diamond blades, while soft

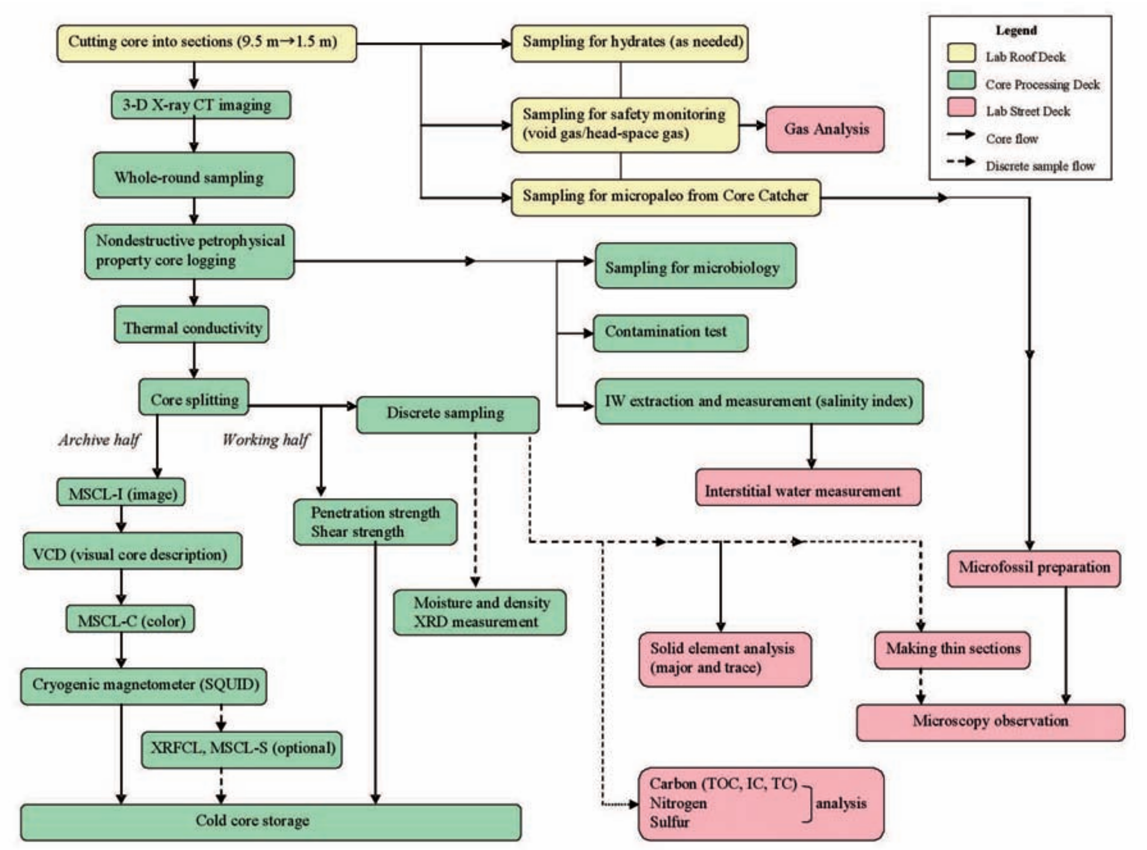


Fig 18. Example of core work flow
Note that sampling and measurement are changeable in response to requests made by scientists.

core samples are split with a thin wire. The working half is distributed to researchers as discrete samples for on-board and onshore analyses. The archive half of the core is stored in a core case for permanent archiving after a multisensor core logger image (MSCL-I), visual core description, multisensor core logger color (MSCL-C) and Cryogenic Magnetometer (SQUID) measurements are completed. An X-ray fluorescence core logger (XRFCL) and multisensor core logger split (MSCL-S) are taken as required. Discrete samples are taken from the working half of the core. Physical property measurements (moisture, density, magnetic susceptibility), X-ray diffraction and geochemical analysis can be measured. Microscopic observations are performed for paleontological and petrological studies such as fossil age determination.

All these data from the working and archive cores are stored in the J-CORES database. All data, including core analytical results, core images (including X-ray CT scan images), downhole logging data, and mud logging data are stored in the workstation located in the Data Integration Center, where secondary processing, integration, visualization, and imaging are performed. These data are also accessible while aboard.

Fig 19. Core cutting area on the Lab Roof Deck
A conveyor system is used to prevent stressing the core.

Fig 20. 3-D X-ray CT Scanner on the Core Processing Deck.

4. NanTroSEIZE Stage 1 operation summary

4.1. NanTroSEIZE

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is implemented on behalf of the Integrated Ocean Drilling Program. NanTroSEIZE is a multiyear ocean drilling project that requires multiple expeditions with teams of scientists from the member countries. NanTroSEIZE is attempting for the first time to drill, sample, and instrument the earthquake-generating or seismogenic portion of the plate subduction zone off the coast of the Kii Peninsula, where devastating earthquakes greater than magnitude 8 have occurred repeatedly throughout history.

The Nankai Trough is an elongated depression feature running from Suruga Bay through the region off the Tokai area, the Kii Peninsula, Shikoku Island, and off Kyushu. The Nankai Trough is one of the active subducting plate boundaries around Japan, where the Philippine Sea Plate is subducting beneath southwest Japan (Fig. 21). Along this subduction zone, sediments on the subducting plate are being scraped off and added to the continental plate, forming an “accretionary prism.” Its development and history are very important in understanding the basic process of orogenesis and continental crust formation. The Nankai Trough is not only one of the most active mega-earthquake zones but also one of the best-studied subduction zones in the world. It has a 1,300-year historically documented record of great earthquakes that typically cause tsunamis, including the most recent ones, the 1944 Tonankai and the 1946 Nankaido magnitude 8 earthquakes.

The ultimate goal of NanTroSEIZE is to understand the mechanism and dynamics of great earthquakes, including sample return from the seismogenic fault zone material, in situ measurement, and observation of properties and states related to seismogenic mechanisms (Tobin and Kinoshita, 2006).

Fig 21. The Nankai Trough and the survey area
The Nankai Trough is one of the active subducting plate boundaries around Japan. The survey area is shown in red.

To achieve these objectives, a total of four stages (one completed) are planned in the overall NanTroSEIZE project (Figs. 21 and 22).

- Stage 1 (2007-2008)
  Riserless drilling at six sites was planned across the Nankai Trough off Kumano in order to obtain overall features from the sediment layer seaward of the plate subduction region to the accretionary prism and to the forearc basin. The Logging While Drilling (LWD) tool will be used first to obtain the properties of the sediment layer and the fault zones, followed by core sampling and downhole measurements. This stage was already completed in 2007-2008, as described in the following section.
- Stage 2 (2009)
  The first scientific riser drilling is planned above the seismogenic portion of the Tonankai Earthquake. Its primary objective is to prepare a hole ready for future deployment of a long-term borehole observatory system (Araki et al., 2008). Partial core sampling, logging, and some downhole experiments are also planned.
- Stage 3
  Drilling 5,500-6,000 m deep into the seismogenic fault zone is planned. Samples from the seismogenic zone as well as logging data will be collected.
- Stage 4
  Long-term observatory systems will be installed into the ultradeep boreholes. NanTroSEIZE boreholes ultimately will be connected to the seafloor cable network, allowing for real-time access to data at the seismogenic fault zone.

4.2. NanTroSEIZE Stage 1

NanTroSEIZE Stage 1 consisted of three expeditions: Expedition 314, Expedition 315, and Expedition 316. These expeditions were completed in 2007 and 2008. Here we briefly summarize the results from these expeditions, but full scientific results will be published as Expedition Reports by the shipboard scientists.

4.2.1. Expedition 314

(1) Overview

Expedition 314 was implemented from 21 September to 15 November 2007. The survey area is shown in Fig. 23.

The primary goals of Expedition 314 were to obtain a comprehensive suite of geophysical logs and other downhole measurements at six sites across the Nankai accretionary

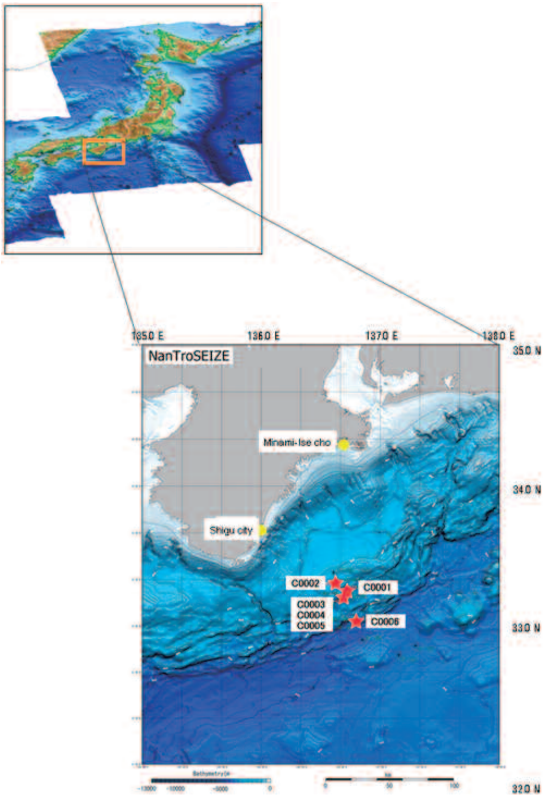


Fig 23. Survey area of Expedition 314

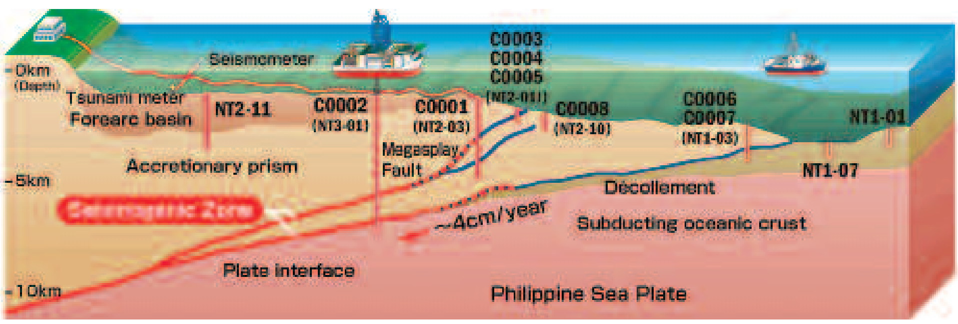


Fig 22. Conceptual section showing the drill sites planned in the NanTroSEIZE
The shallower portion of sites annotated with "C000#" were already drilled during Stage 1.

complex using the most sophisticated logging-while-drilling (LWD) technology. LWD is a technique to measure geological formation properties while drilling, by attaching, just above the drill bit, a suite of sensors to obtain borehole images, bulk density, porosity, P-wave velocity, natural gamma-ray intensity, resistivity, caliper, etc. This method has been proved very useful for drilling into geologically complex and unstable formations, especially in the Nankai Trough, and for acquiring scientific data. LWD logs also provided useful information for the coring operation during the following expeditions, as well as for safety monitoring and risk mitigation.

Coauthors of this report M. Kinoshita (JAMSTEC-IFREE, Japan) and H. Tobin (Department of Geology and Geophysics, University of Wisconsin-Madison, USA) were the co-chief scientists, while the science party on board comprised 16 scientists from 6 countries.

A summary of drilling data and results is shown in Tables 3 and 4.

Table 3. Drilling data during Expedition 314

Proposed site	Site name	North latitude	East longitude	Water depth (m)	Drilling depth (mbsf*)		
					Pilot hole	GeoTech hole**	LWD hole
NT2-03	C0001	33°14.3'	136°42.7’	2,180	1,000.0	30.5	77.5
							976.0
NT3-01	C0002	33°18.0'	136°38.2'	1,970	-	-	1,401.5
NT2-01D	C0003	33°13.4'	136°42.1'	2,453	-	-	530.0
NT2-01I	C0004	33°13.2'	136°43.2'	2,524	400.0	-	400.0
NT2-01E	C0005	33°13.6'	136°43.1'	2,446	524.0	-	-
NT2-01G		33°13.4'	136°43.2'	2,454	37.0	-	-
NT1-03	C0006	33°01.6'	136°47.6'	3,830	885.5	-	885.5

*mbsf: meters below the seafloor
**GeoTech hole: Collect core samples to evaluate soil density for upcoming riser drilling

Table 4. Summary of drilling results during Expedition 314

Proposed drill site	Drill site name	Drilling results
NT2-03	C0001	Drilled into a thrust sheet in the hanging wall of the megasplay fault system. Logged and imaged deformed accretionary prism rocks and collected data on stresses in prism system. Piloted the planned first riser drilling site.
NT3-01	C0002	Succeeded drilling the deepest hole ever into an accretionary prism, both in scientific and LWD drilling history. Imaged and logged data clearly identifying the basal layer of methane hydrate at 400 mbsf and the boundary between basin sediment and the underlying accretionary prism. Piloted the 2nd planned riser drilling site to be attempted to 6,000 mbsf.
NT2-01D	C0003	The original plan was to penetrate the splay fault zone at 710 mbsf. However, drilling was aborted at 525 mbsf where the lower part of the drill pipe disconnected because of excessive pressure and torque inside of the borehole. Abandoned retrieval (released on 29 October 2007). However, recovered data such as density, resistivity, and gamma-ray intensity are valuable to characterize properties in the active accretionary prism.
NT2-01I	C0004	Drilled through the splay fault at 300 mbsf. Pilot drilling was done first and confirmed the drillability with LWD. High-quality images and log data were acquired. The splay fault zone anticipated at approximately 300 mbsf was very well-imaged and logging data detected fault properties. For the first time, drilling through the megasplay fault was done successfully.
NT2-01E	C0005	Planned to drill and log into the splay fault. Pilot drilling was done first to confirm drillability with LWD. Drilling became difficult at 524 mbsf, and after attempt to remedy borehole status, abandoned because of the excessive risk.
NT2-01G		Planned to drill and log into the splay fault. Determined to abandon drilling because of limited time remaining on the expedition.
NT1-03	C0006	Drilled a point 1 km landward from the toe of the accretionary prism. Pilot drilling was done to confirm drillability for LWD. Drilled through early formation stage layer of the accretionary prism, including the frontal fault zone, and reached 885 mbsf.

(2) Primary results

A total of 12 boreholes were drilled at six sites. LWD drilling was conducted at five sites in the Nankai Trough accretionary complex off Kumano. Drilling conditions were severe at three sites due to strong deformation within the accretionary prism, caused by plate convergence and by interseismic stress accumulation. Furthermore, operations were conducted within the strong Kuroshio Current, which was often stronger than 5 knots. However, with the drilling capability of the *Chikyu*, drilling was successfully completed down to 400-1,400 m below the seafloor, and high-quality in situ physical properties as well as borehole images were obtained.

Images of the borehole walls using electrical resistivity were useful for deducing the stress conditions at each drill site. It was found that the stress condition and geologic structure of the uppermost 1-1.5 km of accretionary prism is very different above

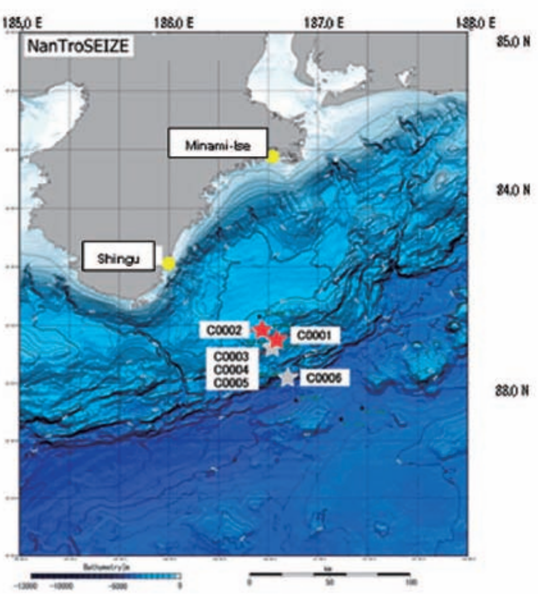
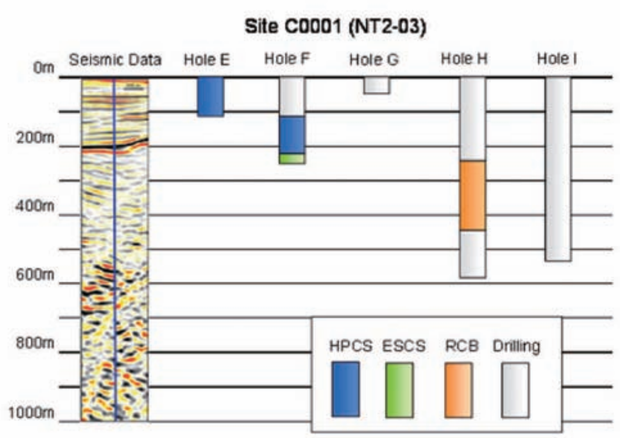


Fig 24. Survey area of Expedition 315



Drilling site: C0001 (proposed site: NT2-03)			
North latitude: 33°14.0', East longitude: 136°42.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
E	2,188.5 m	0 m–18.1 m	Collected samples with the Hydraulic Piston Core Sampling System (HPCS)
F	2,187.5 m	108.0 m–229.8 m (HPCS) 229.8 m–248.8 m (ESCS)	Collected samples with the Hydraulic Piston Core Sampling System (HPCS) and Extended Shoe Coring System (ESCS)
G	2,187.0 m	-	Abandoned drilling since ROV cable tangled with drill pipe right after starting core sampling with the Rotary Core Barrel Sampling System (RCB).
H	2,197.0 m	240.0 m–458.0 m	Collected samples with the Rotary Core Barrel Sampling System (RCB). Skipped coring the difficult portion and tried to collect samples from 600 mbsf or deeper; borehole wall was not stable. Moved to next site.
I	2,198.5 m	-	Tried to collect samples with the Rotary Core Barrel Sampling System (RCB) from 600 mbsf or deeper, but borehole wall was not stable. Moved to next site.

Fig 25. Site C0001 (NT2-03)

the seismogenic zone between the thrust sheet above the mega-splay (Sites C0001 and C0004) and the landward side of the Kumano Forearc Basin (Site C0002). These data are useful to infer the formation process of the accretionary prism and seismogenic mechanisms in the Kumano Basin.

At Site C0002, a methane hydrate-rich zone was identified at 220 m to 400 m below the seafloor based on high-resistivity image and low gamma ray data. Hydrates are concentrated in sandy layers of numerous turbidites in this zone.

4.2.2. Expedition 315

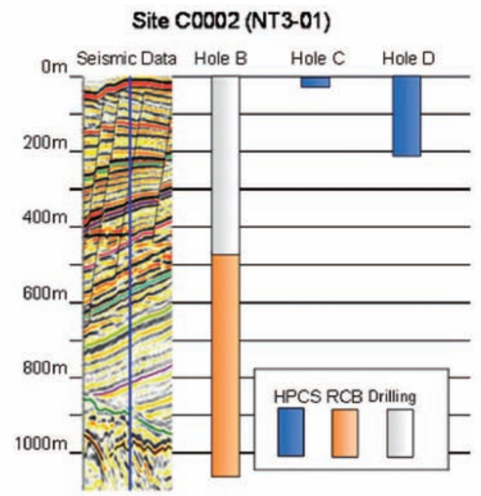
(1) Overview

Expedition 315 was implemented from 16 November to 18 December 2007. The survey area is shown in Fig. 24.

The main scientific objective of this expedition was to obtain detailed profiles of the upper limit of the plate boundary at the shallow part of the Nankai Trough Seismogenic Zone by means of drilling and collecting core samples. Due to difficult operational conditions mainly related to the strong Kuroshio Current, the wellhead installation for future riser drilling was postponed.

Dr. Juichiro Ashi (Graduate School of Frontier Sciences, University of Tokyo, Japan) and Dr. Siegfried Lallemant (Earth Sciences Department, Cergy-Pontoise University, France) were the co-chief scientists, while the science party on board comprised 25 scientists from 6 countries.

A summary of coring operations is shown in Figs. 25 and 26.



Drilling site: C0002 (proposed site: NT3-01)			
North latitude: 33°18.0', East longitude: 136°38.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
B	1,937.5 m	475.5 m–1,057.0 m	Collected samples with the Rotary Core Barrel Sampling System (RCB). Abandoned further coring since borehole wall conditions never improved despite great efforts.
C	1,937.1 m	0 m–13.77 m	Collected samples with the Rotary Core Barrel Sampling System (RCB). Abandoned further coring since borehole wall conditions never improved despite great efforts.
D	1,937.1 m	0 m–204.0 m	Collected samples with the Rotary Core Barrel Sampling System (RCB). Abandoned further coring since borehole wall conditions never improved despite great efforts.

***About core sampling systems**
Hydraulic Piston Core Sampling System (HPCS): Applied to very soft formations. A stub-edge tip like a knife enters layers using hydraulic pressure and collects core samples without a rotating drill bit.
Extended Shoe Coring System (ESCS): Applied to soft formations that are difficult to collect. The tip of the system can adjust to layer intensity using spring power.
Rotary Core Barrel Sampling System (RCB): Applied to layers of middle to high density. Collects samples while rotating a drill bit and scraping layers. Good for consolidated layers with fewer ruptures.
Drilled only: Zone where only drilling is done, with no core sampling, in accordance with scientific objectives

Fig 26. Site C0002 (NT3-01)

(2) Primary operational results

At the two sites (Site C0001 and Site C0002), a total of eight holes were drilled, and core samples were successfully recovered.

Site C0001 targeted a small slope basin overlying the accretionary prism, previously identified on 3-D seismic reflection profiles obtained during a preliminary site survey. Here, "slope basin" means a geological formation created by sediment accumulated in the depression formed on the surface of the accretionary prism. Samples were collected from the 200-m-thick recent slope basin and the underlying accretionary complex down to a final depth of 458 mbsf. At Site C0002, the objective was to drill through the thick Kumano Forearc Basin composed of alternating layers of sandstone and mudstone, and core samples were successfully collected down to 1,057 mbsf, reaching the upper part of the old accretionary prism.

The data collected at this site would provide important new constraints for the scientific models but also critical information for the engineers who are preparing future deep riser drilling at this site.

Many small faults were described and measured in the samples obtained during this expedition both by visual observation and by nondestructive 3-D structural analyses with a CT scan (See Fig. 27). The results confirm the present stress condition revealed by Logging While Drilling (LWD) during the previous Expedition 314 and provide new insights in the temporal changes of the stress field.

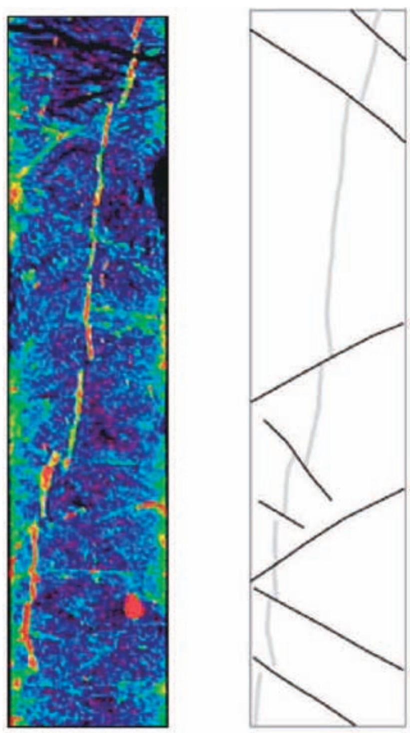


Fig 27. X-ray CT scan image of collected core sample
Many small faults were identified by displacement of fractures (vertical lines). 3-D analyses of data reveal detailed changes of stress fields recorded on strata. Left: X-ray CT scan images. Colors mainly indicate differences in density. Right: Sketch showing fractures (thick gray lines) and small faults.

In addition, age determinations obtained by combining micropaleontology and paleomagnetic studies were critical to understanding the evolution of this part of the Nankai subduction complex.

During the coring operation, a sensor embedded in the core sampling system obtained good quality data of in situ temperature. These new data used with thermal conductivity measured in the cores will result in more accurate estimates of the heat flow and thus in a better knowledge of the temperatures at greater depths near the seismogenic zone.

Core samples and data collected and analyzed during this expedition were highly valuable for a better understanding of the seismogenic zone processes. In order to achieve this goal, a large number of samples will be dedicated to intensive mechanical studies conducted by both onboard and shore-based scientists in their institutes after the cruise.

4.2.3. Expedition 316

(1) Overview

Expedition 316 was implemented from 19 December 2007 to 5 February 2008. The survey area is shown in Fig. 28.

The main scientific objective of this expedition was to comprehensively evaluate the deformation, structural partitioning, and fault zone physical characteristics at the frontal

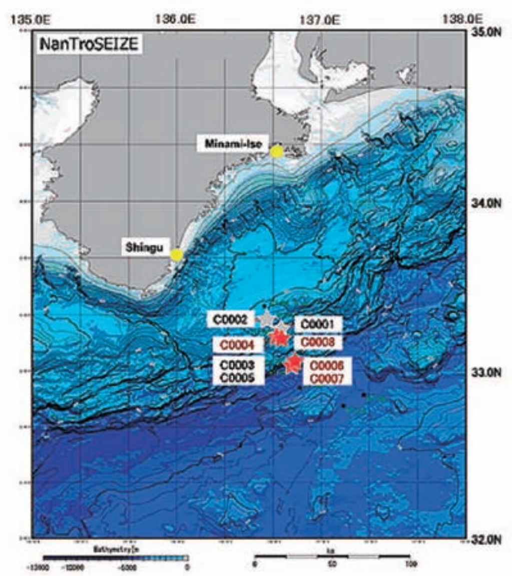


Fig 28. Survey area of Expedition 316

thrust and at the megasplay system in the Nankai Trough. Dr. Gaku Kimura (Department of Earth and Planetary Science, University of Tokyo, Japan) and Dr. Elizabeth J. Screaton (Department of Geological Sciences, University of Florida, USA) were the co-chief scientists, while the science party on board comprised 26 scientists from 10 countries.

A summary of coring operations is shown in Figs. 29, 30, 31 and 32.

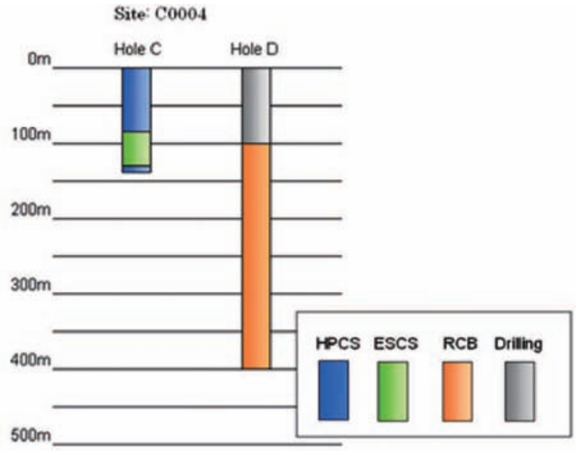
(2) Primary operational results

At four sites (Sites C0004, C0006, C0007 and C0008; see Fig. 28), a total of 13 holes were drilled, and core samples from fault zone were successfully recovered.

Site C0004 is located along the slope of the accretionary prism landward of the inferred intersection of the megasplay fault zone with the seafloor. At this site, the accretionary prism was sampled and the megasplay fault zone was successfully drilled. The cores from the fault zone record a complex history of deformation, based on structural observations and two age reversals suggested by nanofossil evidence. The sediments underneath the fault zone were sampled to understand their deformation, consolidation, and fluid flow history. Drilling at this site examined the youngest sediments on the slope overlying the accretionary prism; these sediments consist of slowly deposited marine sediments and redeposited material from further upslope. This redeposited material provides information about past slope failures, which may be related to past megasplay movement and earthquakes that may cause tsunamis.

Moreover, at Site C0007 the plate boundary frontal thrust was drilled through, and thrust fault material was successfully recovered. One of the recovered cores documents an age reversal of more than 1 million years. This interval exhibits deformation caused by fault movement from large pieces to fault gouges.

More than 5,000 samples were taken from these cores to be further examined by an international group of scientists. The data collected at these sites and from postcruise analysis of



Drilling site: C0004 (proposed site: NT2-01I)			
North latitude: 33°13.0', East longitude: 136°43.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
C	2,627.0 m	0–89.2 m (HPCS) to 127.2 m (ESCS) to 135.0 m (HPCS)	131 m cored, 135 m recovered in slope basin and slope apron deposits. Evidence for unconformity, minor faulting, and understanding of sedimentary processes in shallow trench slope deposits.
D	2,630.5 m	0–100.0 m (drilled) to 400.0 m (RCB)	300 m cored, 130.7 m recovered in accretionary prism deposits, upper portion of megasplay, and underthrust slope basin deposits. Evidence for faulting; recovery of a wide variety of fault rocks. Understanding of the internal deformation of the accretionary prism and the mechanism by which the prism rocks are being thrust up and over slope basin deposits. Will shed light on timing and degree of thrust faulting in the megasplay system.

Fig 29. Site C0004

samples would provide important new constraints on models of the evolution of the subduction zone and its relationship to earthquake and tsunami generation.

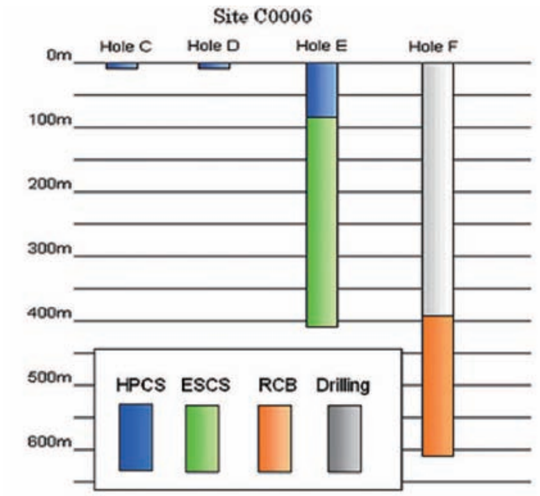
5. Mechanical failures

Since its completion there have been a few mechanical failures, both small and large, in *Chikyu* operations. Among the largest were failures of the azimuth thrusters and the riser tensioners. The latter failure was previously discussed in Section 2.2.2.(4). As for the azimuth thruster failures, they were revealed in March 2007 when the *Chikyu* was undergoing a periodical inspection in dry dock.

5.1. Revelation of broken gears on the azimuth thrusters

The *Chikyu* was undergoing a periodical inspection in the dock of the Sasebo Shipyard of Sasebo Heavy Industries Co. Ltd. in Sasebo City, Nagasaki Prefecture, from 23 February to 22 April 2008. During the inspection, some cracks and chips were revealed on the gear teeth of some of the azimuth thrusters. As discussed in Section 2.1.1, the *Chikyu* has six azimuth thrusters, to which the dynamic positioning controller issues commands for direction and power. Three azimuth thrusters are on the bow and the other three are on the stern (see Fig. 4 in Section 2.1.1). Their propeller diameter is 3.8 m.

The red square in Fig. 33 shows the damaged part. Damage



Drilling site: C0006 (proposed site: NT1-03B)			
North latitude: 33°01.0', East longitude: 136°47.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
C	3,880.5 m	0–9.5 m (HPCS)	Single core in sediments above the hanging wall of the frontal thrust. Hole abandoned because sediment-water interface was not recovered.
D	3,877.5 m	0–9.5 m (HPCS)	Same as above
E	3,875.8 m	0–79.3 m (HPCS) to 409.4 m (ESCS)	409 m cored, 330.3 m recovered in sediments deposited on the hanging wall of the frontal thrust and in rocks making up the accretionary prism material that has been transported along the frontal thrust. Several age reversals, recovery of many different kinds of fault rocks, recovery of a wide array of materials comprising the thrust sheet. Will shed light on the internal deformation and tectonic history of the deformed accretionary prism.
F	3,875.5 m	0–395.0 m (drilled) to 603.0 m (RCB)	208 m cored, 56.4 m recovered in the rocks making up the older portions of the hanging wall of the frontal thrust system. Several faults and different kinds of fault rocks recovered in association with age reversals. Will shed light on the internal deformation and history of the hanging wall of the frontal thrust system. Hole had to be abandoned due to deteriorating drilling conditions.

Fig 30. Site C0006

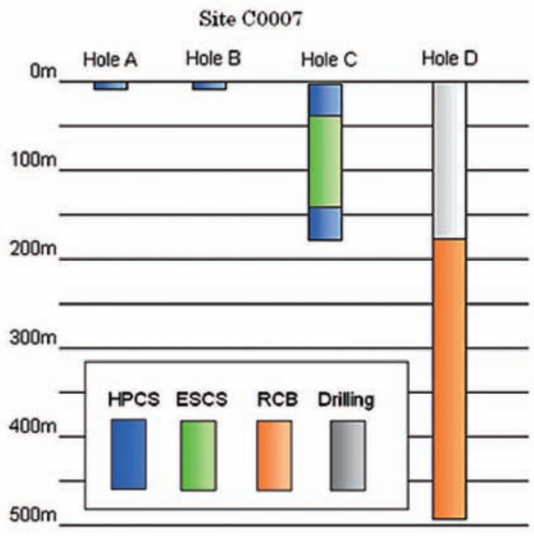
was identified on three out of six wheel gears, and one of those was replaced by a standby reserve (see Figs. 34 and 35). This was the first overhaul inspection of azimuth thrusters since the *Chikyu*'s delivery in July 2005. The gear material is nickel-chrome molybdenum forged steel treated with carburizing and case-hardening.

5.2. Causes and solutions

JAMSTEC, with the assistance of outside experts, investigated the cause and found that several factors were involved, including design and manufacture, the gear material, and assembly and adjustments made to the thrusters. Among them, preparation of gear material was considered a main cause. Projected future preventative measures included the use of improved materials, designing, and manufacturing, and more careful assembly and adjustment. Therefore, it was decided all six gears would be completely replaced with newly designed ones, which were to be produced over a period of months.

5.3. Repair jobs

It takes months to prepare six gears of 3.8 m in diameter. So the repair jobs, including the repair work of the riser tensioners, began in October 2008 and are scheduled to be completed in March 2009 (Fig. 36). After repairs, several functional and



Drilling site: C0007 (proposed site: NT1-03A)			
North latitude: 33°01.0', East longitude: 136°47.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
A	4,081.0 m	0–3.1 m (HPCS)	Single core taken at the sediment-water interface.
B	4,081.0 m	3.1–12.6 m(HPCS)	Single core taken from 3.14 to 12.5 m. For operational and curatorial reasons the hole was renamed, but is the same as Hole A and Hole C.
C	4,081.0 m	12.6–43.0 m(HPCS) to 147.5 m (ESCS) to 176.0 m (HPCS)	163.4 m cored, 59.3 m recovered in the sediments uplifted by transport along the frontal thrust. Will shed light on the timing and extent of thrust faulting along the frontal thrust. As a result of coring in sand, the hole had to be abandoned after mechanical failure of the coring equipment.
D	4,049.0 m	0–175.0 m (drilled) 493.5 m (RCB)	318.5 m cored, 87.9 m recovered in uplifted trench deposits and into older materials transported along the frontal thrust. Sampling of a wide array of faults and fault rocks, and sampling of the material in the footwall of the frontal thrust will shed light on the timing and degree of shortening, the mechanisms for internal deformation within the accretionary prism, and the tectonic history of the frontal thrust region.

Fig 31. Site C0007

operational tests will be performed from the middle of March 2009 in preparation for IODP expeditions off the coast of Japan's Kii Peninsula.

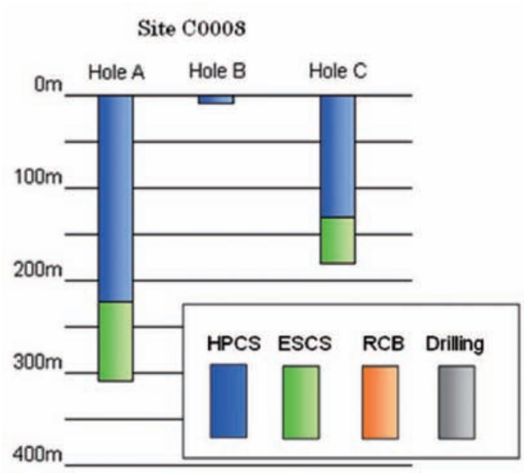
6. Perspective

JAMSTEC is now working toward development of the following advanced technologies:

- Ultra-deep-hole drilling technology (7,000 m below seafloor)
- Ultra-deep-sea drilling technology (in 4,000 m of water)
- Long-term borehole monitoring system (LTBMS)
- Extremophiles recovery technology that maintains original environmental conditions

In Stage 4 of NanTroSEIZE, JAMSTEC plans to install the LTBMS in boreholes at depths of 3,500 m and 6,000 m. By monitoring strain, seismicity, temperature, pressure, and their changes at the plate boundary with this measuring system, behavior of the earthquake-causing fault can be directly recorded in real time. The system needs to be able to withstand severe environmental conditions at 6,000 m below the seafloor at temperatures of 170ºC.

LTBMS consists of a telemetry system, various sensors, a wellhead and an external battery module. The telemetry system consists of the subsea module, telemetry cables, and downhole modules. The telemetry system has interfaces for sensors, an



Drilling site: C0008 (proposed site: NT2-10A)			
North latitude: 33°12.0', East longitude: 136°43.0'			
Hole name	Water depth	Core sampling depth (below seafloor)	Summary of results
A	2,751.0 m	0–224.7 m (HPCS) to 357.7 m (ESCS and HPCS)	357.7 m cored, 271.2 m recovered in clay and sand deposited in a slope basin just trenchward of the megasplay fault system. Recovery of a wide array of sedimentary materials and sedimentary structures will shed light on the depositional systems and changes in depositional patterns associated with structural changes in the accretionary prism over recent geological periods. Understanding the character of slope basin deposits before they are incorporated into the accretionary prism during underthrusting, and comparison to similar materials sampled beneath the megasplay fault, will allow understanding of the changes in physical state of materials over time during tectonic compression and thrust faulting.
B	2,796.3 m	0–9.5 m (HPCS)	Single core recovered in clay and sand deposited in a slope basin just trenchward of the megasplay fault system. Hole abandoned because sediment-water interface was not recovered.
C	2,797.0 m	0–139.1 m (HPCS) to 176.2 m (ESCS)	176.2 m cored, 189.6 m recovered in a slope basin just trenchward of the megasplay fault system.

*About core sampling system: see the end of (1) in Section 4.2.2

Fig 32. Site C0008

acoustic transponder and a submarine cable.

As a part of the development of LTBMS, JAMSTEC started developing an experimental prototype of the telemetry system with IODP funding in February 2007. In U.S. fiscal year (USFY) 2007, JAMSTEC defined the operational requirements of the LTBMS and the engineering specifications for its telemetry system assuming the target hole as the 3.5 km riser hole in the C0001 site. In the process of defining these requirements, JAMSTEC confirmed the feasibility of some technical features, such as high-speed downhole data transmission, accurate time synchronization between the land station and the downhole systems, deployment, and so on (Namba et al., 2008).

In parallel with this project, installation of a submarine optical cable network for monitoring earthquakes in the Kumano Basin is in progress. Once the monitoring system is installed in Stage 4 of NanTroSEIZE and the network is connected, an ideal setting for real-time collection of monitoring data will be established. Preparation of the fundamental equipment is underway in high gear, and commissioning is scheduled in 2012 or 2013.

The *Chikyu* and JAMSTEC continue to challenge the new frontier of earth and life sciences in order to meet the expectations of the IODP and the global community.

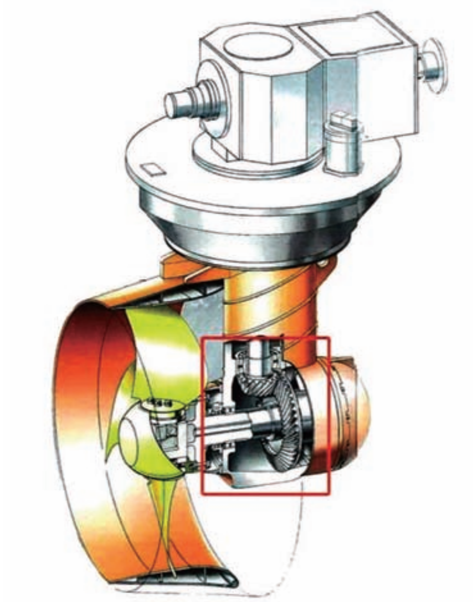


Fig 33. Azimuth thruster
The red square shows the damaged part.

Fig 35. Enlarged picture of the gear

Fig 34. Wheel gear
Damage was identified on three out of six wheel gears.

Fig 36. Azimuth thruster unit being pulled out of the Chikyu at the port of Kobe in November 2008

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We extend our appreciation to IODP-MI for its support for the preparation and execution of the NanTroSEIZE expeditions. We are proud to have worked with excellent partners, including Global Ocean Development Inc., Seadrill Limited, Marine Works Japan Ltd., and Nippon Marine Enterprise Ltd. Finally we would like to thank Dr. Mizuho Ishida, the editor in chief of JAMSTEC-R, for providing us with the opportunity to present this summary.

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