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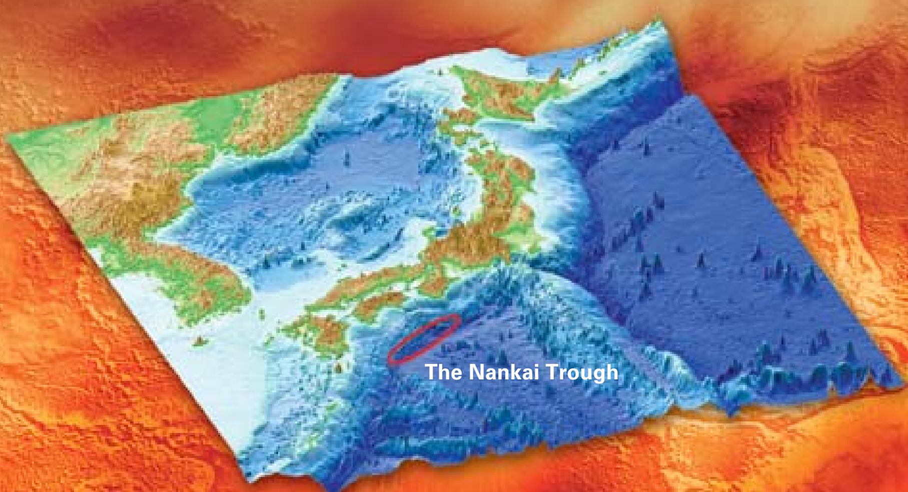
Investigating the Occurrence of Great Earthquakes

Setting the stage for comprehensive deep-sea drilling research in the Nankai Trough seismogenic zone

The magnitude 9.0 great earthquake that occurred off the coast of Sumatra on December 26, 2004 caused enormous damage to many countries in the region around the Indian Ocean, and cost the lives of more than 200,000 people. Ongoing initial investigations into the mechanics and dynamics of this earthquake suggest that several focal areas of previous earthquakes along this fault zone were triggered in rapid succession by the initiating earthquake. Similar geometry and geology characterize the Nankai Trough subduction zone in Japan, where it is thought that a similar great earthquake could occur in the future. The Nankai Trough marks the boundary between the Eurasian Plate and the Philippine Sea Plate., Over the last 500 years, great earthquakes have occurred along the Nankai Trough every 90 to 147 years. The Houei earthquake (1707), thought to be the strongest in recorded history along the Nankai Trough, resulted in the destruction of a wide area from offshore Shikoku to offshore Shizuoka Prefecture. The recorded descriptions of the Houei earthquake bear a striking resemblance to the results of the recent Sumatra earthquake.

The Nankai Trough, where great earthquakes have occurred repeatedly over the past 1500 years, has proved to be an excellent laboratory for investigation of the generation and dynamics of earthquakes along subduction plate boundaries. Planned ultra-deep-sea drilling to be implemented under the auspices of the Integrated Ocean Drilling Program (IODP) is a crucial aspect of upcoming research initiatives. It is expected that future investigation and research in the Nankai Trough will clarify the mechanism of great earthquakes, and useful knowledge will be obtained to forewarn of, mitigate and possibly prevent disasters.



The figure above shows the bathymetry of the areas surrounding the Japanese Archipelago. The Nankai Trough extends from the southeast (offshore Kii Peninsula) to the east (offshore Shikoku Island) and reaches depths of up to 5,000 m below sea level. It marks the subduction plate boundary between the Philippine Sea Plate (downgoing slab) and the Japan Islands (overriding Eurasian plate), and it attracts attention as a focal area for trench-type great earthquakes (after "What is Happening Inside the Earth?" by Kobunsha Shinsho).

Background Image: Bathymetry of the western Pacific and Indian Oceans. Adapted from "What is Happening Inside the Earth?" by Kobunsha Shinsho.

Why Do Great Earthquakes Occur?

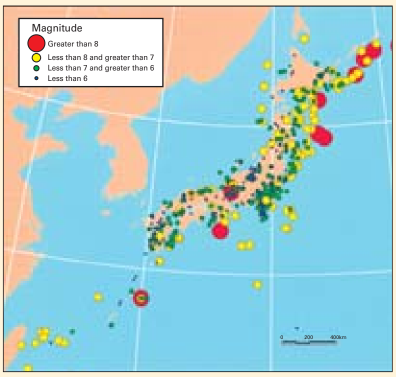
The earth is divided into several mechanical layers. The upper layer, the lithosphere, is divided into many plates: 10 major plates and many minor, smaller plates that move around the surface of the earth. Each plate moves at different velocity and in a different direction from all the other plates. These areas of collision generate enormous stresses that build over the entire length and depth of the plate boundary zone. Thus, the majority of those plate-boundary earthquakes are located along subduction zones and collision zones where plates come together.

Earthquakes in Japan can be categorized into two main groups, plate boundary and intraplate earthquakes. The vast majority of the plate boundary earthquakes occur along the subduction zones that comprise the eastern margin of the Japanese Islands. The deep, trough-like bathymetry of the Kuril Trench, Japan Trench, Izu-Ogasawara Trench, Nankai Trough, and the Ryukyu Trench mark the surface expression of subduction zones where oceanic lithosphere is being forced into the interior of the earth beneath overriding oceanic (in the case of the Izu-Ogasawara subduction zone) or continental lithosphere (in the case of the Kuril, Japan, Nakai, and Ryuku subduction zones). During subduction, the overriding plate is dragged downward due to frictional contact with the subducting slab, and strain builds over time in the affected plate. When the strength of the lithosphere (or the frictional strength of the contact between the downgoing slab and the overriding plate) is exceeded, the upper plate attempts to relieve the strain by snapping back to an equilibrium (lower energy) configuration, and slip along the plate boundary or associated fault zones is the main mechanism that allows this energy release. The rapid motion of the plates results in the release of extremely large amounts of energy over a short period of time - an earthquake.

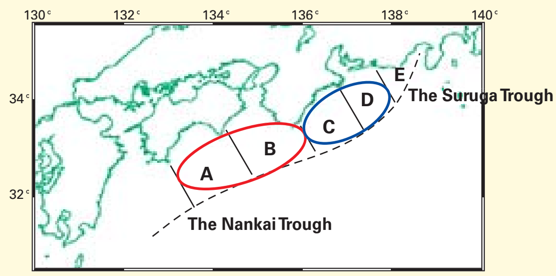
Intraplate earthquakes occur in areas away from plate boundaries as a result of stresses and strains transmitted through the rigid plate from the plate boundary, as a result of pre-existing weaknesses, as a result of volcanic activity, loading, and a variety of other possible reasons. Strain energy builds up in the lithosphere and is released through breakage and slip along fault zones. If the release of strain in one area results in increased strain or stress in another area, there is a higher probability that repeated earthquakes will occur in that region; areas where such cycles of strain increase, release and repeated earthquakes are called active fault zones, and there are about 2,000 such active fault zones in Japan.

Most of the large-scale earthquakes (magnitude greater than 8.0) observed in Japan fall into the subduction plate-boundary category. Due to their potential for great impact on lives in Japan and elsewhere in the world, great earthquakes are currently the subject of ongoing investigations aimed at clarifying the mechanism of trench type earthquakes. The area where the most advances in research have been made is in the Nankai Trough.

Professor Masataka Ando of Nagoya University says, "It is clear that great earthquakes have occurred repeatedly in the Nankai Trough, as many historical records and accounts, as well as ongoing geological investigations demonstrate. The oldest earthquake recorded occurred in 684 (the Hakuho earthquake described in the Chronicles of Japan), we have records from about 1,300 years from that date onward, and we have more detailed information on this than in any other place. Because the Nankai trough plate boundary is near land and is relatively shallow compared to other trenches, it is easier to investigate, which is one reason why research has advanced to the current level. Many researchers are also interested in it because such a large population is concentrated along the Japanese coastline, and it is predicted that any future great earthquake will cause considerable damage. In addition, according to past data, there is a high possibility that a great earthquake will occur in the near future."



The distribution of observed or reported earthquakes in Japan from 1885 to 2003 showing that most large-scale earthquakes (magnitude above 8.0) occur along subduction zones (after "Searching for the mechanisms behind the occurrence of earthquakes" page 21, published by the Ministry of Education, Culture, Sports, Science and Technology).



Dominical year	Destroyed areas					Interval of occurrence
684	A	B	C	D	E	
887	A	B				203 years
1099	A	B	C	D	E	209 years
1361	A	B				262 years
1498	A	B	C	D	E	137 years
1605	A	B	C	D		107 years
1707	A	B	C	D	E	102 years
1854	A	B	C	D	E	147 years
1944			C	D		90 years
1946	A	B				
	Nankai earthquake		Tonankai earthquake		Tokai earthquake	

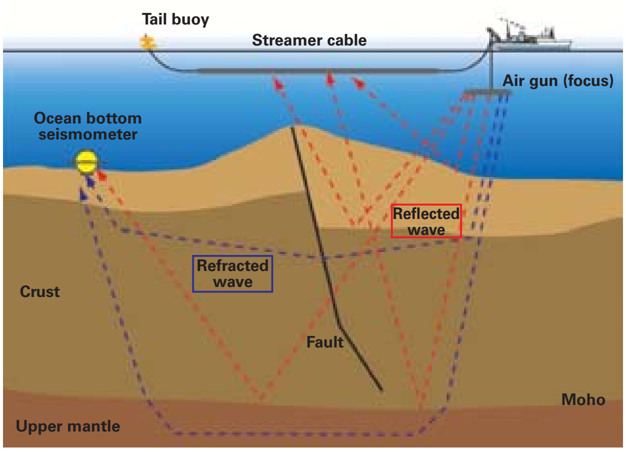
The table shows the location and timing of great earthquakes along the Nankai Trough. The repetition patterns of great earthquakes along the Nankai (A, B, red), Tonankai (C, D, blue), and Tokai (E, white) sections of the Nankai Trough are displayed (after Blue Earth, March/April, 2004, page 35).

The Challenge: Understanding the Earthquake Mechanism

Earthquake archaeology research (termed "paleoseismology") includes investigation of the extent and age of uplift or other earthquake-related surficial features (e.g. coastal terraces, earthquake scarps, offset stream beds, offset roads, and many others) and is coupled with descriptions recorded in ancient documents. Such investigations are gradually clarifying the history and repeat intervals of great earthquakes and tsunami in the regions affected by the Nankai Trough. There are, however, many unknown aspects of the generation and mechanics of subduction zone earthquakes. Various integrated scientific investigative tools are employed, often in sequence, in order to investigate the earthquake mechanism.

Seismic surveys are conducted to understand the structure and geometry of the earth's crust deep underground by generating images of subducting slabs as they dive beneath overriding plates, including defining the shape of the plate boundary, the thickness and number of sedimentary layers above and below the plate boundary, the presence and distribution of basement rocks such as granites or oceanic basalts, and the number, shape, size, relative age, and type of faults that cut these rocks. Seismic surveys use an artificial source of high-intensity noise (usually an air gun) that generates a sound signal at a known time with known strength. The survey vessel tows cables with numerous attached sensors (called hydrophones) that record the arrival time, strength, phase and other characteristics of sound waves reflected from sub-seafloor geological boundaries. These signals are processed and produce a seismic reflection profile, which is then interpreted to create a geological cross-section of the earth in that location.

Geodetics is a method that uses the Global Positioning System (GPS), an array of satellites and receivers designed to record precise locations on the earth's surface, to measure the relative change in location between two or more fixed points on separate tectonic plates. The rate and magnitude of those relative movements are recorded over long periods (generally periods of more than a year, and ideally more than five years are required for a reasonable degree of confidence in measurement accuracy) and the results are used to model plate motions and infer the resulting strain and deformation along the boundary between those plates. There are currently more than 1,000 geodetic reference points distributed around Japan. In 2001, the Japanese-based GPS observation network began recording a change in the relative motion between the Philippine Sea Plate and the Tokai region (Eurasian and North American Plates), and this attracted the attention of earthquake researchers. Prior to the summer of 2000, the Tokai region had a consistent history of northwestward movement relative to the Philippine Sea Plate; this was attributed to strong coupling between Tokai crustal blocks and the top of the downgoing Philippine Sea slab. However, after the summer of 2000, the Tokai crustal blocks began moving in the opposite direction, toward the southeast, suggesting that the connection between the two plates had weakened significantly and that the Tokai region was attempting to move back (rebound) to its original position. Currently, the motion of the Tokai region is very slow, probably too slow to generate a large earthquake. Similar "creeping" motion has been documented along other fault zones and is part of a broad spectrum of modes of plate motion (creeping, slow-



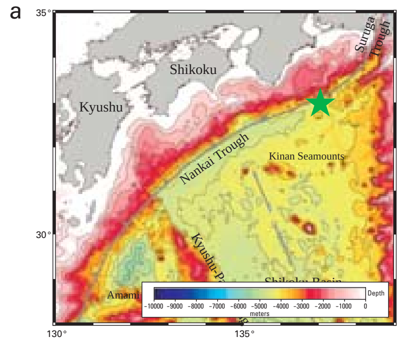
Investigation has been conducted to understand the structure beneath the seafloor by generating sound waves at a known time and with known strength using an airgun (photograph on the right), recording the reflected waves with a towed array of sensitive microphones called hydrophones, and recording the refracted waves using ocean bottom seismometers (photograph on the left). These complementary data are analyzed to produce structural cross sections and crustal velocity models.

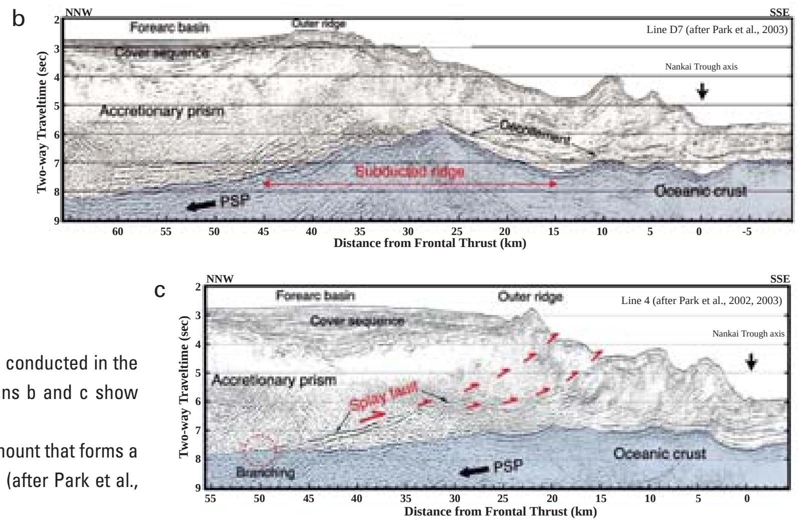
◆ Deep Sea Drilling Research Initiatives

Expectations for unprecedented new discoveries.

Professor Masataka Ando
Research Center for Seismology, Volcanology and Disaster Mitigation, Graduate School of Environmental Studies, Nagoya University

While great earthquakes have occurred repeatedly along the Nankai Trough, they do not always occur in the same way every time. For example, a tsunami was recorded at the time of the Keicho earthquake of 1605, but no damage was reported as a result of any strong seismic shocks. This may be a tsunami earthquake. I expect that by actually drilling the earth's crust, we will discover totally unpredictable factors that will explain the diversity of earthquakes and the large differences in their surface expression and impact. There could be surprising discoveries that will challenge existing models, for example discovering a fault plane in a different location or with different properties than predicted from current research, discovering new faults, or new types of fault rocks, and so on.





The sub-seafloor structure as imaged by seismic surveys conducted in the Kumanonada region of the Nankai Trough. Cross sections b and c show results from two parallel survey tracks about 50 km apart.
Cross section b shows a subducted oceanic ridge or seamount that forms a large-scale irregularity or asperity on the plate boundary. (after Park et al., 2003, taken from "CDEX Technical Report, vol. 1")

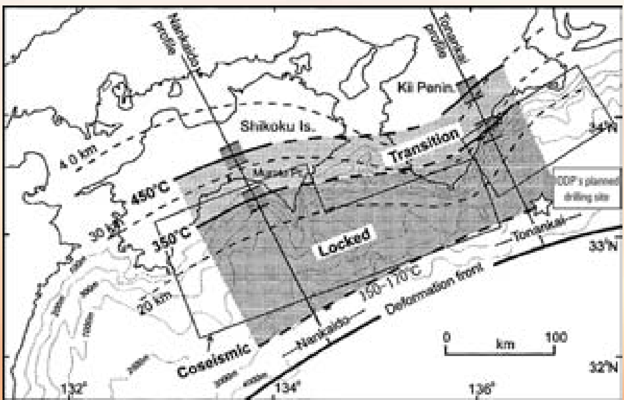
slipping, stable sliding, stick-slip), all of which generate unique kinds of seismic energy and waveforms.

The physical nature of the boundary surface or zone between two plates is never identical between locations. If the surface is very rough on a large scale, the boundary may be physically locked and strain energy will accumulate until the strength of the locked area (or the rocks that make the lock) is exceeded. Failure of the rocks in the locked area could be very rapid, resulting in an earthquake. On the other hand, if the plate boundary surface or zone is characterized by smooth surfaces and weak rocks like clays, then no locking will occur and stable sliding will take place with little or no earthquake activity. In order to understand the generation mechanism(s) and dynamics of subduction zone earthquakes, it is necessary to understand the shape, roughness, composition, and physical properties of the rocks that make up the plate boundary zone.

Group Leader Masataka Kinoshita of JAMSTEC says, "The important factors that we must understand in order to determine the frictional characteristics of the plate boundary zone are the geometry and shape, the temperature and pressure conditions, and the presence or absence of both free (liquid) water and/or interstitial water (bound up in minerals) on the boundary surface."

"It is assumed that plate boundary constituents are basically the same as or directly derived from marine sediments currently found near the axis of the trench, for example, subducted clay minerals. Also, water exists in sediments at the surface and presumably in rocks along the plate boundary. As these rocks are subducted to deep regions, the pressure increases, the temperature increases, and the material composition changes from wet to dry and from smooth to rough. Such a transformations should change the frictional characteristics of the plate boundary zone from one that promotes stable sliding to one that may generate earthquakes."

Both macroscopic perspectives such as the structure and geometry of crustal blocks coupled with understanding of the dynamics of large-scale plate motions, and microscopic perspectives such as material science investigations of the physical properties of plate-boundary-zone rocks and fluids will be required in order to understand the generation and mechanics of great earthquakes.



Inferred temperature distribution at depth along a section of the Nankai Trough plate boundary zone. The plate boundary zone is deeper and inferred temperatures higher toward the north-northwest due to plate geometry and plate motion direction (after Hyndman and Wang, 1995).

◆ **Deep Sea Drilling Research Initiatives**

Understanding earthquake precursors from subduction zone thermal structure.

Masataka Kinoshita
Group Leader, the Institute For Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology

I specialize in researching the flow of heat from the interior of the earth. I have great expectations that *D/V CHIKYU* will acquire highly accurate subduction zone thermal structure data through deep drilling at in the Nankai Trough. Temperature is one of the important elements in determining the location, rate, and mechanism of metamorphic changes in the rocks that make up the plate boundary, so to understand in detail the environment where great earthquakes occur, it is important to clarify the thermal structure of the entire plate boundary zone and the surrounding crustal blocks.

D/V CHIKYU will provide clues to help solve the mystery of earthquakes

In 2003, in the Shimanto Belt (a geological terrane representing uplifted rocks that originally came from a subduction zone) on the Pacific Ocean side of southwestern Japan, there was a new discovery that shed light on the earthquake mechanism in subduction zones. A type of glassy, partially melted rock called "pseudotachylyte," considered to represent an "earthquake fossil" was discovered in Kubokawa Town in the southern part of Kochi Prefecture.

When an oceanic plate is subducted, geological features (called "accretionary prisms") are formed as a result of the scraping of seafloor sediment off of the downgoing slab and accretion of those sediments along onto the overriding plate. As the plates continue to move toward one another, accretionary prisms grow over long periods of time, and are subject to intense defomation, faulting, and uplift, and in some cases these rocks become a permanent part of the overriding plate and are preserved above sea level. A fault rock containing pseudotachylyte was discovered in one such remnant of an accretionary prism that was once associated with the Nankai Trough. The pseudotachylyte, glassy material made from rock melted by frictional heat imparted to the rock during a rapid slip event, was preserved along the trace of a reverse fault that branched upward from the plate boundary and cut through the accretionary prism. Because the material both forming and surrounding the pseudotachylyte was subject to very high temperatures, radioactive elements in those rocks and their relative abundances are reset to zero at the time of the heating event, and the age of the material can be determined through radiometric dating. This particular sample is about 50 million years old and was formed during a reverse-slip subduction zone type earthquake; it is only several millimeters thick, but it contains a wealth of information regarding the physical properties, and physical property changes related to seismic activity, of rocks that make up the plate boundary zone. Although pseudotachylytes have been documented along many faults all over the world, this was the first time that such rocks have been found in subduction-zone related rocks in an accretionary prism. Soon after the initial discovery in Kubokawa, similar fault rocks formed during a subduction zone earthquake in an accretionary prism were discovered in Nobeoka, Miyazaki Prefecture.

"It is an important discovery. Examining these rocks in detail will provide extremely useful clues helpful for determining what happens in the damage zone along faults in subduction zones during great earthquakes. For example, the faulted rocks surrounding the pseudotachylyte discovered in Nobeoka were badly damaged during the earthquake as a result of rapid pressure changes that came about as a result of heating and release of water from pores in the rocks and from mineral lattices. It is assumed that water was present along the fault that hosted the ancient earthquake, and that the water might have played an important role on the formation of pseudotachylyte at the time of the earthquake," Professor Gaku Kimura of the University of Tokyo said. "However," Professor Kimura continued, "these ancient 'earthquake fossils' will not clarify everything. It is still important to extract 'living' fault rocks from currently active seismic zones. For this too, there are great expectations for the development of what would be a history-making technological observation method."

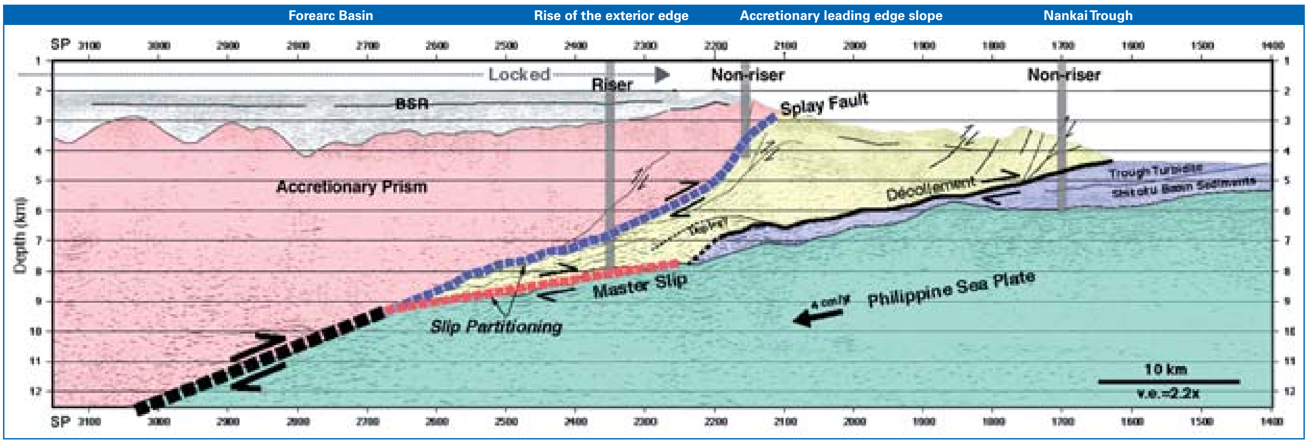
Professor Kimura further explained the significance deep sea drilling, comparing it to medical science. "In the past, geophysical earthquake observation and research was like diagnosing with a stethoscope. Geological examination of fault rocks that related to ancient earthquakes was like dissecting a dead body, similar to the work of medical pioneers during the Edo period. Nobody had seen the interior of a living human body by cutting open it, only that of a dead body. Thanks to advances in deep sea drilling, we have now come to the point where we can probe the living earth, figuratively speaking, by direct investigation and observation, like looking inside a living human body using a scalpel and a microscope. It might be said that the age of the stethoscope is evolving into that of direct observation."Research into earthquakes, subduction zone dynamics, and fault rocks has been a target of current and past deep sea drilling operations conducted as a part of the Ocean Drilling Program (ODP), which was active in drilling research around the world from 1985 to 2003. The scientific drilling vessels utilized in previous investigations were limited to drilling depths of less than 2,500 meters due to the technical parameters of those drilling sys-

◆ Deep Sea Drilling Research Initiatives

Data collected regarding the character and behavior of rocks in active fault zones will shed light on the dynamics of past earthquakes.

Professor Gaku Kimura
Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo Senior Scientist (additional post), IFREE, JAMSTEC

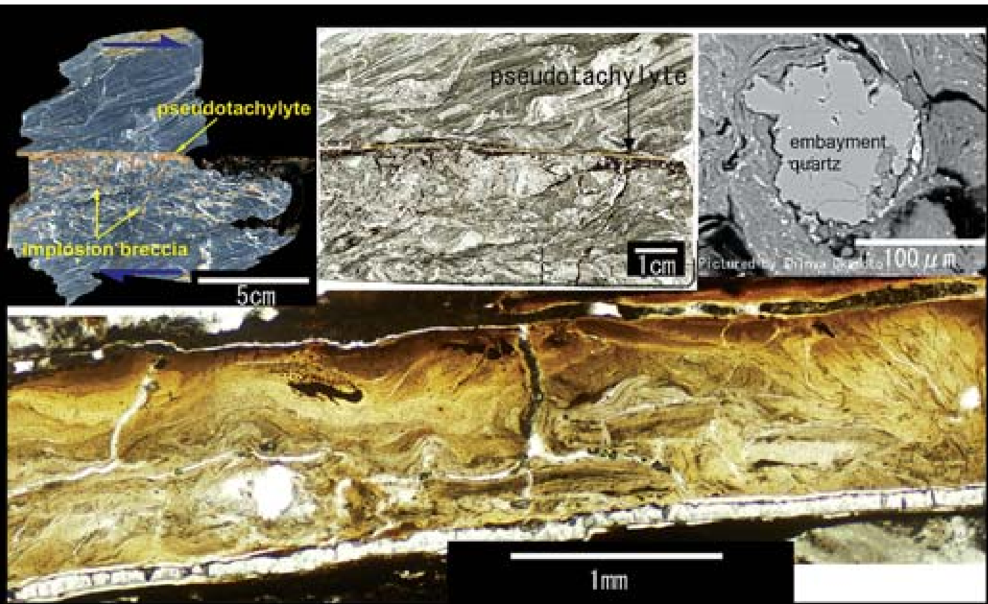
We estimate that over the last one million years thousands of great earthquakes have occurred along the Nankai Trough. The geological record of these earthquakes remains preserved in the sedimentary record and along faults. Water is found in various forms (liquid water, aqueous fluids, bound in minerals like clay) along the plate boundary and along subduction-related fault zones. Current research indicates that such water plays an important role during earthquakes. We are examining how evidence for the role of water in earthquakes is recorded in the "dead rocks" - preserved and exhumed fault rocks such as the pseudotachylytes discussed earlier. If we can sample fault rocks currently forming in the earthquake generation zone and observe the environment where those rocks are forming through a combination of deep sea drilling and monitoring of the borehole, the behavior of water in the fault zone will be clarified, and at the same time, we can understand more about the preserved record of ancient earthquakes. These "living rocks" should be important clues for understanding what happened in the past.



A cross section of the focal areas of the Nankai and Tonankai earthquakes. Drilling into a wide array of subduction zone components, such as the plate boundary zone (dashed red line), branch faults in the forearc and accretionary prism (dashed blue line), and in surrounding areas to provide a baseline for measurement and comparison will shed light on subduction zone earthquake generation and dynamics (after Park et al., 2002).

tems - the maximum depth of scientific drilling in the past was 2,111 m below the seafloor off Central America in the Pacific Ocean. Nine boreholes have been drilled in the Nankai Trough, with a maximum penetration of about 1,300 m below the seafloor. In order to extract fault rocks from the seismogenic (earthquake generation) zone, it is necessary to drill to depths of at least 6,000 m below the seafloor.

The *D/V CHIKYU*, the world's largest dedicated scientific deep-sea drilling vessel, was completed and delivered in the summer of 2005, and researchers have great expectations for it. The riser drilling system loaded onto the *D/V CHIKYU* allows the circulation of drilling fluid that lubricates, cleans, and stabilizes the borehole during drilling operations, allowing for the drilling of deeper, safer boreholes in a wider variety of geological environments. Boreholes can and will be further protected and stabilized by the installation of casing pipe, allowing for deeper drilling and eliminating some of the restrictions and risks of past (riserless) drilling systems. The *D/V CHIKYU* aims to drill to depths of up to 7,000 m below the seafloor, a depth considered impossible in past scientific drilling operations. This depth enables the penetration of the Nankai Trough plate boundary zone and inferred seismogenic zone. Of course, many difficulties and technical challenges need to be overcome, but if it such deep drilling operations prove feasible in the Nankai Trough, then precious clues and unique data can be collected that will shed light on the generation and dynamics of great earthquakes.



Altered from Shin'ya Okamoto, Gaku Kimura, Shigeru Takizawa, and Haruka Yamaguchi, A hydrous seismogenic fault rock indicating a coupled lubrication mechanism: thermal pressurization of interstitial fluid and frictional melting - An Example from a major out-of-sequence thrust in an accretionary prism, Submitted to Geology.

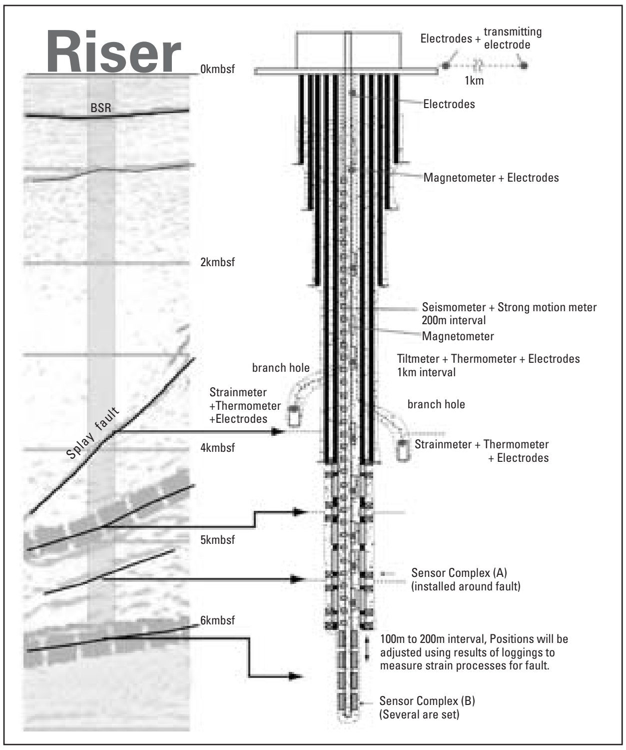
Photographs of pseudotachylyte (melted or partially melted fault rock generated along faults as a result of frictional heating and melting caused by rapid fault movement, followed by rapid cooling) discovered along thrust faults in the Kyushu Shimanto Belt and in Nobeoka. Important clues useful for clarifying the mechanics of subduction zone earthquakes were obtained through electron microscopy. The photograph on the upper left shows a piece of highly fractured, ground up fault rock (called "cataclasite") containing pseudotachylyte. The photograph in the middle is a narrow pseudotachylyte vein along the fault plane. The photograph on the right is an eroded and partially melted quartz grain. From these melting and erosion textures, it is clear that rapid shearing contributes to frictional fusion at high temperature and forms pseudotachylyte. The photograph on the bottom shows an enlargement of the pseudotachylyte vein pictured in the top center photograph (provided by Shinya Okamoto et al., Graduate School of the University Tokyo).

The *D/V CHIKYU* will Pioneer Earthquake Research

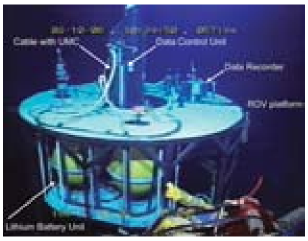
In October 2003, the Integrated Ocean Drilling Program (IODP) officially began as an international scientific project in which Japan, the U.S., the European Union, and several other nations will participate. It is a grand project, opening up a new stage of earth science for the 21st century. By conducting deep sea drilling, Japan, together with the U.S., is playing a leading role in promoting the program. The *D/V CHIKYU*, completed this summer, will operate as the main IODP drilling vessel.

As discussed above, the Japanese archipelago is the site of several plate boundaries that have been the locus of powerful subduction zone earthquakes, including the Japan Trench, the Nankai Trough, the Izu-Ogasawara Trench, the Kuril Trench, and the Ryuku trench. The Nankai Trough is the favored candidate site for deep sea drilling. Why the Nankai Trough? Executive Director Kiyoshi Suehiro of JAMSTEC explained the reason as follows.

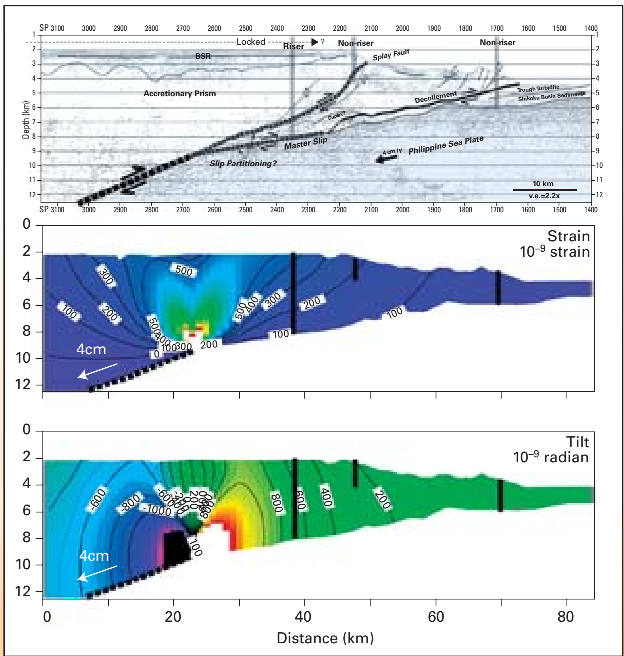
"The drilling target must occur along a fault zone that could cause a future earthquake of magnitude 8 class. Historical, observational, geophysical, and geological data from the Nankai Trough indicate that great earthquakes have occurred at intervals of from 100 to 200 years. In addition, the Nankai Trough appears to be poised to generate another large earthquake based on both the historical record and on geodetic data. Another important issue in deciding on a target is whether it is technically possible to reach the fault that would cause a great earthquake. The total length of subduction zones that could cause a trench type earthquake extends over tens of thousands of kilometers around the globe. The places that can be reached with present drilling technologies are very limited due to water depth and



Various investigations, technical feasibility studies, and engineering design initiatives are now under way to determine what type of sensors should be installed in the boreholes drilled into or near the seismogenic zone (Shinohara et al., 2003).



During ODP leg 195 a broadband earthquake monitoring station was established in a borehole drilled into the western Philippine Sea at a depth of 5,719 m below sea level (Shinohara et al., in press).



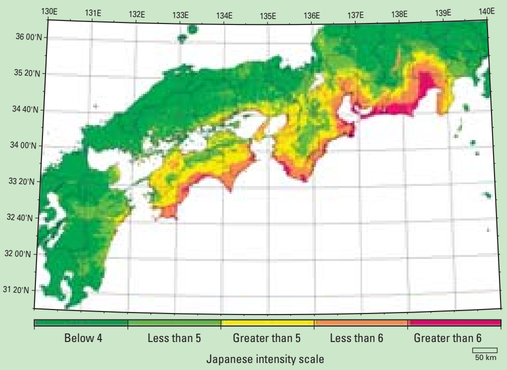
The results of model calculations of strain (middle) and tilt (lower) caused by 4 cm of slip along the Nankai Trough plate boundary (thick bold dashed line in cross section at the top). These models were run in order to estimate the values that should be recorded by downhole seismic monitoring installations (Shinohara et al., 2003) in proposed borehole locations (thick vertical lines).

◆ Deep Sea Drilling Research Initiatives

Measuring plate motion and seismicity using long-term downhole monitoring.

Executive Director of Research Kiyoshi Suehiro
Japan Agency for Marine-Earth Science and Technology

I would like to deploy and connect sensors to measure and continuously monitor crustal movement and earthquakes in the borehole over a period of years. If this idea gets put into practice, it will be possible to record measurements of plate motion, stress, strain, and seismicity every second over long time periods. Placing sensors in a few boreholes is not enough, however, we cannot drill in many places. In order to proceed with two-dimensional observation, it is necessary to lay down use marine cables to record measurements of movements of the earth crust using a network of seismometers installed on the seafloor. In order to make the most of the downhole monitoring data, it will be crucial to connect the borehole monitoring system to the seafloor observation networks.



A surface intensity map (showing the force, degree of shaking, and potential damage) compiled by the Central Disaster Prevention Council, showing the effects of an earthquake caused by the simultaneous rupture of seismogenic zones that caused the Tokai, Tonankai, and Nankai earthquakes (provided from page 262 of volume 2 of "Earthquake Prediction Map Overview of all Japan", Earthquake Research Committee of the Headquarters for Earthquake Research Promotion, Ministry of Education, Culture, Sports, Science and Technology).

target depth constraints, but the Nankai Trough, where the downgoing plate is being subducted at a gentle angle and the seafloor above the target zone is relatively shallow, is the best target."

The most promising candidate area in the Nankai Trough for initial *D/V CHIKYU* drilling operations is in the Kumanonada area off Cape Shio, Kii Peninsula, Japan, corresponding to the seismogenic zone that generate Tonankai earthquakes.

"As a result of continuous discussions among international researchers, we are moving in the direction of drilling in the Kumanonada region. It is important to drill in an area where rapid slip would generate strong seismic waves. In other words, we would like to aim at a place that has stored strain energy relatively efficiently and where that strain energy will be relieved by an earthquake. In addition, the site must be in an area that the *D/V CHIKYU* can reach with its drilling capability. Nobody has seen what a fault that can generate a magnitude 8.0 earthquake looks like. We have the difficult proposition of investigating using several boreholes (limited to extremely narrow coverage) a feature (the seismogenic zone of a major fault) that extends over a very wide area. It is a scientific challenge of deep sea drilling as to how we can combine deep sea drilling achievements with the understanding of the entire earthquake phenomenon," Executive Director Suehiro says.

Another important role anticipated by IODP and the scientific community for *D/V CHIKYU* deep sea drilling, together with the extraction of fault rocks for earthquake research, is the use of downhole wireline logging and long term borehole monitoring to make the most of the holes drilled deep into the seismogenic zone. "If we install sensors to measure strain and tilt in the boreholes that reach the seismogenic zone, we will have the data necessary to begin to understand the location along the fault where locking between the plates is occurring. We think that by analyzing those data we can fairly precisely estimate the potential location of a future earthquake. Temperature and pressure are important parameters used to understand earthquake mechanics, and are important factors that determine the size, strength, and location of seismic events along a fault zone; monitoring changes in these parameters will shed light on earthquake generation. In addition, various downhole monitoring tools will be installed to measure and record seismic data, water composition, temperature, and flow rate data, and to the volume and type of microbial organisms present in the borehole over time. These sensor packages are all being discussed in terms of both science and engineering, and should contribute to the understanding of the entire spectrum of the sub-surface environment, including investigation into the seismogenic zone, the earthquake mechanism, and possibly earthquake prediction," says Associate Professor Masanao Shinohara of Earthquake Research Institute of the University of Tokyo.

So far in ODP, various wireline logging initiatives and long term monitoring projects have been undertaken in several legacy (previously drilled) boreholes. A Japanese research team that conducted long term monitoring of legacy holes using a seismometer package succeeded in obtaining records over more than 400 days, and this team and similar groups in Japan, in coordination with other IODP-affiliated research and design teams are in a position to lead the world in borehole monitoring technological and research achievements.

Great technical problems remain to be solved in terms of implementation and installation of monitoring packages in the deep boreholes drilled by *D/V CHIKYU*. Associate Professor Shinohara says, "Riser drilling enables us to drill deeper than with non-riser drilling and that is a considerable asset. However, it can also create problems, for example, how to set the sensors and supply the electric power, and so on." There is no doubt that deep sea drilling in the Nankai Trough, to be conducted by the *D/V CHIKYU*, will bring new understanding of the seismogenic zone, the earthquake mechanism, and the deep-earth environment; such operations may provide crucial clues in the mitigation and possible prediction of great earthquakes. We are looking forward to the task of expanding the horizons of the geological, geophysical and biological sciences through the undertaking of this grand project.

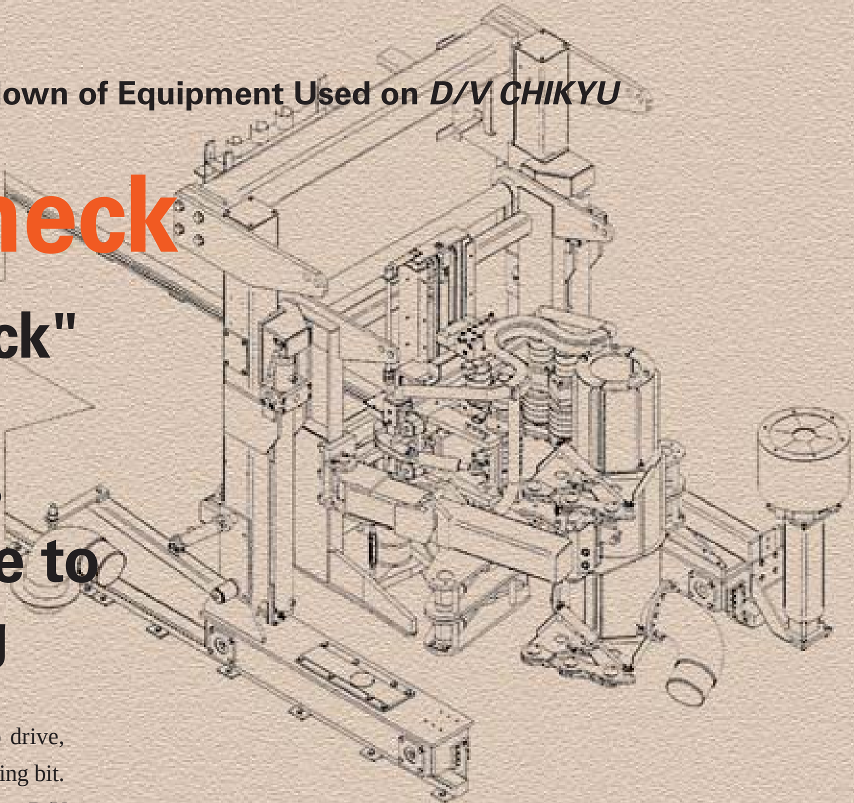
◆ Deep Sea Drilling Research Initiatives

Long term deep borehole monitoring will improve the degree of precision of predicting earthquakes.

Associate Professor Masanao Shinohara
Earthquake Observation Center
Earthquake Research Institute, University of Tokyo

I have great expectations for improved geodetic observations using borehole monitoring techniques. Put simply, the achievements made by measuring strain and tilt in the borehole will be useful in clarifying the earthquake mechanism in this subduction zone, and at the same time aiding in the determining the location of future slip events and perhaps the site of the next great earthquake. All these important measurements are obtained through borehole monitoring, which will also be useful for constraining model calculations concerning the potential scale and magnitude of future earthquakes in different areas along the plate boundary. I think this will lead to improvements in the precision of earthquake prediction.

Iron Roughneck



The "Iron Roughneck" safely, quickly and efficiently connects sections of drill pipe to the main drill string

The deep sea drilling apparatus is powered by the top drive, which turns the drill pipe that is tipped by the drilling or coring bit. The drill pipe is inserted into the riser pipe connecting the *D/V CHIKYU* with the blowout prevention device at the seafloor. The length of one section of drill pipe is 9.5 m. The end of each pipe has a threaded connector for linking sections together, and the sections must be sequentially and precisely connected in order to lower the drill pipe and the drill bit to the sea floor and down into the borehole. For example, when drilling to a depth of 1,800 m below the sea floor in water depths of 2,000 m, 400 drill pipe sections must be linked.

On the drill floor, the repeated work of tightening and loosening the threaded ends of each drill pipe section must be completed in order to raise or lower the drill string and drill bit, in order to remove the drill string in order to install casing pipe, and in order to open the drill string and extract a core sample. The Iron Roughneck automatically, safely, and quickly clamps onto, lifts, positions, and then connects or disconnects drill pipe sections by tightening or loosening the threaded connectors.

The iron roughneck is built around a heavy-duty frame equipped to move under power around the drill floor. This frame supports articulated grasping arms that can move laterally and vertically, and are coupled to an assembly consisting of several rotating heads that are matched to the diameter of the drill pipe and are used to turn the drill pipe depending on whether pipe is being connected or disconnected from the drill string. Different manipulator arm assemblies can be mounted or removed from the frame depending on the diameter or type of pipe being used.

Operation of the iron roughneck proceeds as follows:

1. Move from standby position to work position on the rig floor.
2. Manipulator arms moved up or down according to the position of the linking pipes, and laterally to correctly position the pipe.
3. Wash, oil, and coat the threaded connector ends with protective grease (conducted by the drilling crew).
4. Grasp the pipe to be connected or disconnected above the connector end, and the pipe that is to remain in position below the complementary connector end.
5. Spin the pipe that is to be removed/connected while stabilizing the pipe that is connected to the drill string.
6. Tighten and lock the connecting parts by applying a designated torque to the connected pipes.
7. Return to the standby position.

The iron roughneck rotates the drill pipe at about 100 turns per minute, so, including the final tightening, it takes only 10 seconds or so to link the pipes. All the work, including detecting the linking position and applying the torque for tightening, is done automatically under the oversight of rig floor drilling crew, thereby increasing the speed and safety of the drilling operation.

The iron roughneck used for connecting drill pipe sections to the drill string. There are different manipulator arms that can be used on the iron roughneck drill pipe or casing pipe sections with different diameters.

Maneuvering a drill pipe section into position in combination with the hydraracker (the manipulator arm on the left), the iron roughneck secures the upper and lower pipe sections and links them together.

The drill string assembled by the iron roughneck passes down through the riser pipe linking the *D/V CHIKYU* to the blowout preventer installed at the seafloor (above).

Connecting the pipe section to the drill string by rotating the upper pipe section. The iron roughneck does the connecting while spraying water onto both sections in order to wash the connecting ends and to prevent heating from friction between sections (above).

For removal of drill pipe sections from the drill string, the process is reversed. A mud bucket and pumping assembly (right) catches and removes drilling mud (the special fluid used for riser drilling) from the drill string in order to avoid overflow from the drill string onto the rig floor.

Site surveys in the Shimokita area

Site surveys are a critical stage in the determination of drilling locations

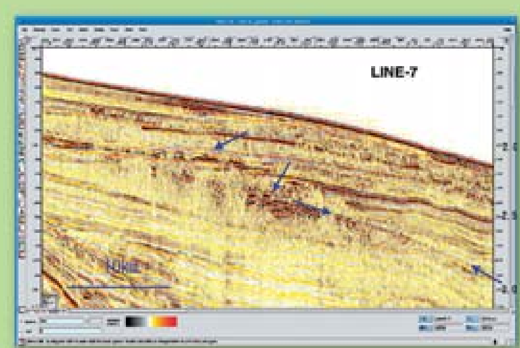
Deep sea drilling using *D/V CHIKYU* will take place at a single location on the seafloor over a period of several months; therefore the determination of a suitable drill site is crucial to the success of the mission. Site survey investigations are used to search for an ideal drilling point where drilling with either riser or non-riser systems can be carried out safely; the important criteria include information regarding water depth, seafloor condition, weather and current information, geological hazards (gas, hydrocarbon, methane hydrate, pressurized fluids, faults, and etc), and geological structures required to plan the construction of the well itself. These pieces of information are collected through a series of site surveys and are critical to the achievement of the scientific objectives of deep sea drilling.

Starting in Japanese fiscal year 2001, the Center for Deep Earth Exploration (CDEX), together with researchers, conducted investigations, observations and data collection and analysis in order to narrowing down candidate drilling sites from more than 12 areas around Japan to one area, and from several potential drill sites in that area to the two final sites selected.

The first investigations conducted in order to determine a suitable drill site were a series of low-resolution, widely spaced (in 2002), and high-resolution, closely spaced (in 2003) reflection seismic surveys. The thickness, inclination, disruption and relative position of the sedimentary strata, the presence and style of faults, the presence, size and shape of any gas or hydrocarbon deposits, and other crucial pieces of information were noted, compared to previous results and complementary analyses, and then used to make the final determination of drill site location.

In addition to the seismic reflection survey and subsequent geological analysis, several other crucial investigations were carried out in order to complete the site survey. Tidal and current surveys using acoustic doppler current profilers measured the strength and direction of surface ocean currents and tidal cycles that could potentially have an impact on the ability of *D/V CHIKYU* to maintain position over the drill hole. In addition, currents and tidal effects on the ocean bottom and in the middle of the water column were measured in order to determine their impact on the long drill string and the riser pipe that connects the drill ship to the Blowout Preventer (BOP). Seafloor bathymetry surveys (swath sonar) and seafloor texture and structure surveys (deep-tow sidescan sonar) were carried out in order to determine the slope, roughness and the geological character of the seafloor; these data were critical for choosing a stable location for initiating the drill hole and setting the BOP on the seafloor in a safe and secure manner. Short (10 to 50 meter) seafloor core samples were collected with a piston coring device to determine the density, firmness, mineralogy, and possible fluid or gas content of the shallow sediments; these data were essential for evaluating the stability and safety of the BOP installation site, and for determining the potential for any gas or fluid escape risks. Site survey operations investigated the entire spectrum of geological, geophysical, oceanographic and meteorological characteristics of the proposed test-drilling site in order to satisfy the requirements for safe and efficient drilling and vessel operations. Final drill sites were selected in through cooperation between operations, drilling, and research departments in order to assure that maximum scientific achievement coupled with maximum safety are achieved.

Similar site surveys are underway in a number of potential drilling locations for continued operations testing, and for upcoming international operations as a part of IODP. Site surveys have been ongoing in the Kumanonada region of the Nankai Trough, regarded as a promising place for the first international operation. Several high- and low-resolution seismic reflection surveys, as well as oceanographic, bathymetric, and seafloor survey operations have been completed. Soon a high-resolution three-dimensional seismic reflection survey will be completed in the potential drilling area in order to aid in the detailed development of well-drilling and well-casing strategies, to finalize any estimates of drilling hazards and drilling requirements, and to collect detailed, high-resolution data needed to determine potential scientific drilling targets.



A small section of a seismic reflection survey line showing sub-seafloor structure and sedimentary architecture. The blue arrows indicate the presence of free gas, water, or gas hydrate deposits, all of which are potential drilling hazards.

The research and development group designed the world's best scientific drilling system

With so many peoples' dreams at stake, there is only one way forward: Go for it!

The Research and Development Group, Technology Department, CDEX.

Many of the latest drilling and marine technologies such as the riser drilling system and the dynamic positioning system, are integral components of the *D/V CHIKYU*. The members of the research and development group designed this system and integrated these components into the drilling vessel through exhaustive research, cooperation with industrial shipbuilders and oilfield services providers, and close consultation with scientists, engineers, and marine architects.

Masanori Kyo, Subleader for design of the sub-sea system including the riser drilling system and Blow-Out Preventer (BOP) says, "During design and construction of *D/V CHIKYU*, we have proceeded with our job with many staff members who speak different languages, come from different cultures, and have different experiences and training. Though we sometimes had intense discussions with clashing opinions, we are very happy that the goal we all shared, construction of the *D/V CHIKYU*, has been completed. Various events occurred during the design and building process that presented challenges and ultimately helped to construction process come to fruition: one memorable event occurred during 1/1000 model testing of riser system operations in Dam Lake when we were essentially doomed by a typhoon; we learned many important lessons from such events and it is a good memory for us now."

In the same way, researcher Miyazaki, in charge of the research and development of the sub-sea system says, "An enormous number of people, including those from overseas, were engaged in the project from the beginning to its completion. I am very pleased that I was engaged in the construction of the world's most advanced drilling vessel. I think it was a really rewarding job." Researcher Inoue, in charge of development, design, and confirmation testing of the drilling system, such as the drilling equipment on the drill floor says, "The *D/V CHIKYU* is a drilling vessel that will be used for the grand purpose of developing future earth and life sciences. I feel that I have had invaluable experiences in performing my tasks, which gives me a sense of achievement as a researcher. I am grateful to have been a part of the team as my design philosophy was reflected in the construction process."

The rig floor with the drilling equipment is lined up and ready for operations is a symbol of the group's collaborative effort.

There are, however, many challenges that must be faced before *D/V CHIKYU* comes on line for international IODP operations. Researcher Wada, in charge of developing the core barrel and mud fluid circulation system, looks back and says, "The *D/V CHIKYU* was constructed by mobilizing the best equipment in each specialized field. We had terrible trouble combining them in the same platform and achieving full performance without problems. Having understood all the features of each device, having had in-depth meetings with domestic and overseas engineers, and cooperated with shipyards, we overcame many troubles one after another.

The *D/V CHIKYU* was completed without mishap, but the job is not yet finished. Researcher Miyazaki says, "Deep sea drilling operations on an actual testing site will be conducted in the near future. Until the drilling work is implemented smoothly, various problems might come up. In proceeding with scientific drilling, we will most likely need to develop new technologies. To cope with these might be more difficult than what we have done in the past." It appears that their busy days will go on for the time being.

From the left:
Subleader, Masanori Kyo
Researcher, Eigo Miyazaki
Researcher, Kazuyasu Wada
Researcher, Tomoya Inoue




IODP and *D/V CHIKYU* will appear in many areas around Japan!

These events were intended to introduce the public to the Integrated Ocean Drilling Program (IODP) and *D/V CHIKYU*. We held exhibitions displaying photographs of the *D/V CHIKYU* taken from various angles for visual impact, and we introduced the CHIKYU HAKKEN website to provide information about *D/V CHIKYU* schedule and operations.

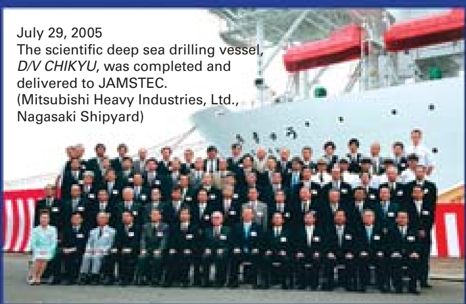
Exhibition staff members dressed in CDEX shipboard work gear at the exhibition, which allowed visitors to experience the atmosphere on the vessel. Event information: http://www.jamstec.go.jp/chikyu/

May 22 to 26, 2005
2005 Joint Meeting for Earth and Planetary Science (Makuhari, Chiba Prefecture)

June 20 to 23, 2005
Asia-Oceania Geoscience Society (AOGS) The 2nd Annual Convention (Singapore)

August 16 to 21, 2005
Summer Holiday Science Square (National Science Museum, Ueno, Tokyo)

D/V CHIKYU route and port calls (fiscal year 2005)



July 29, 2005
The scientific deep sea drilling vessel, *D/V CHIKYU*, was completed and delivered to JAMSTEC.
(Mitsubishi Heavy Industries, Ltd., Nagasaki Shipyard)

From October to November 2005
Installation test of the Blow-Out Preventer (BOP)
(Off eastern area of Shimokita Peninsula)

August 2005
Sailing
Basic operation test and vessel operation training
(Off Nagasaki)

From December 2005 to February 2006
Basic operation and maintenance testing

Beginning of March 2006
Dockyard inspection and routine maintenance
(Nagasaki shipyard of Mitsubishi Heavy Industries, Ltd.)

Friday, September 2, 2005
Docking at Honmoku (Yokohama Dockyard & Machinery Works, Mitsubishi Heavy Industries, Ltd.)

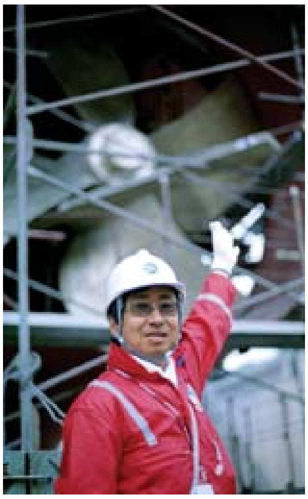
Saturday, September 10, Sunday 11, and Monday 12, 2005
Open to the public
(Yokohama City and Yokosuka City)

Monday (national holiday), September 19, 2005
Open to the public (Nagoya City)

End of August 2005
Basic operation test and vessel operation training
(Off Shikoku)

For the FUTURE **Perspective of CDEX Director-General Asahiko Taira**

The completion of the deep sea drilling vessel, *CHIKYU*! A long and hard road continues towards international operations



The deep sea drilling vessel, *D/V CHIKYU*, was completed and delivered to the Japan Agency for Marine-Earth Science and Technology on July 29, 2005.

It took about five years to construct, and more than 15 years from the start of initial development research. We are relieved that we could finish the process of construction without any serious mishaps. Considering the international nature of this operation, we cannot keep from being pleased.

The *D/V CHIKYU*, unlike an automobile, cannot be used immediately after delivery. In order to make the *D/V CHIKYU* function properly and efficiently, many people must apply their ingenuity and think about how we should operate it to get maximum achievements. The drilling system of the *D/V CHIKYU* is comprised of many major cutting-edge components such as the riser pipe, the blowout prevention device to be set at the seafloor, the system called Tensioner supporting the riser pipe, the derrick hanging the drill pipe, the draw works pulling up and down the pipes, the pipe racker handling the pipe, and so forth. Unless these components function systematically, dependably, and efficiently, deep sea drilling will be impossible. If just one of them does not function properly, all will stop. During the two-year test operation period, it is important for us to tune up the *D/V CHIKYU* in order to make the best use of it.

It will take time to work on getting the system operational, but we cannot do this indefinitely. We wish to face the challenge of deep sea drilling as soon as possible. How we balance these competing needs and desires may be the biggest challenge for us in the near future.

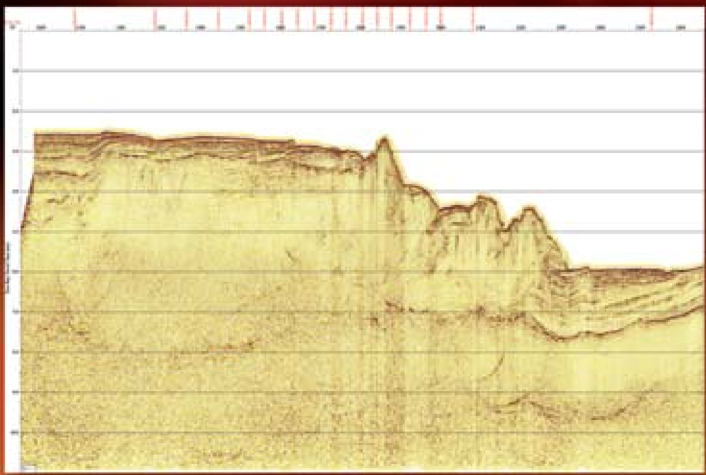
Also, during the test operation period, deep sea drilling and coring operations will be conducted in several areas including the Shimokita region. We would like to make this not only a test or training operation, but also a scientific achievement. We expect the first achievement to be in the extremophile research field. In this field, the deeper you drill, the more you achieve. The first scientific achievement the *D/V CHIKYU* delivers could perhaps be in this field.

When the test operations are complete, the first site for international operations will be the Nankai Trough, starting September 2007, as is described in the opening article. The Nankai Trough is the most promising target for research into the seismogenic zone through deep sea drilling. It is very important to trace the changes that occur during subduction, from data regarding the character of the oceanic plate and the sediments deposited on the ocean floor to the seismogenic zone deep beneath the overriding plate. It may be that the Nankai Trough is, for now, the only place where such research can be carried out.

Until now, it has been considered that micro earthquakes hardly ever occur in the Nankai Trough. However, due to advances in placement and sensitivity of seafloor observation networks, we now know there are various movements, including slow slip. Certainly, deep sea drilling implemented by the *D/V CHIKYU* will extract core samples. We are sure that if we conduct long-term observations in the borehole, we will be able to shed light on the dynamic system of the Nankai Trough, such as how the subduction zone is moving and what is happening there. Deep sea drilling will allow us to discover surprising phenomena that have not been predicted so far. Such expectations make my heart swell.

Cover's Note

Figure of Subduction Dynamics Obtained by Seismic Prospecting



The image used for this issue's cover is a figure of the subduction dynamics of the Nankai Trough obtained by seismic prospecting. To make real scientific achievements, and to conduct deep sea drilling safely and effectively, various advance investigations are made of the sea area. Geological structure prospecting using seismic waves (i.e., sound waves) is one of them. This is to understand the structures or situations under the seafloor by emitting artificial seismic waves into the sea from the research vessel, catching the waves bouncing back from the seafloor or the boundary of the strata under the seafloor with the sensor, and analyzing its records. We can get images of the depth of the strata under the seafloor and their inclination, and where possible, drilling obstacles such as the existence of gas or water stored underground. Now, detailed advance investigations, including seismic prospecting, are conducted in the Nankai Trough for the day when the *D/V CHIKYU* begins deep sea drilling.

CHIKYU HAKKEN
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