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Contributed Paper

Ocean Science Drilling Explorations with D/V Chikyu: Frontier and Challenging

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Abstract

Many international ocean science drilling programs (e.g. DSDP, ODP, IODP) have been conducted in the oceans all over the world for more than fifty years. A new phase of IODP (International Ocean Discovery Program) with three drilling platforms: the drilling vessel "JOIDES Resolution" by the US, the drilling vessel "Chikyu" by Japan, and the MSP (Mission specific platform) by Europe, began in 2013. Chikyu, operated by JAMSTEC since 2007, is the only riser drilling research vessel, which reaches to a total depth of 10,000m from sea surface. Our science approach to subsurface analyses is the integration of seismic surveys, well logging, core analysis, and long term observations. There are many successful projects achieved and on-going by D/V Chikyu. The purpose of NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) is to understand earthquake mechanism in the Nankai trough, where the Pacific plate is subducting under Japan that has hosted historical large earthquakes and has potential for future earthquakes or tsunami. We surveyed many holes with well logging data and cores analysis. J-FAST is a project to study the faults, associated with the great earthquake in east Japan in 2011. The residual friction produced temperature anomaly was observed successfully with temperature array sensors in the borehole. The study of living organisms and their condition in the subsurface is important to understand the evolution of life on earth. The study off-shore Shimokita in 2013 clarified the limit of the micro-bios existence and the carbon cycle system subsurface there. Deep water hydrothermal deposits is a frontier for metal resources and active ore developemnt. We are developing unique approaches at the seafloor and subsurface with logging while drilling and coring in Okinawa. The challenges will be introduced with these targets, purpose, operations, and science achievements.

Keywords: ocean science drilling, D/V Chikyu, IODP

1. Introduction

Though there is no clear definition of "Science drilling," one of them is to explore science using the drill hole and holes drilled to know the earth in present, past, and future. The purpose is to develop a basic science to understand the earth rather than industrial oil and gas exploration and production, and engineering drilling. The US science drilling ship has been used for more than fifty years and provided us many scientific results. D/V Chikyu joined to IODP (International Ocean Discovery Program) in 2007. She can operate a riser drilling system to approach deeper and more challenging targets. Ocean science drilling, the D/V Chikyu specifications, and its laboratory facilities are described in this paper. The four recent projects and science are highlighted, and the role of science drilling in science development is discussed.

2. SCIENCE DRILLING AND D/V CHIKYU

2.1 Science Drilling and IODP

IODP is one of the international organizations for international ocean scientific drilling projects (http://www.iodp.org/). The Project Mohole led by the US started with the target to explore the mantle by drilling across the Mohorovicic discontinuity in 1959. Reaching the mantle had not been accmplished at the end of the project in 1961, but science drilling had successfully developed into wider fields and a deeper understanding of the earth. The project had been continued to DSDP (Deep Sea Drilling Project) leaded by the US using with D/V Glomer Chalenger in 1968-1975, ODP (Ocean Drilling Program) leaded by the US and twenty two countries in 1975-2003, IODP (Integrated Ocean Drilling Program) led by the US and Japan, and twenty five countries in 2003-2013. These programs have achieved many scientific results in many fields such as solid earth, climate, earthquake, biosphere frontiers, etc. Then the current IODP (International Ocean Discovery Program) started in 2013 [1]. For major science themes, 1) climate and ocean change: reading the past, informing the future, 2) biosphere frontiers: deep life, biodiversity, and environmental forcing of ecosystems, 3) earth connections: deep process and their impact on earth's surface environment, and 4) earth in motion: processes and hazards on human time scales, drives the program. Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Iceland, India, Ireland, Italy, Japan, The Netherlands, New Zealand, Norway, People's Republic of China, Portugal, Republic of Korea, Spain, Sweden, Switzerland, United Kingdom, and United States all contribute to this program. IODP Sample and Data Request is available at http://iodp.tamu.edu/curation/index.html, digital data is available at http://sio7.jamstec.go.jp/.

The current IODP uses three drilling platforms. The US operates the JOIDES Resolution riser-less drilling vessel, Japan operates the D/V Chikyu riser drilling ship (Figure 1), and ECORD (European Consortium for Ocean Research Drilling) operates mission specific ships. Science drilling vessel D/V Chikyu joined science drilling program from 2007.

Figure 1. D/V Chikyu.

Organization and evaluation procedure of science drilling proposals areas following and in Figure 2. Proposals and site survey data from the international science community are submitted to the IODP support office. The IODP Science evaluation panel, and the IODP environment protection and safety panel evaluate science and recommend proposals for drilling. Each platform has a facility board to determine which proposals are drilled. Proposals are forwarded to the appropriate platform facility board, when they are approved. The board considers science priority, resources, ship track efficiency, risks, etc. Shipboard participants selected by the national committees.

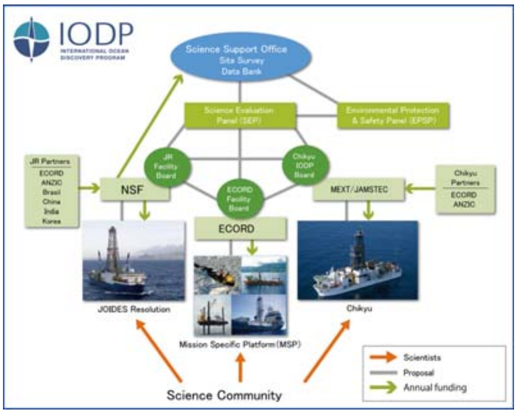

Figure 2. IODP organization and proposal flow.

2.2 D/V Chikyu

D/V Chikyu is owned by JAMSTEC (Japan Agency for Marine-Earth Science and Technology), and her implementation organization is CDEX (Center for Deep Earth Exploration), one of the centers in JAMSTEC. D/V Chikyu is able to operate riser and riser-less drilling system that reaches 10,000m below sea surface (max drill pipes length). Table 1 and 2 show her ship and drilling specifications, respectively.

Table 1. Chikyu shipspecifications.

Ship classification	Class NK: Mobile offshore drilling unit
Navigation area	All ocean (worldwide)
Length	210m
Breadth	38.0m
Height (from ship bottom)	130m
Depth	16.2m
Complement	200 people
Propulsion system	1 side thruster 6 azimuth thrusters
DPS	NK DPS-B
Generator	35,000kW

Table 2. Chikyu drilling specifications.

Drilling system	Riser system Riser-less drilling system
Max water depth	2,500 m (riser) 10,000 m (riserless)
Blow-Out Preventer	Weight: 380 tons Height: 14.5 m Pressure: 103 MPa
Length of drilling string	10,000 m
Riser pipe	Length: 27 m Diameter: approx. 50 cm
Drill pipe	Length: 9.5m 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	Lift capacity 1,250 tons 5,000 horsepower (3,728 kW)

Our scientific drilling approach includes taking formation cores, well logging, and long term monitoring in boreholes. Scientists carry out observations, measurements, writing cruise reports in the laboratory during the cruise. D/V Chikyu has a state-of-art laboratory. Two co-chief scientists and around 20 to 30 scientists are organized for the cruise by their specialty and nationality taking account of the science target.The laboratory floor map of D/V Chikyu is shown in Figure 3. Various core analysis and measurement are available as in Table 3. X-CT image and physical properties like natural gamma ray, resistivity, sonic velocity, gamma-gamma density, magnet sustainability with MSCL (Multi Sensor Core Logger) are measured for all cores. Other measurements and analysis are required depending on the scientific objective. The half "working half cores" are used measurement aboard, and the other half "archive half cores" are stored at one of core repository in Kochi Core Center JAMSTEC in Japan, Texas A&M University in the US, and Bremen University in Germany. Any scientists can request core samples for their research purpose.

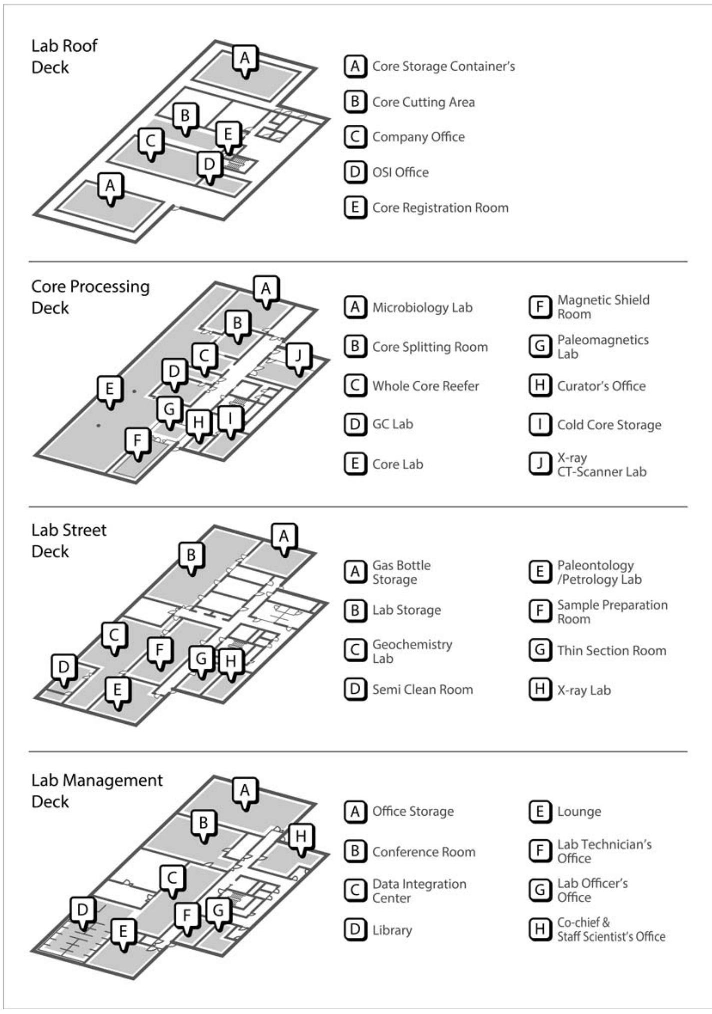

Figure 3. Laboratory area in D/V Chikyu.

Table 3. Measurement and analysis items in the laboratory.

Category	Measurement and analysis
Geochemistry	Bulk Carbon-Nitrogen-Sulfur Analysis (CHNS/O Analyzer), Carbonate Analysis (Carbonate Analyzer), Interstitial Water Chemistry Analysis for Anions (Ion Chromatography), Interstitial Water Chemistry Analysis for Minor Cations (ICP-AES), Interstitial Water Chemistry Analysis for pH and Alkalinity (Titrator), Interstitial Water Chemistry Analysis for Trace Cations (ICP-MS), IW Chemistry Analysis for Dissolved Phosphate (Spectrophotometer), IW Chemistry Analysis for Dissolved Silicate (Spectrophotometer), IW for chlorinity (Titrator), IW for major Cations (Ion Chromatograph), IW for Refractive Index (Refractometer), IW sampling (Squeezing Sysytem), NH4 Measurement for Interstitial Water (Spectrophotometer), Rock Eval Anaysis (Rock Eval 6 Standard), Soluble Organic Compound Analysis (HPLC), Whole Rock Chemistry Analysis for major elements (ICP-AES), Whole Rock Chemistry Analysis for major elements (XRF), Whole Rock Chemistry Analysis for trace elements (ICP-MS w/ HMI, LA), X-ray Diffraction Analysis (X-ray Diffractometer)
Gas Chemistry	Contamination Testing (GC-ECD), Head Space Gas Analysis (GC-FID, GC-NGA), Volatile and Soluble Organic Compound Analysis (GC-MSD), Volatile and Soluble Organic Compound Analysis (GC-TCD/FID), Volatile and Soluble Organic Compound Extraction (ASE)
Physical property	3D X-ray CT Scanning, Close up and Micro Imaging (SEM-EDS), Close-up Imaging (Close-up Photo System), Core Logging (MSCL-W/S), Elastc Wave Velocity Analysis, Elastc Wave Velocity Analysis under High-Pressure, Infrared Camera, Moisture and Density Analysis (Penta-pychnometer, Electric balance), Particle Size Analysis (Laser Diffraction Particle Size Analyzer), Polarization Microscope (I, J, Q, R, S, T), Reflectance Spectroscopy and Colorimetry (MSCL-Color), Stereomicroscope (G, N, O, P, U, V), Thermal Conductivity Analysis (Thermal Conductivity), Thin Section Equipments, Vane Shear Strength and Penetration Tests
Remanent magnetization	Anhysteric Remanent Magnetization (ARM), Fluxgate Magnetization (Fluxgate Mangetometer), Magentic Susceptibility Analysis (MS2B), Magnetic Susceptibility Analysis (Kappabridge), Remanent Magnetization (AFD), Remanent Magnetization (Hall-Effect Gaussmeter), Remanent Magnetization (Pulse Magnetizer), Remanent Magnetization (Thermal Demanetizer), Remanent Magnetization Analysis (Spinner Magnetometer)

3. RECENT SCIENTIFIC PROJECTS

Recent science drilling projects using D/V Chikyu are summarized in Figure 4 and Table 4. Details of the projects are available at http://www.jamstec.go.jp/chikyu/e/. Four projects are very unique and challenging, like drilling at seismogenic zone and severe borehole conditions, described shortly as follows.

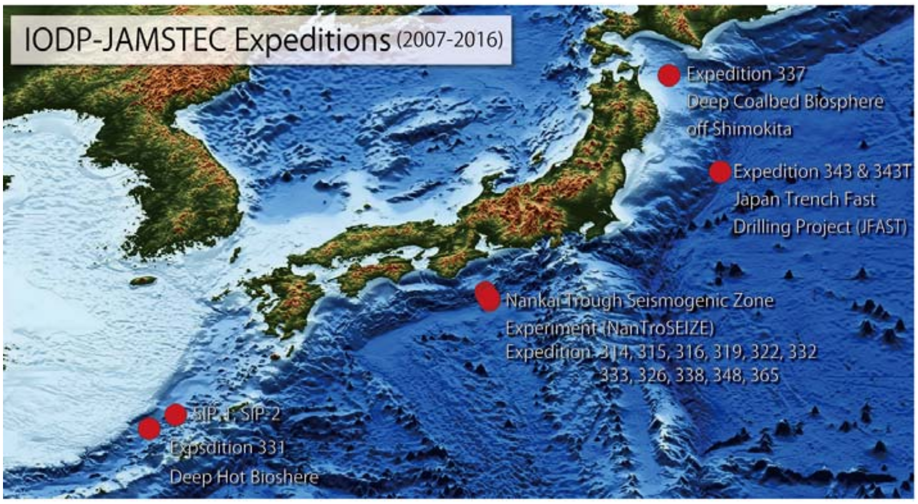

Figure 4. Map of recent science drilling activities with D/V Chikyu.

Table 4. Recent science drilling activities with D/V Chikyu.

Year	Cruise No.	Project	Water depth (m)	Total depth fromseafloor (m)
2007-on-going	IODP-314, 315, 316, 319, 322, 326, 332, 333, 338, 348, 365	NanTroSEIZE	1,939 m (C0002 hole)	3,058.5 m (C0002 hole)
2012	IODP-343	Japan Trench Fast Drilling Project (J-FAST)	6,890 m	850.5 m
2012	IODP-337	Deep Coalbed Biosphere off Shimokita	1,180 m	2,466 m
2010 2014 2016	IODP-331 SIP-1 SIP-2	Deep hot biosphere SIP HOT 1 pathfinder SIP HOT 2	1,130 m 1,161 m 1,602 m	151 m 230.6 m 238.0 m

3.1 NanTroSeize

The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a big complex ocean drilling project that will be conducted over several years with multiple expedition teams of scientists from all around the world. The mission of NanTroSEIZE is to understand the mechanism of mega-earthquakes. NanTroSEIZE attempts for the first time to drill, sample, and instrument the earthquake-causing, or seismogenic portion of Earth's crust, where violent, large-scale earthquakes have occurred repeatedly throughout history. The Nankai trough is located beneath the ocean off the southwest coast of Japan. It is one of the most active earthquake zones globally. The plan for NanTroSEIZE includes drilling very deep below the ocean to observe earthquake mechanisms. Figure 5 shows the schematic of a section of the site and implementation plan. Core samples will be collected in order to study the frictional properties of the rock, and sensors are to be installed deep beneath the seafloor to record earthquakes up close. The sensors and sample data are expected to yield insight into the processes responsible for earthquakes and tsunami. The data may shed light on how water and rock interact in subduction zones to influence earthquake occurrence.

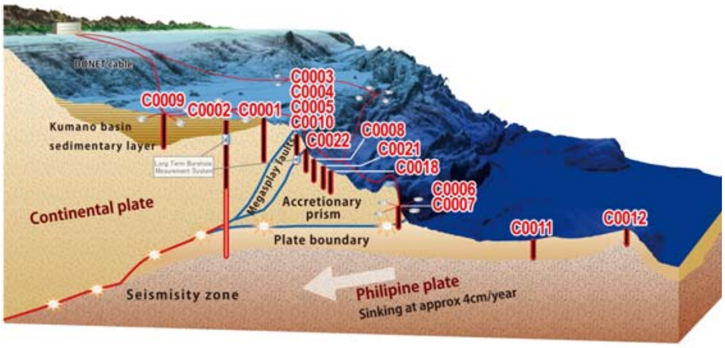

Figure 5. Schematic of NanTroSEIZE project.

A 3D seismic survey was conducted at the study area in 2006. Moore et al. [2] reported the mechanism of tsunami caused by the mega-splay faults. Drilling with LWD and coring along transecting of Nankai trough have started to grasp the study area since 2007 [3]. During the IODP expedition 332 [4], a number of sensors (pore-fluid pressure meter, strain meter, broadband seismometer, tilt meter, array thermometers) were installed at approximately 750-940 m depth in a borehole drilled to approximately 1000 m beneath the seafloor off the Kii Peninsula at Site C0002 (ocean depth 1938 m) by D/V Chikyu. Since 2013, it was connected and has started operation with DONET (Dense Ocean floor Network System for Earthquakes and Tsunamis), which is a unique development program of submarine cabled real-time seafloor observatory network. This program has aimed to establish the technologies of large scale real-time seafloor research and surveillance infrastructure for earthquake, geodetic and tsunami observation and analysis. Details of DONET is available at http://www.jamstec.go.jp/donet/e/index.html.

One of main objectives in this project is to take downhole logs, cores, and to install observatories at mega-splay faults. The drilling operation in the latest IODP expedition 348 in 2014 reached a depth of 3058.5 m below the seafloor. It is the world record for the deepest scientific ocean drilling and we successfully obtained data on the physical properties of the geologic strata from logging while drilling (LWD), as well as lithological samples (cuttings and cores) from deep in the interior of the accretionary prism [5]. These data and samples are the first ever collected from an active accretionary prism, and cored a substantial fault zone deep within the prism. The detail of the project is available at https://www.jamstec.go.jp/chikyu/e/nantroseize/index.html.

3.2 Japan Trench Fast Drilling Project (J-FAST)

The project was to understand the very large fault slip that occurred near the axis of the Japan trench during the 2011 Tohoku earthquake [6]. D/V Chikyu was able to drill down from the deep sea ocean floor to the plate boundary fault zone. The team took on challenges to understand the properties of the rocks and measure frictional heat at the fault. The expedition team succeeded in LWD to 850.5 m below the seabed at a water depth of 6,890m, reaching the plate boundary zone that caused the 2011 Tohoku Earthquake and the following tsunamis. They successfully obtained geophysical data of the formations and recovered sub-seafloor geological cores at depths between 648 and 844.5 m[7, 8].

The temperature observatory array was successfully installed in the borehole across the plate boundary in July 2012, and recovered them in on April 2013 [9]. The detail of the project is available at http: //www.jamstec.go.jp/chikyu/e/exp343/.

3.3 Deep Coalbed Biosphere off Shimokita

The IODP expedition 337 with D/V Chikyu aims to perform riser-drilling over 2,200 m below the seafloor off Shimokita Peninsula of Japan, northwestern Pacific Ocean[10, 11]. To understand the deep life and hydrocarbon system in the marine subsurface, Expedition 337 explores the deeply buried coal formation that may produce natural gas and tackles some fundamentally important scientific questions related to earth and life co-evolution. The expedition team successfully acquired core samples and geophysical property data from the formations between 1,276.5 to 2,466 m below the seafloor offshore Hachinohe (at a water depth of 1,180 m), as part of its mission to understand the deep carbon system and sub-seafloor biosphere, which is considered to be an important role in the system. The detail of the project is available at http://www.jamstec.go.jp/chikyu/e/exp337/.

3.4 Hydrothermal sediments in Okinawa Trough(HOT)

The aim of this expedition was to figure out distribution of the sub-seafloor hydrothermal fluid reservoirs in the Iheya North field as the first step for building a scientific theory of genesis of inactive deposits and concealed mineral deposits (buried sub-seafloor). Core samples were taken at the five sites across the Iheya North Knoll including the sub-seafloor hydrothermal fluid reservoir in the IODP expedition 331 in 2010 by D/V Chikyu [12, 13]. The results obtained from the drilling operations and cored samples indicated the possible existence of enormous sub-seafloor hydrothermal fluid reservoirs that were much more expansive that expected from the extension of seafloor hydrothermal activities. Probably at around the cap rock layers that sealed the hydrothermal fluid reservoirs, sub-seafloor massive black-ores (Kuroko) were found. These findings suggested that the sub-seafloor hydrothermal fluid regimes of the Iheya North field, and other mid Okinawa Trough hydrothermal systems, had great potential to host sub-seafloor hydrothermal mineral deposits such as noble metals and base metals (Cu, Pb, Zn, etc) for future marine mineral resources of Japan [14]. Using AUV exploration, two new hydrothermal systems in the Iheya North Knoll were found in 2013. The new hydrothermal fields named as Iheya North Natsu and Aki fields are located at 1.5 km south-southeast and 3.0 km south from the Iheya North Original field, respectively.

The primary scientific objective of this SIP ("Next-generation Marine Resources Survey Technologies" in the Cross-Ministerial Strategic Innovation Promotion Program) drilling cruises (CK14-04/Expedition 907) is to test a hypothesis that the Iheya North Original, Natsu and Aki fields form an enormous, complex hydrothermal system rooted from a common gigantic subseafloor hydrothermal fluid reservoir potentially covering the whole Iheya North Knoll. Surely, justification of this hypothesis is directly coupled to the finding of a gigantic sub-seafloor hydrothermal mineral (Kuroko) deposit from an aspect of marine mineral resource development. LWD tools are used to detect a common gigantic sub-seafloor hydrothermal fluid reservoir beneath the three hydrothermal fields. Particularly, temperature monitoring, resistivity and gamma ray intensity while drilling are tested to find the rapid temperature increase by breakout of cap rock structure of the sub-seafloor hydrothermal fluid paths, the complex structures of porous layered sub-seafloor hydrothermal fluid paths and the localization of thickness of sub-seafloor hydrothermal mineral (Kuroko) deposits.

D/V Chikyu drilled six sites with logging while drilling across the Iheya North Knoll including the sub-seafloor hydrothermal fluid reservoir found by the IODP expedition in 2010 and newly discovered hydrothermal fields between 2012 and 2013. As a result, data on distribution of the sub-seafloor hydrothermal fields in the Iheya North Field and physical properties were obtained.

4. Conclusion

It has been nine years since D/V Chikyu joined the IODP science drilling program in 2007. Ocean science drilling has developed for more than fifty years, but there are still many unknown and discoveries to be made. Our science targets are getting more challenging, e.g. deeper and more difficult conditions, and more complicated operations and experiments to explore science in future. D/V Chikyu can only have availability to reach ultra-deep earth and conduct challenging experiments. Not only the drilling operations, the acquisition of a sufficient number and quality of cores are important for advanced analysis and measurements so that the science is accomplished. Cores measurement and analysis in laboratory as soon after cutting cores aboard are required in Geochemical, biological, and Geomechanical studies. Deep sea and subsea are most exiting scientific frontiers. Drilling capability and advanced laboratory on D/V Chikyu are expected to cut new edge of science.

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