Integrated Ocean Drilling Program
Expedition 331 Scientific Prospectus

Deep Hot Biosphere

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Abstract

The possible existence of functionally active, metabolically diverse microbial ecosystems within the deep seafloor beneath sites of hydrothermal venting (the so-called "subvent biosphere") has been predicted, but is as yet unproved, by a number of interdisciplinary investigations in a variety of hydrothermal systems within different tectonic and geological settings. Integrated Ocean Drilling Program (IODP) Expedition 331, Deep Hot Biosphere, proposes to characterize subseafloor microbial ecosystems within the context of their physical, geochemical, and hydrogeologic setting in the Iheya North hydrothermal field in the mid-Okinawa Trough at three primary drilling sites (INH-4D, INH-5D, and INH-1D) and three contingency sites (INH-1C, INH-3C, and INH-2C).

An important objective of this project is to determine the compositional and isotopic shift in biologically essential chemical compounds in the hydrothermal fluids, including carbon dioxide, methane, hydrogen, sulfur/sulfide, ammonia, oxygen, and various organic compounds, which are variably enriched or depleted by physical, chemical, and biological processes throughout the hydrothermal fluid pathways in the mid-Okinawa Trough. These chemical reactants and products support the activity and functions of unique subseafloor microbial communities within different habitats of hydrothermal fluid migration. Extremely high concentrations of dissolved C-bearing gases, mainly CO_2 and CH_4, in the hydrothermal fluids, their stable carbon isotopic characteristics, potentially widespread fluid reservoirs in the sediments and pyroclastic deposits, and phase separation and phase partition of hydrothermal fluids provide key clues to understanding how the active deep biosphere operates and interacts with subseafloor hydrothermal systems in the mid-Okinawa Trough. Understanding such interactions is one of primary scientific goals identified in the Initial Science Plan for IODP. During the long history of the Deep Sea Drilling Project, the Ocean Drilling Program, and IODP, Expedition 331 will be the first to drill an active hydrothermal system in a sediment-filled backarc rift along a continental margin. The interdisciplinary approach we propose will provide clues to the evolution and early success of primordial microbial ecosystems on Earth, as well as an understanding of the nature of the deep hot biosphere on present-day Earth.

Schedule for Expedition 331

Expedition 331 is based on Integrated Ocean Drilling Program (IODP) drilling proposal number 601 (available at **www.iodp.org/600/**). Following ranking by the IODP Scientific Advisory Structure, the expedition was scheduled for the research vessel D/V *Chikyu*, operating under contract with the Center for Deep Earth Exploration. The expedition is currently scheduled to depart Shingu, Japan, on 1 September 2010 and to end in Nagoya, Japan, on 3 October 2010 (Table **T1**). A total of 22 days will be available for the drilling, coring, and downhole measurements described in this report (for the current detailed schedule, see **www.jamstec.go.jp/chikyu/**). Further details on the *Chikyu* can be found at **www.jamstec.go.jp/chikyu/.**

Introduction

Microbiologists participating in the Ocean Drilling Program (ODP) and IODP for the past decade have demonstrated that marine subsurface sediments consistently contain more than 10^5 cells/cm^3 even at depths as great as 1000 meters below seafloor (mbsf). On the basis of these findings, it has been proposed that the subseafloor environment has the largest biomass potential on Earth, exceeding that found in terrestrial and oceanic biospheres. Recent geochemical and microbiological data from sediments cored by ODP and IODP provide a picture of the subseafloor biosphere wherein prominent microbial metabolic activity is limited to relatively narrow interface zones between seawater and seafloor sediments and between these sediments and oceanic basement. The deep subseafloor biosphere appears to be, for the most part, composed of inactive or viable but extraordinarily slowly metabolizing microorganisms. Although these hypotheses have not been confirmed, if they are true and low metabolic activity of subseafloor life is ubiquitous and typical, it would likely be explained by a combination of in situ conditions of low temperature and low porosity coupled with extremely low fluxes of inorganic and organic nutrients.

Background

Active subseafloor hydrothermal systems at mid-ocean ridges (MOR), volcanic arcs (VA), backarc basins (BAB), and hotspots are environments with extraordinarily high fluxes of energy and matter. The “subvent biosphere” is the subseafloor biosphere that is predicted to exist just beneath active hydrothermal vents and fluid discharge zones. Subseafloor environments within active hydrothermal systems are the most promising locations for functionally active, metabolically diverse subseafloor microbial ecosystems. The existence of a subvent biosphere has been inferred from many microbiological and geochemical investigations of vent chimney structures and diffuse hydrothermal fluids (generally, those diluted with seawater in the shallow subseafloor). High-temperature hydrothermal fluids with focused discharge and little or no dilution by seawater also provide evidence of indigenous subvent microbes active along flow paths of hydrothermal upwelling, in which abundant H_2, CO_2, CH_4, H_2S, and CO provided as magmatic volatiles and by hydrothermal water-rock reactions are metabolized. Indeed, the possible occurrence of a subvent biosphere has been clearly demonstrated by microbiological and geochemical characterizations of high-temperature hydrothermal fluids in several hydrothermal fields such as the Kairei field on the Central Indian Ridge (CIR) and the Iheya North field in the mid-Okinawa Trough (MOT). In the Kairei field, Takai et al. (2004) proposed the occurrence of a hydrogen-based, hyperthermophilic subsurface lithoautotrophic microbial ecosystem (HyperSLiME) in which hydrogenotrophic hyperthermophilic methanogens within the *Methanococcales* genus dominate. Subseafloor microbial communities are energized by the extraordinarily high concentration of H_2 in the hydrothermal fluids (as high as 8.5 mM), probably derived by serpentinization in the subseafloor. In the Iheya North field, it has been suggested that a variety of microbial communities sustained by different chemolithoautotrophic primary producers are present in subseafloor habitats (Nakagawa et al., 2005). Variability in potential subseafloor microbial communities is likely associated with physical and chemical variation of hydrothermal fluids, controlled by phase separation and phase partition of hydrothermal fluid beneath the seafloor. In addition, hydrothermal environments hosted by organic-rich sediments provide unusual amounts of C_1 compounds (CO_2 and CH_4) in hydrothermal fluids and unique microbial habitats affected by liquid CO_2 and gas hydrates, which have been reported in another deep-sea hydrothermal system (Yonaguni Knoll IV field) in the Okinawa Trough (Inagaki et al., 2004; Nunoura and Takai, 2009; Nunoura et al., 2010). Thus, the abundant supply of energy and carbon sources and the richness of the habitats supported by physical and chemical variations in the MOT Iheya North field provide an ideal setting for the formation of functionally and metabolically diverse subseafloor microbial communities associated with hydrothermal activity.

Geological setting

The Okinawa Trough is a backarc basin extending for ~1200 km, located between the Ryukyu Arc-Trench system and the Asian continent (Lee et al., 1980; Letouzey and Kimura, 1986) (Fig. F1). It is presently undergoing rifting, which began at ~2 Ma and was preceded by an earlier rifting episode during the Miocene. Lee et al. (1980) have proposed that the Okinawa Trough is presently in a "drifting phase" (i.e., oceanic crust spreading characterized by short spreading centers and concomitant transform faults), as typically occurs along mid-ocean ridges and in other actively spreading backarc basins such as the Lau Basin and Mariana Trough. Seismic reflection data also suggest a typical geologic structure for the Okinawa Trough (Letouzey and Kimura, 1986): a high-velocity mantle at ~6000 mbsf overlain by potentially young basalt having an average velocity of 5.8 km/s between ~3000 and 6000 mbsf, an igneous rock layer (4.9 km/s) between ~1000 and 3000 mbsf, and ~1000 m of sediments at the seafloor. Geochemical features of hydrothermal fluids in the Okinawa Trough hydrothermal systems clearly demonstrate a significant contribution from felsic rocks and magma, as described below (Glasby and Notsu, 2003). Thus, it seems likely that the Okinawa Trough is actively rifting a transitional region between continental and oceanic crust.

The drilling proposed here would thus provide the first opportunity to drill into an active hydrothermal system and associated deposits within a backarc basin in continental margin setting. This tectonic difference is reflected in the chemical composition of the deposits. Sulfide samples collected from the Iheya North field show a Zn- and Pb-rich signature that is distinctive from the Fe-rich signature of mid-oceanic ridge sulfides (Halbach et al., 1993) (Fig. F1). This chemical signature is similar to that of Kuroko-type hydrothermal deposits that formed during the Tertiary in northeast Japan, related to opening of the Japan Sea. It is well known, moreover, that many volcanic massive sulfide ore deposits formed throughout geologic time are related to felsic and/or intermediate magmatism, rather than to basaltic volcanism at typical mid-ocean ridges. This suggests that a combination of a sediment-rich setting and arc-backarc magmatism favors formation of hydrothermal ore deposits.

Seismic studies/site survey data

Since the first discovery of submarine hydrothermal activity in the Iheya Knoll and the Izena Hole of the MOT (Momma et al., 1996) (Fig. F2), six highly active, representative hydrothermal fields (Minani-Ensei Knoll, Iheya North, Iheya Ridge, Izena Hole, Hatoma Knoll, and Yonaguni Knoll IV) have been discovered so far (Glasby and Notsu, 2003). The Iheya North field has been the subject of the most intensive interdisciplinary investigations, specifically geochemistry of hydrothermal fluids and sulfide/sulfate deposits and microbial ecology at the seafloor, and has also been monitored for >10 y. The outstanding features of the Iheya North field, some of which are also commonly observed in the other hydrothermal systems of the Okinawa Trough, are as follows:

- It is hosted in thick terrigenous sediments from the Yangtze and Yellow rivers.
- It has extremely high concentrations of gaseous C_1 compounds (CO_2 and CH_4) and ammonia in hydrothermal fluids.
- It contains mostly biogenic CH_4, as evidenced by a highly ^{13}C-depleted carbon isotopic composition and high $C_1/(C_2 + C_3)$ ratio, and CO_2 of mixed (magmatic input and organics-derived) source, with a moderately ^{13}C-depleted value.
- It contains novel liquid CO_2 and CO_2 hydrates in sediments near hydrothermal fields.
- It exhibits phase separation of hydrothermal fluids.

It is believed that these features greatly impact the structure, activity, and functions of the subseafloor microbial ecosystem. Hydrothermal activity in the Iheya North Knoll (27°47′50N, 126°53′80 E; 150 km north-northwest of the island of Okinawa) was first discovered by a camera survey in 1995. Since then, >40 deep submergence vehicle (DSV) and remotely operated vehicle (ROV) dives have revealed details regarding the location of hydrothermal activity and seafloor events (Fig. **F2**). Prior to this proposal, however, there had been few geologic and geophysical surveys of the Iheya North Knoll, and recent surveys have provided important insights into the geological setting and the associated heat flow anomaly, suggesting a hydrothermal discharge-recharge model for the Iheya North hydrothermal system (Table **T2**).

A grid of multichannel seismic (MCS) profiles is available for the Iheya Knoll region (Fig. **F3**). An MCS profile across the Iheya North Knoll (Fig. **F4**) (B–B′ lines in Fig. **F1A**) clearly demonstrates its subseafloor stratigraphic structure and that of the surrounding terrain in the mid-Okinawa Trough. The igneous intrusion penetrates trough sediments that are >1000 m thick (Fig. **F4**). In the middle of the Iheya North Knoll, a central valley exhibits relatively strong subbottom seismic reflectors (as deep as ~350 mbsf), suggesting the existence of sediments or some materials other than massive igneous rock (Fig. **F4**). An interval velocity profile from the detailed velocity analysis of the same MCS section reveals more detailed subbottom structures (Fig. **F5**). Several low-velocity zones are identified within Unit C of the trough sediments (150–200 mbsf) and even within the central valley (150–200 mbsf) (Fig. **F5**). These low-velocity zones may indicate the existence of fluids in permeable zones, representing potential hydrothermal fluid pathways. In particular, the low-velocity zone in the central valley might be a good candidate for a hydrothermal fluid reservoir in the Iheya North field.

Based on seafloor DSV and ROV observations, the Iheya North hydrothermal field and the surrounding central valley are covered with sediments and are characterized by several faults with a north–south trend, with major hydrothermal vent chimneys (mounds) standing along one of the north–south faults. A gridded single-channel seismic reflection survey of the Iheya North Knoll with shorter intervals of generator-injector gun shots does not clearly show faults but indicates instead an unstratified subbottom structure, sometimes extending to just beneath the seafloor, in the central valley of the Iheya North Knoll. This unstratified subbottom structure likely consists of strongly permeable materials but not layered sediments, as strongly suggested by recent coring expeditions in the central valley, JAMSTEC KY05-14 and KY08-01. In all the cores, thick, pumicious flow deposits with coarse to fine grain sizes were found just below the seafloor (Fig. **F6**). These pumice layers often contained abundant gas-filled voids and were polluted by elemental sulfur and sulfide deposits (Fig. **F7**), suggesting the input of gas-rich hydrothermal fluids (Kinoshita et al., 2006). Geochemical analyses of pore water samples also supported the input of typical gas phase–enriched hydrothermal fluid in Iheya North field. These site survey data consistently suggest that multiple and thick volcanic pyroclastic deposits fill the central valley of the Iheya North Knoll, providing both potential hydrothermal fluid recharge paths and reservoir and discharge paths.

Geochemical studies of pore fluid extracted from the pumiceous sediment revealed unusual chemical profiles just below the *Calyptogena* clam colony, including low Cl and high CH_4 concentrations. The Na/Cl ratio and $\delta^{13}C(CH_4)$ value are both close to those of the high-temperature venting fluid; these observations can be explained by intrusion of hydrothermal fluid into the surface pumice layer. Together with the occurrence of elemental sulfur in the sediment, these results strongly suggest lateral migration of vapor-rich hydrothermal fluid into the layer of pumiceous sediment. The isotopic compositions of carbon and sulfur can be attributed to microbial sulfate reduction within the sediment, which produces the H_2S utilized by *Calyptogena*. Microbial population analysis confirmed delta-proteobacteria (including sulfate-reducing bacteria) and ANME 2c archaea (including methane-oxidizing archaea) as predominant groups.

In addition to seafloor surveys of the subvent biosphere, several ODP and IODP drilling explorations have been conducted. For example, microbiologists and biogeochemists participated in drilling expeditions to the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge (ODP Leg 158) (Reysenbach et al., 1998), the hydrothermal fields of Middle Valley on the Juan de Fuca Ridge (ODP Leg 169) (Cragg et al., 2000), the PACMANUS field in the Manus Basin (ODP Leg 193) (Kimura et al., 2003), and on the flank of the Juan de Fuca Ridge (IODP Expedition 301) (Expedition 301 Scientists, 2005). These studies have found that, while there is evidence for microbiological processes occurring in hydrothermal sediments, it is very difficult to sample indigenous microbial communities and document their activity and biological signatures from rocky materials without contamination. Heretofore, potentially indigenous subvent microbial communities have been detected only at ODP Sites 1188 and 1189 in the Manus Basin. Unfortunately, their physiological characteristics as well as their in situ populations remain poorly documented.

The supporting site survey data for Expedition 331 are archived at the **IODP Site Survey Data Bank.**

Scientific objectives

Previous ODP and IODP expeditions provide lessons in exploring the subvent biosphere: a strong interdisciplinary collaboration of microbiology with related science fields based on clearly defined scientific objectives with a feasible drilling strategy is essential to successfully investigating the subvent biosphere and clarifying the structure and community dynamics of a subseafloor microbial ecosystem associated with hydrothermal activity. Here, we propose IODP Expedition 331, Deep Hot Biosphere, with the goals of obtaining direct evidence of the existence of a functionally active, metabolically diverse subvent biosphere in its physical, geochemical, and hydrogeologic context within the Iheya North field in the mid-Okinawa Trough. This proposal directly addresses one of the primary themes of the IODP Initial Science Plan, the Deep Biosphere and the Subseafloor Ocean.

This project will be conducted by an interdisciplinary group of onboard and shore-based scientists including microbiologists, geochemists, hydrogeologists, mineralogists, geophysicists, and geologists. The major scientific objectives of the Expedition 331 drilling program are as follows:

1. To directly prove the existence of a functionally active, metabolically diverse subvent biosphere associated with subseafloor hydrothermal activity in the Iheya North field by drilling.
2. To clarify the architecture, function, and impact of subseafloor microbial ecosystems and their relationship to physical, geochemical, and hydrogeologic variations along the overall hydrothermal fluid pathway on the basis of
   a. Characterizing variability in the biomass, diversity, structure, and function of microbial communities in various habitats occurring in vertical and horizontal extensions of subseafloor hydrothermal flow;
   b. Characterizing compositional and isotopic variability in fluid chemistry associated with hydrothermal abiotic and biotic processes in vertical and horizontal extensions of subseafloor hydrothermal flow;
   c. Characterizing compositional and isotopic variability in mineral formation and alteration of sediments throughout hydrothermal abiotic and biotic processes; and
   d. Reconstructing subseafloor hydrothermal fluid pathway and hydrogeologic structure by means of distribution and transportation of naturally existing microbial and chemical tracers relevant to hydrothermal activity together with geophysical site survey data.
3. To recover core samples of hydrothermal sulfides for mineralogical and geochemical studies. Mineral assemblage and chemical composition would constrain physical and chemical conditions of mineralization. Studies of fluid inclusions in sulfide minerals would constrain fluid temperature and provide evidence for subseafloor phase separation. Isotopic study of sulfur, lead, and possibly iron would provide information on magmatic and crustal contributions to the hydrothermal system. Dating of hydrothermal deposits would constrain duration and timing of hydrothermal activity. Application of recently developed microanalytical techniques such as laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) would provide new insight into the sources of hydrothermal metals. Drilling can help to constrain the size and geometry of the sulfide deposits and hydrothermal alteration zones, which can modify sediment permeability and influence hydrothermal flow paths. Because microbial habitat relies on hydrological structure as well as temperature structure, these studies would provide important insights into the settings of the subseafloor biosphere.

4. To recover and analyze interstitial waters from interbedded pumiceous volcanic material and terrestrial sediment, which are expected to reveal further cases of lateral fluid intrusion and possibly the existence of a hydrothermal reservoir within the sediment layer. Geochemical studies of pore fluid composition would document the contribution of any hydrothermal component. The isotopic composition of oxygen and hydrogen would constrain the fluid migration history, including phase separation and possible formation of CO_2 hydrate. Organic geochemistry together with carbon and sulfur isotopic compositions would provide evidence for in situ diagenesis enhanced by fluid intrusion and may demonstrate effects of microbial metabolism supported by the hydrothermal fluid.

Drilling strategy

Proposed drill sites

Drilling at proposed Site INH-1D is designed to penetrate the major hydrothermal discharge path along the normal fault and precisely penetrate the huge North Big Chimney (NBC) (a center of hydrothermal discharge directly from a deeply sourced fluid). We will penetrate the associated hydrothermal mound to a maximum depth of 50 mbsf (Fig. **F1B**). This hydrothermal mound is ~30 m in height and ~6 m in diameter, so drilling will sample proximal hydrothermal deposits and fluids (Fig. **F8**). These samples will be used for age estimation of the deposits, for detailed mineral and fluid chemistry, and for microbiological investigation of subvent microbial communities along the main discharge path. This hydrothermal mound is expected to consist of massive metal sulfides and sulfates. It will therefore be drilled with conventional drilling equipment supplied by Baker-Hughes Inteq (BHI), which has a better chance of obtaining good core recovery from hard materials.

Proposed Sites INH-4D and INH-5D are designed to drill and core the relatively high and low heat flow areas near the discharge Site INH-1D, penetrating the margin of the local discharge-recharge zone to depths of 100 and 200 mbsf, respectively. Based on seismic reflection data, they are expected to penetrate sediments, pumiceous deposits, and the interface with igneous basement (Fig. **F5**). These cores will provide information on subseafloor microbial habitats and communities within more vertically and horizontally broad gradients of physical and chemical variation, which could be affected by mixing with ambient seawater recharge, formation of liquid and/or solid CO_2 with methane, and subseafloor microbial activity along hydrothermal flow paths. These sites will be drilled using the hydraulic piston coring system (HPCS) to refusal, followed by coring with the BHI system.

Drill site priority

Completion of Site INH-4D (HPCS coring to refusal, industrial drilling and coring as deep as possible, and casing and capping) is the first priority, as this site has the highest potential to access functionally active subseafloor microbial communities and their geochemical environments occurring in the mixing zones between hydrothermal discharges and recharges. HPCS coring at Site INH-5D (to refusal) is proposed as the second priority to obtain additional microbiological and geochemical samples potentially hosting microbial communities and more moderate geochemical mixing environments. Because industrial drilling and coring would take considerable time to complete, we would move to the third prioritized operation of industrial drilling and coring at Site INH-1D (as deep as 18 mbsf). When industrial drilling and coring at Site INH-1D is completed, we would return to Site INH-5D and complete industrial drilling and coring as deep as possible, along with casing and capping. These operations would provide subseafloor samples such as relatively clean samples for microbiological and geochemical (fluid chemistry) investigations at two different subseafloor hydrothermal mixing zones and hydrothermal deposits at sites influenced by the highest, moderate, and lowest input of the end-member hydrothermal fluid. If these operations are completed before the end of the expedition, we will be able to complete operations at Sites INH-1C and INH-3D.

Logging/downhole measurements strategy

The only downhole measurement we will be making is temperature, using the advanced piston corer temperature tool (APCT-3) in the shoe of the HPCS.

Postdrilling strategy

Recently, an in situ cased-hole fluid sampler (DEEP-SAMPLER) and a microbial colonization device (BIO-SAMPLER), which were mentioned as possible third-party tools for postdrilling investigation in the IODP 601-Full3 proposal, have been developed by a research group for the principal proponent. These sampling tools have enabled us to retrieve indigenous subseafloor fluids and microbes from the seafloor through cased or cemented holes using an ROV. Development of these types of third-party tools greatly extends the usefulness of IODP drill holes, provides research opportunities for investigating subseafloor fluid flow and microbial communities, and permits long-term monitoring of drilling-induced disturbance of seafloor and subseafloor environments. In order to assure the applicability of these postdrilling sampling and monitoring tools, the protection of the hole and the preservation of subseafloor fluid flow are essential. Thus, full casing of the drilled holes using heat-resistant materials that are chemically tolerant to H_2S, CO_2, O_2, and Cl, together with the deployment of screens at appropriate depths corresponding to the subseafloor hydrothermal fluid paths, is planned during the expedition as follows (Fig. **F8**):

1. For proposed Site INH-1D, casing and cementing operations are impossible because of expected unstable seafloor and subseafloor conditions. But, for alternative Sites INH-1C, INH-2C, and INH-3C, steel casing and sealing by wellhead cap are possible.
2. For proposed Site INH-4D (and proposed Site INH-5D), drilling operations are expected to encounter fluid outflow due to the possible penetration of subseafloor hydrothermal fluid paths. Thus, cementing may be impossible, but casing and sealing by wellhead cap are possible.

Core flow and sampling strategy

The core flow for Expedition 331 will be modified to accommodate the potential risk for elevated H_2S gas to levels hazardous to health, as well as to ensure that sampling for microbiological studies is possible (Fig. **F9**). These modifications include adjustments to fit the 4 inch aluminum liners used with the BHI system into the work flow. These cores will be crane-lifted in a container from the aft deck to a point near the core processing deck.

Sampling (and data sharing) strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations policy posted on the Web at **www.iodp.org/program-policies/.** This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of Co-Chief Scientists, Expedition Project Manager, and IODP curator on shore and curatorial representative on board ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postcruise sampling.

Shipboard scientists are expected to submit sample requests (at **smcs.iodp.org/**) 3 months before the beginning of the expedition. Based on sample requests (shore based and shipboard) submitted by this deadline, the SAC will prepare a tentative sampling plan, which will be revised on the ship as dictated by recovery and cruise objectives. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. Modification of the strategy during the expedition must be approved by the Co-Chief Scientists, Expedition Project Manager, and curatorial representative on board ship.

The minimum permanent archive will be the standard archive half of each core. All sample frequencies and sizes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the cruise objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

If some critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. These intervals may require special handling, a higher sampling density, reduced sample size, or continuous core sampling by a single investigator. A sampling plan coordinated by the SAC may be required before critical intervals are sampled.

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Table T1. Operations and time estimates for Expedition 331.

	September																															October				
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5
SP to Shingu																																				
Unloading/loading	Shimizu																																			
Transit to INH4					Transit																															
Survey etc																																				
INH-4D										INH-4D																										
INH-5D																	INH-5D																			
Port Call at Nago																			Transit																	
INH-1D																				INH-1D																
INH-5D																						INH-5D														
Transponder rec.																																				
Transit to Nago																																				
SP departure																																				

Table T2. Recent surveys of heat flow in the local hydrothermal recharge/discharge Iheya North hydrothermal field used during Expedition 331. (**See table notes.**)

Cruise	Chief scientist	Operation	Ship	Period	Measurement for site survey
KR01-09	K. Takai	Piston corer	*Kairei*	July–August 2001	HF, bathymetry, gravity, magnetism, SBP, coring
NT02-06	F. Inagaki	*Shinkai* 2000	*Natsushima*	April–May 2002	Observation, HF, sampling
KY02-11	K. Takai	MCS	*Kaiyo*	November–December 2002	MCS
NT03-09	F. Inagaki	*Hyper-Dolphin*	*Natsushima*	August–September 2003	Observation, HF, sampling
KY05-14	M. Kinoshita	NSS	*Kaiyo*	January 2005	HF, coring
YK06-09	T. Oji	*Shinkai* 6500	*Yokosuka*	July 2006	SCS, observation, HF, sampling
KY07-03	T. Okano	MCS	*Kaiyo*	May 2007	MCS
YK07-07	T. Tsukioka	AUV/Urashima	*Yokosuka*	May 2007	High-resolution bathymetry, side-scan sonar imaging
NT07-11	S. Nakagawa	*Hyper-Dolphin*	*Natsushima*	June 2007	Observation, HF, sampling
NT07-13	S. Nakagawa	*Hyper-Dolphin*	*Natsushima*	July 2007	Observation, HF, sampling
KY08-01 Leg 2	F. Yamamoto	Piston corer	*Kaiyo*	January 2008	Coring
KY08-01 Leg 3	M. Kinoshita	Piston corer	*Kaiyo*	January–February 2008	Coring
KR10-02	T. Okano	MCS	*Kairei*	January 2010	MCS

Notes: MCS = multichannel seismic, NSS = navigable sampling system, AUV = autonomous underwater vehicle. HF = heat flow, SBP = subbottom profiler, SCS = single-channel seismic.

Figure F1. A. Area map of the Iheya North Knoll, showing proposed drill sites (INH-1C, INH-1D, INH-2C, INH-2D, INH-3C, INH-3D, INH-4D, and INH-5D), Expedition 331. Inserts show the Iheya North Knoll in relation to Okinawa, and Okinawa in relation to major tectonic components. (**Continued on next page.**)

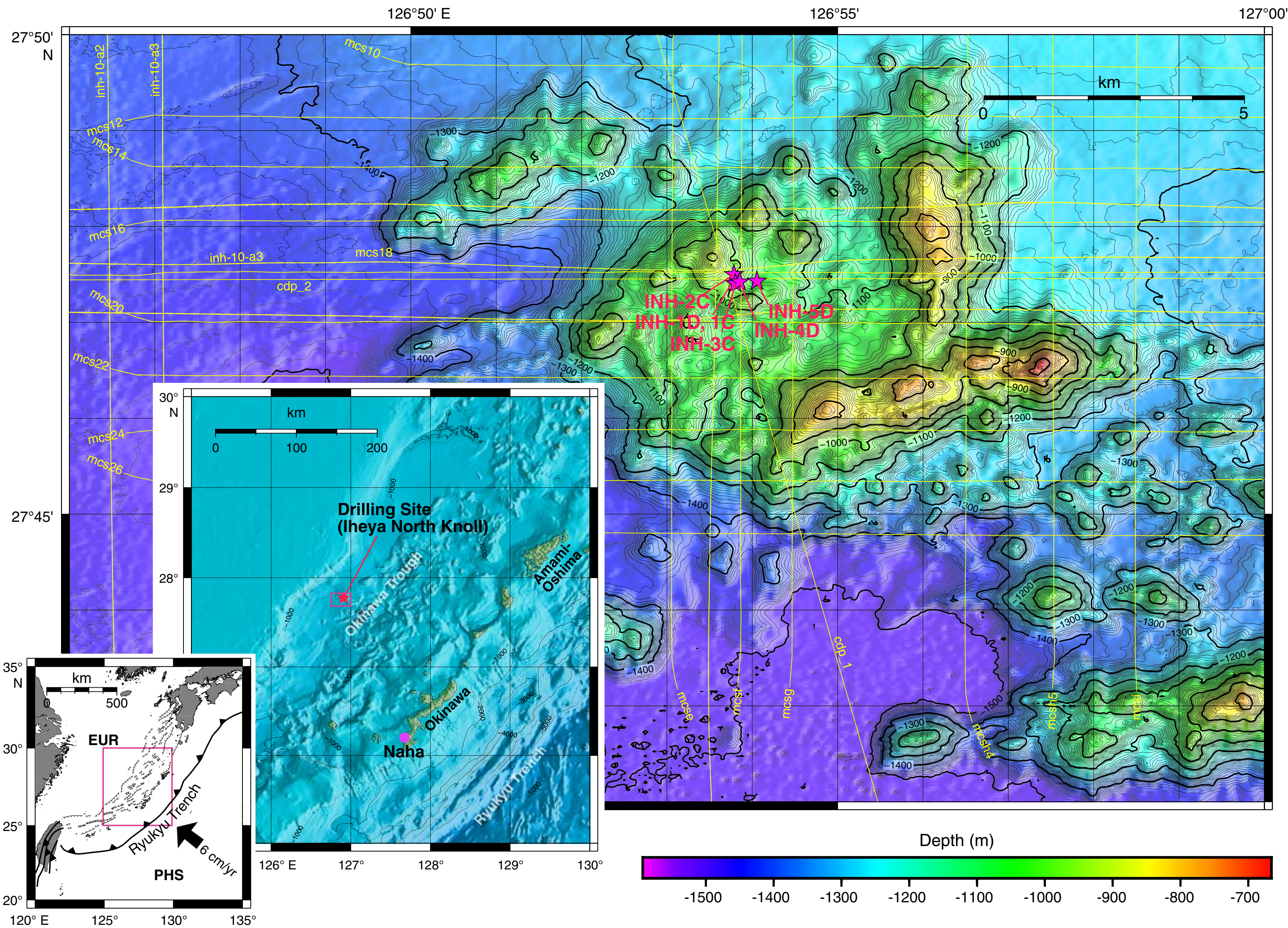


Figure F1 (continued). B. Close-up of proposed sites, Expedition 331. NBC = North Big Chimney, NEC = North Edge Chimney, SBC = South Big Chimney.

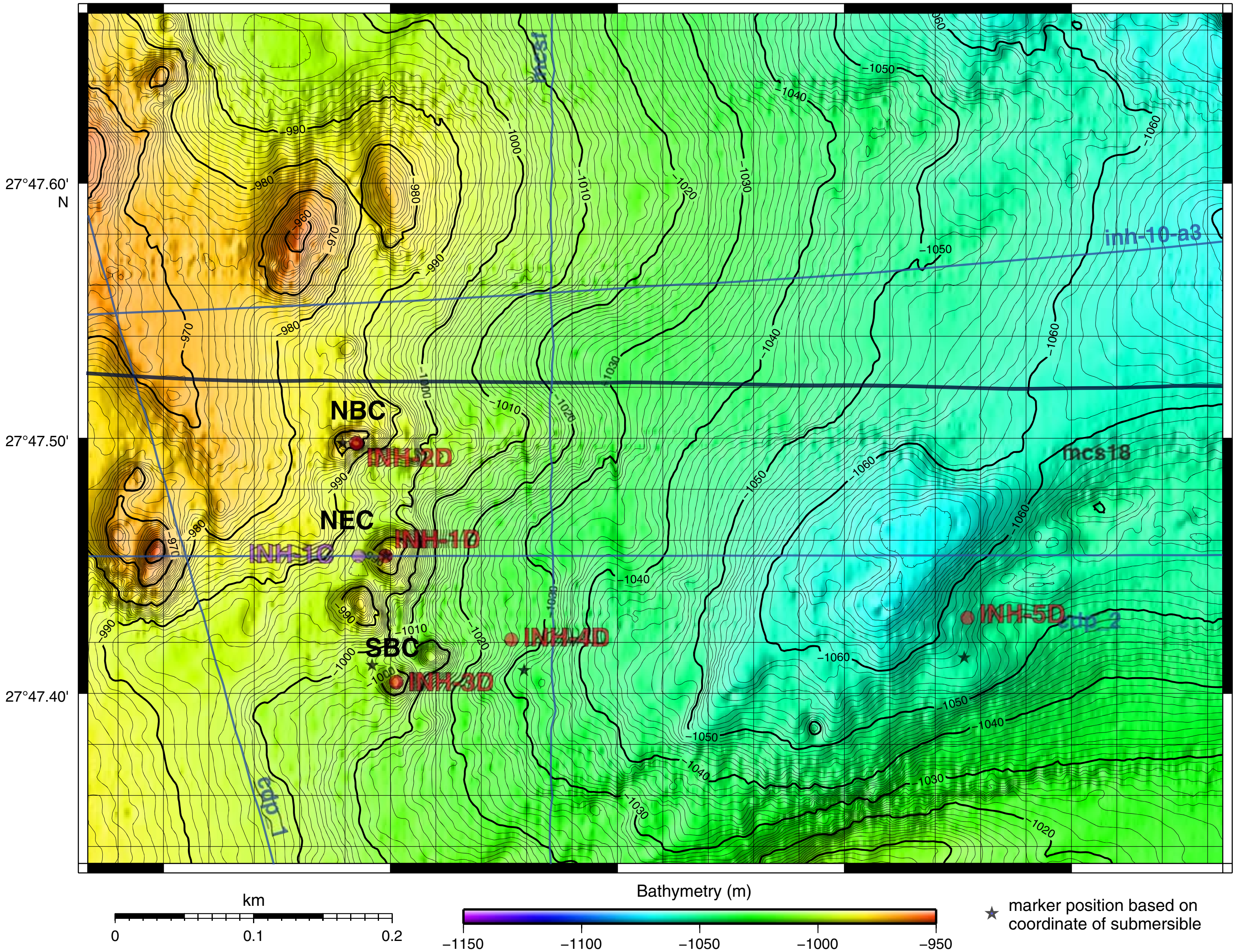


Figure F2. Data from the Iheya North Knoll, Expedition 331. **A.** Submarine hydrothermal activity at the Iheya North Knoll. **B.** Local hydrothermal fluid discharge-recharge model of a west–east section of the Iheya North Knoll.

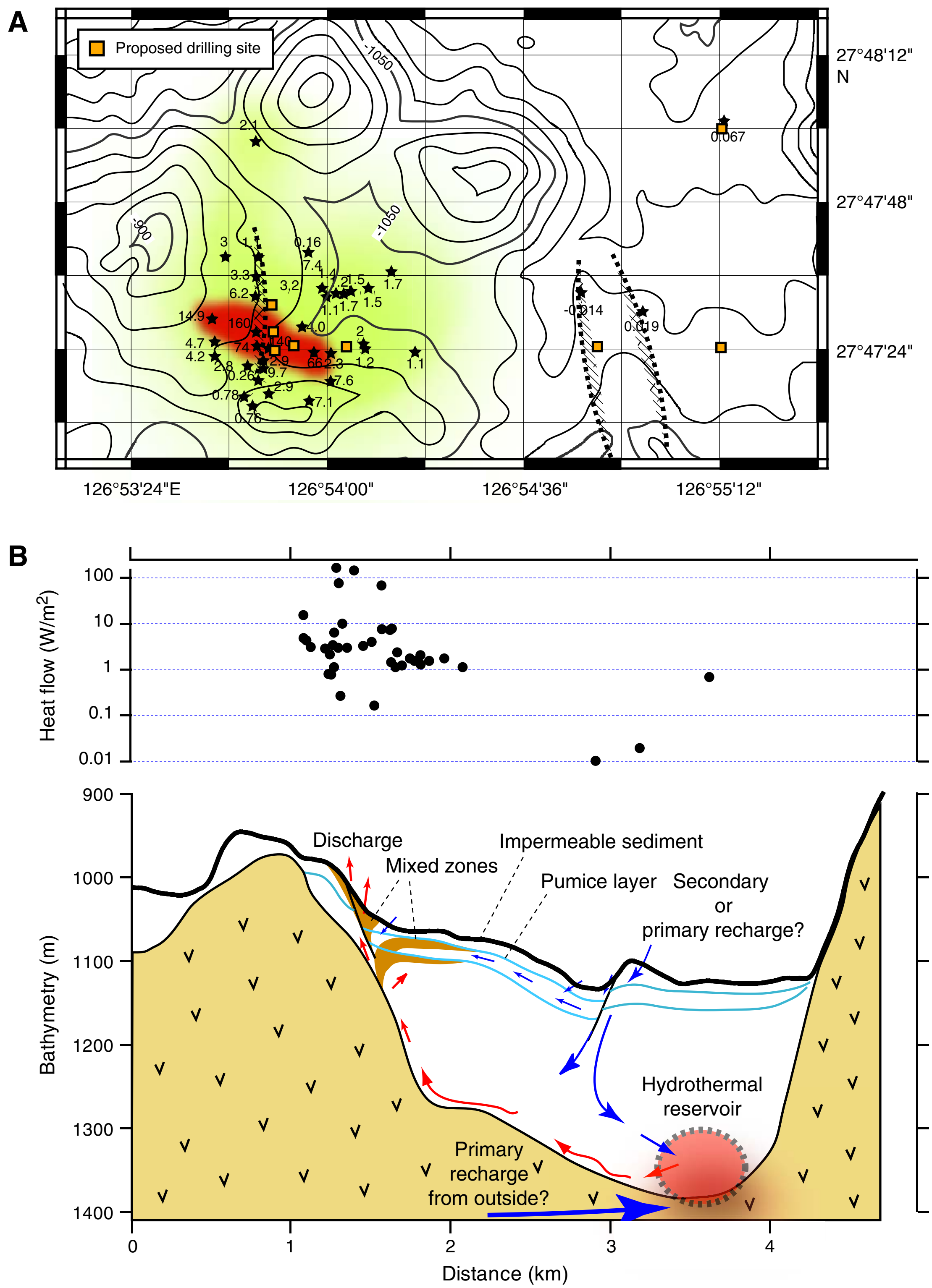


Figure F3. Multichannel seismic lines for the Iheya North Knoll, Expedition 331. MCS = multichannel seismic, SCS = single-channel seismic, HD = high density.

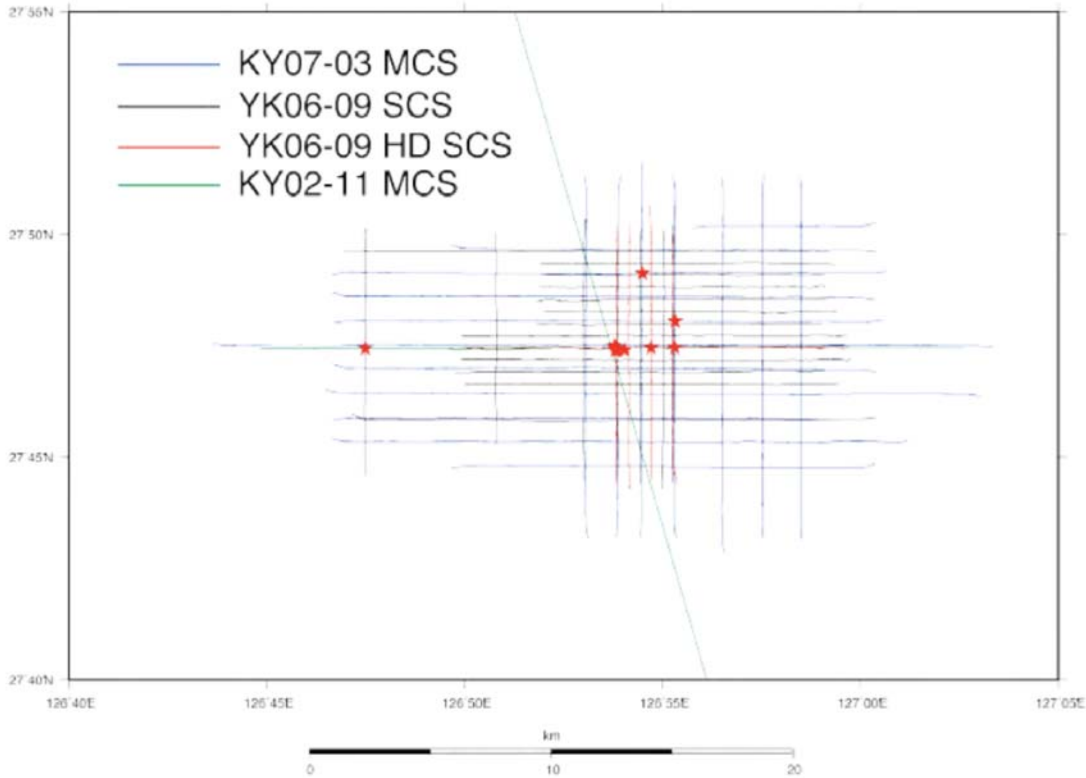


Figure F4. Profile of multichannel seismic Line MCS18 (highlighted in Fig. **F1B**), Expedition 331. CDP = common depth point.

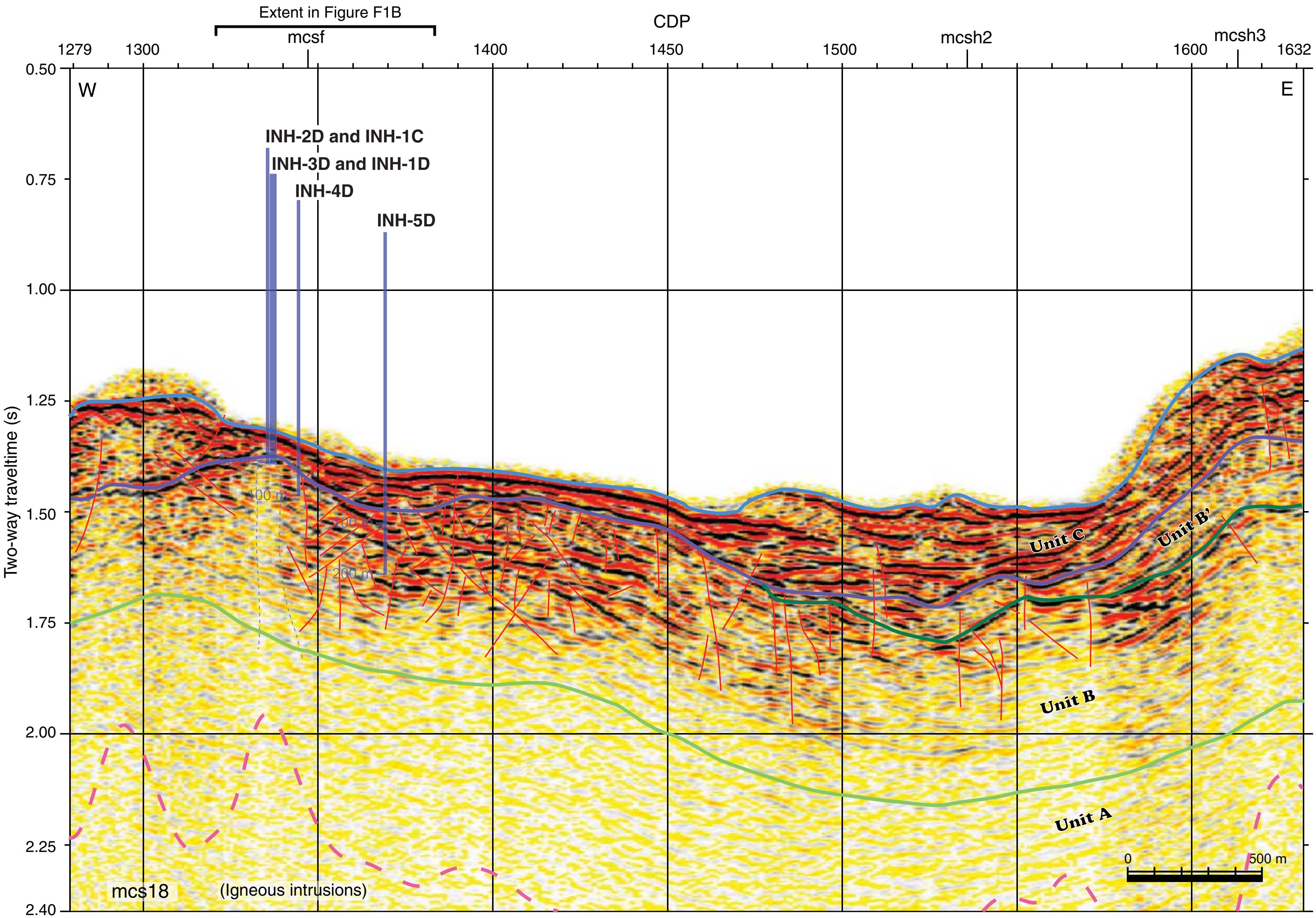


Figure F5. Internal velocity profile from same MCS section intervals as Fig. F3, including units (low velocity zones, etc), Expedition 331. CDP = common depth point.

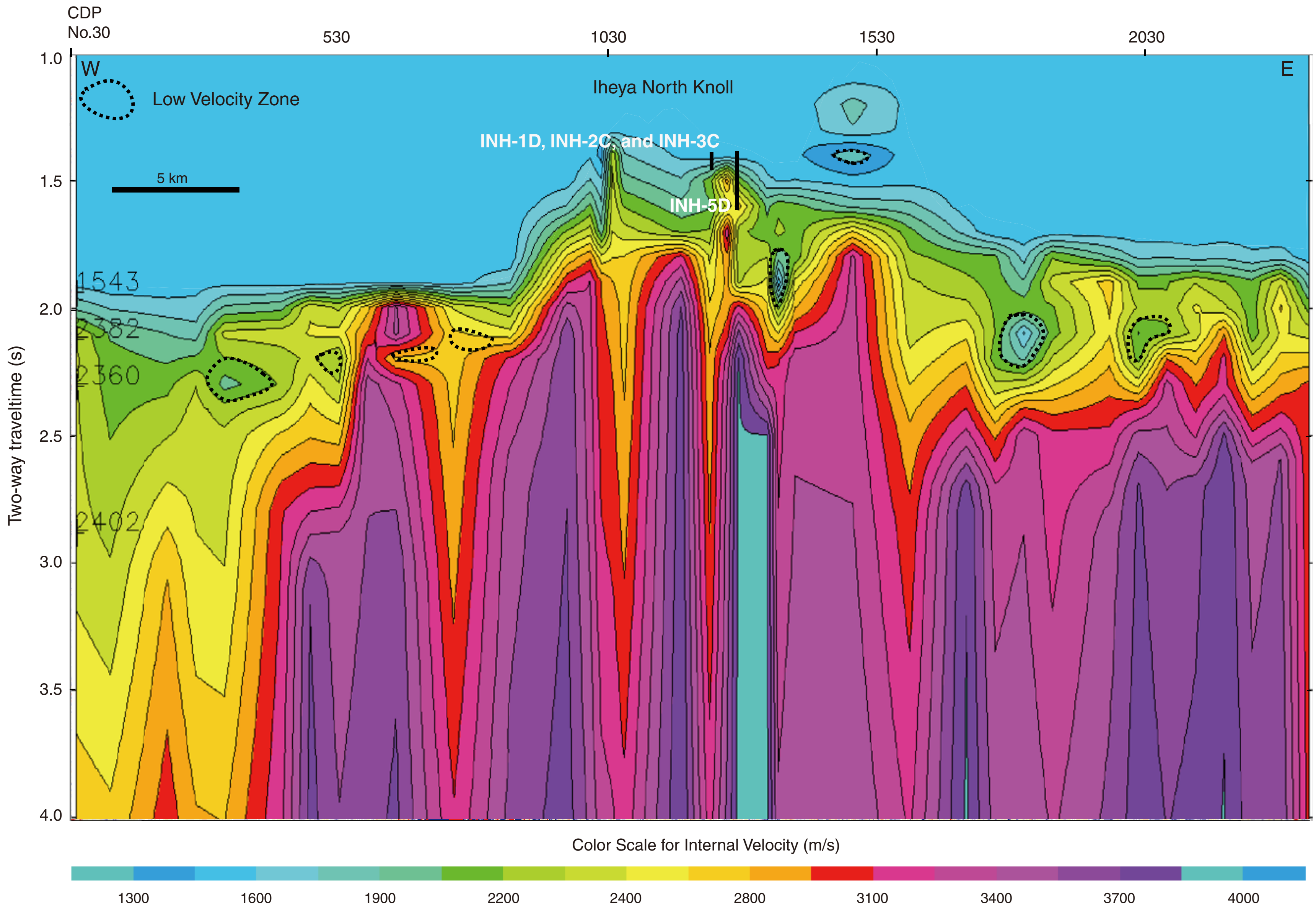


Figure F6. A-B. Thick pumicious flow deposits found in cores just below seafloor from Central Valley just north of the Iheya North Knoll, Expedition 331.

Figure F7. Gas-void blanks in pumice layers filled with elemental sulfur and sulfide deposits, Expedition 331.

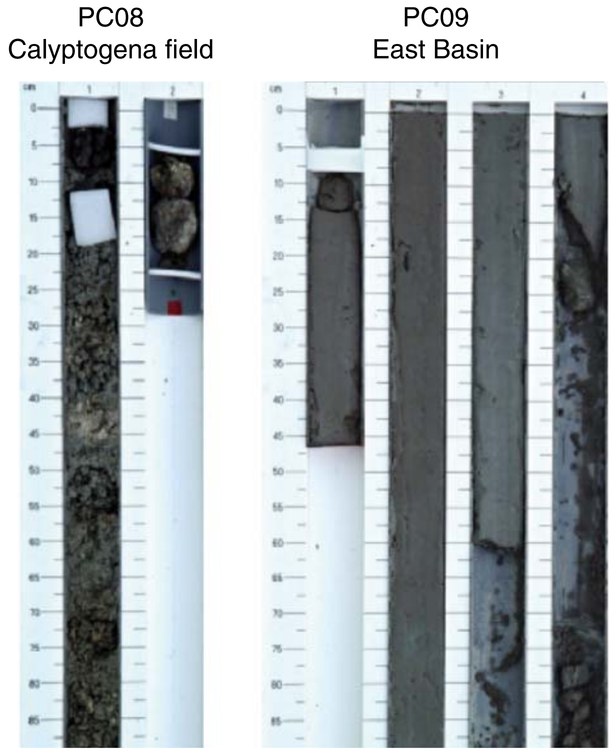


Figure F8. Drilling strategy for proposed Sites INH-1C, INH-1D, INH-2D, and INH-3D, Expedition 331.

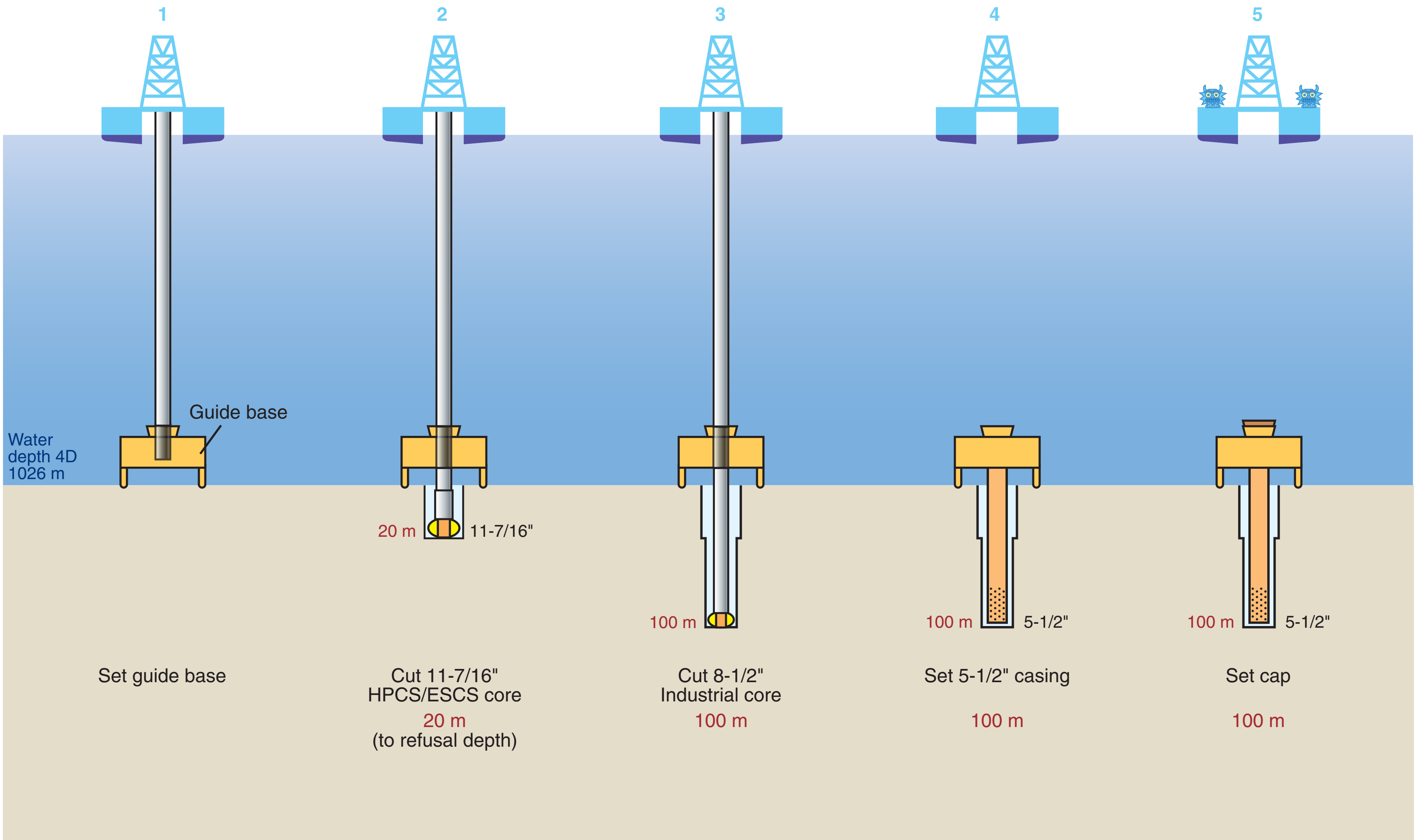
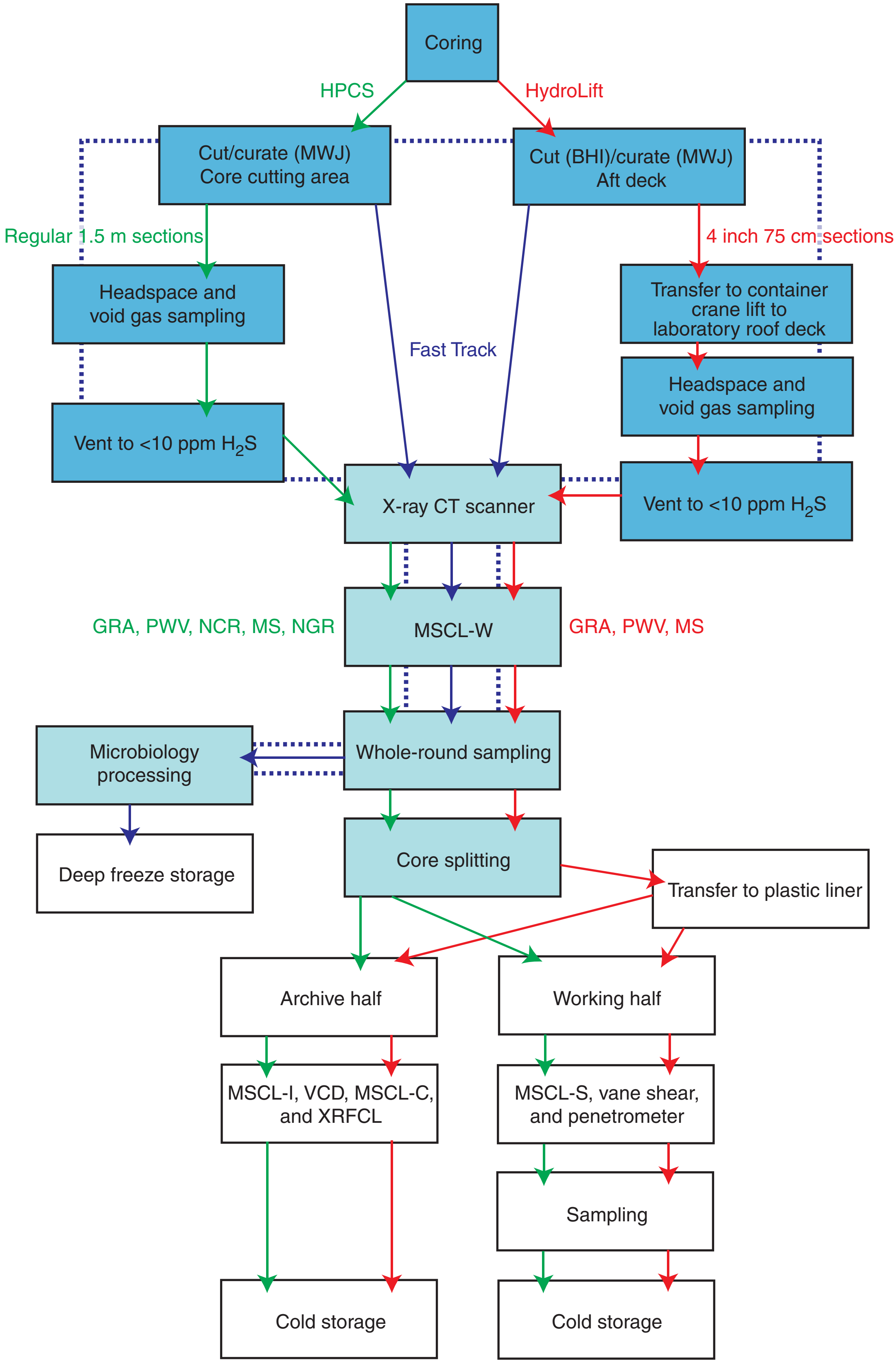


Figure F9. General core flow for Expedition 331.



Site summaries

Site INH-1D

Priority:	Primary
Position:	126°53.7979′E, 27°47.4538′N
Water depth (m):	982 m
Target drilling depth (mbsf):	50 m (basement)
Approved maximum penetration (mbsf):	50 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): MCS A-A′, SCS-F
Objective:	North Big Chimney hydrothermal mound
Drilling program:	Coring to refusal (XCB [ESCS] and RCB [MDCB])
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Hydrothermal sulfide and sulfate deposits.

Site summaries (continued)

Site INH-1C

Priority:	Alternate for INH-1D
Position:	126°53.7860′E, 27°47.4538′N
Water depth (m):	995 m
Target drilling depth (mbsf):	50 m (basement)
Approved maximum penetration (mbsf):	50 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): MCS A-A′, SCS-F
Objective:	North Big Chimney hydrothermal mound
Drilling program:	Coring to refusal (XCB [ESCS] and RCB [MDCB])
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Hydrothermal sulfide and sulfate deposits.

Site summaries (continued)

Site INH-2C

Priority:	Secondary
Position:	126°53.7718′E, 27°47.4981′N
Water depth (m):	982 m
Target drilling depth (mbsf):	50 m (basement)
Approved maximum penetration (mbsf):	50 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): MCS A-A′, SCS-F
Objective:	North Edge Chimney hydrothermal mound
Drilling program:	Coring to refusal (XCB [ESCS] and RCB [MDCB])
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Hydrothermal sulfide and sulfate deposits.

Site summaries (continued)

Site INH-3C

Priority:	Secondary
Position:	126°53.7900′E, 27°47.4020′N
Water depth (m):	1003 m
Target drilling depth (mbsf):	50 m (basement)
Approved maximum penetration (mbsf):	50 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): MCS A-A′, SCS-F
Objective:	South Big Chimney hydrothermal mound
Drilling program:	Coring to refusal (XCB [ESCS] and RCB [MDCB])
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Hydrothermal sulfide and sulfate deposits.

Site summaries (continued)

Site INH-4D

Priority:	Primary
Position:	126°53.8533′E, 27°47.4211′N
Water depth (m):	1026 m
Target drilling depth (mbsf):	100 m (50 m sediments and 50 m basement)
Approved maximum penetration (mbsf):	100 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): SCS-F, SCS-F2, MCS-F
Objective:	Local discharge-recharge zone
Drilling program:	APC or HPCS coring to refusal, then use XCB (ESCS) or RCB (MDCB)
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Sediments: Pelagic sediments and pumicious flow deposits with hydrothermal alteration. Basement: Igneous rocks and hydrothermal sulfide and sulfate deposits.

Site summaries (continued)

Site INH-5D

Priority:	Primary
Position:	126°54.0454′E, 27°47.4296′N
Water depth (m):	1057 m
Target drilling depth (mbsf):	200 m (150 m sediment and 50 m basement)
Approved maximum penetration (mbsf):	350 m
Survey coverage (track map; seismic profile):	Primary line(s): MCS B-B′, MCS-18, SCS-18 Crossing line(s): SCS-F2
Objective:	Local discharge-recharge zone
Drilling program:	APC or HPCS coring to refusal, then use XCB (ESCS) or RCB (MDCB)
Logging program:	Standard IODP measurements, formation fluid sampling, borehole temperature, and pressure.
Nature of rock anticipated:	Sediments: Pelagic sediments and pumicious flow deposits with hydrothermal alteration. Basement: Igneous rocks and hydrothermal sulfide and sulfate deposits.

Expedition scientists and scientific participants

The current list of participants for Expedition 331 can be found at **www.jamstec.go.jp/chikyu/eng/Expedition/okinawa/exp331.html.**