International Ocean Discovery Program Expedition 385T Preliminary Report

Panama Basin Crustal Architecture and Deep Biosphere: Revisiting Holes 504B and 896A

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Abstract

International Ocean Discovery Program (IODP) Expedition 385T aimed to take advantage of a transit of the R/V *JOIDES Resolution* from Antofagasta, Chile, to San Diego, California (USA), to accomplish new sampling and data collection from legacy borehole observatories in Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) Holes 504B and 896A on the southern flank of the Costa Rica Rift. In addition, the US Science Support Program organized the participation of 3 Outreach Officers to evaluate the performance of the *JOIDES Resolution* Outreach Officer program as well as 2 educators and 12 undergraduate students for a shipboard "JR Academy." Our scientific objectives were to collect (1) new Formation MicroScanner logs from Hole 504B for improving lithologic interpretations of crustal architecture at this archetype deep oceanic crust hole and (2) fluid samples from both holes for evaluating the crustal deep biosphere in deep and warm oceanic crust. These operations in Holes 504B and 896A have direct relevance to Challenges 5, 6, 9, 10, 13, and 14 of the IODP 2013–2023 Science Plan. Accomplishing both of these scientific objectives required the removal of old wireline CORK observatories, including associated inflatable packers that were installed in the cased boreholes in 2001. The fluid sampling plan also included testing a new Multi-Temperature Fluid Sampler. Despite successfully removing the CORK wellhead platforms from both holes, we were unable to remove the packers stuck in casing at both locations after 48 h of milling operations in Hole 504B and 2 h of milling operations in Hole 896A, thus precluding accomplishing any of the scientific objectives of the expedition. We provide an assessment of the final state of the holes and recommendations for possible future operations.

Background

Hydrothermal circulation in fast- to intermediate-spreading upper oceanic crust impacts the transport of heat from Earth's interior and global elemental cycling. Our understanding of these processes stem in large part from coring and logging operations in a handful of archetype reference holes drilled over several decades, including Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP) Hole 504B, ODP/Integrated Ocean Drilling Program/International Ocean Discovery Program (IODP) Hole 1256D, and Integrated Ocean Drilling Program Holes U1301A, U1301B, U1362A, and U1362B in the Pacific Ocean. Borehole observatories installed in some of these holes and in other ocean crust locations have been critical for determining fluid flow properties, chemical cycling, and microbiological impacts in the subseafloor biosphere. Revisiting such reference holes to advance our knowledge of upper oceanic crust processes with application of more advanced tools is a cost-effective leveraging of these important legacy sites. The objective of Expedition 385T was to revisit two legacy holes on the Costa Rica Rift flank, Hole 504B and ODP Hole 896A (Figure **F1**; Table **T1**), to further the understanding of the link among mid-ocean ridge to off-axis volcanic crust construction and hydrological, geochemical, and microbiological processes. This expedition was based on two Ancillary Project Letters (APLs): 769-APL2 (Revealing the in situ crustal architecture in DSDP/ODP Hole 504B) and 921-APL (Restoring and sampling ODP Hole 896A for linked crustal, fluid, and biosphere studies).

Motivation for examining the in situ crustal architecture in Holes 504B and 896A

Hole 504B, located on 5.9 Ma crust south of the Costa Rica Rift in the eastern equatorial Pacific (Figure **F1**), is one of the best-studied holes in the history of ocean drilling and has been a "reference site" for intermediate-spreading upper ocean crust (Becker, 1989; Wheat et al., 1996; Dilek, 1998; Fisher, 1998; Alt and Teagle, 1999; Furnes and Staudigel, 1999; Schouten and Denham, 2000; Chan et al., 2002; Bach and Edwards, 2003; Johnson and Pruis, 2003; Peucker-Ehrenbrink et al., 2003; Alt and Bach, 2004; Bach et al., 2004). Results from Hole 504B revealed important information on hydrology and chemical flux in the upper ocean lithosphere, including heat flow, alteration petrology, and hydrothermal geochemistry and their implications on the deep biosphere. These results also revealed information on the geophysical characteristics of the upper ocean crust, including magnetic and physical properties and seismic expression.

Although the core-based downhole lithostratigraphy plays a key role in understanding the evolution of both axial and off-axis hydrothermal alteration, it has been a great challenge to derive a reliable downhole stratigraphy model of any drilled upper crustal section because of low core recovery rates (typically <30%). The core recovery rates during a series of drilling expeditions in Hole 504B was no exception, and currently available Hole 504B downhole lithostratigraphy may be highly erroneous because of (1) biased recovery of rock, fractures, and alteration types (e.g., loss of highly altered breccia materials and fracture fillings); (2) uncertainty of the in situ location of recovered core pieces; and/or (3) inconsistent core description criteria on board between several cruises. Consequently, critical elements can be missing in understanding the crustal accretion process, crustal hydrogeology, crustal alteration processes, and changes in physical properties in ocean crust represented by the Hole 504B crust.

Integrating high-quality wireline logging and recovered core data has been proven to provide an important compliment to shipboard lithostratigraphic records, which is the case for archetype crustal reference Hole 1256D in superfast-spreading 15 Ma crust on the Cocos plate (Tominaga et al., 2009). From the Hole 1256D logging data, quasi-2-D resistivity contrast images of the borehole wall, the so-called electrofacies acquired by Formation MicroScanner (FMS) logging runs, were found particularly useful in deciphering the detailed crustal architecture with unprecedented resolution (i.e., centimeter scale). A volcanostratigraphy model was built by translating these FMS electrofacies into end-member lava flow types observed in the modern day East Pacific Rise. The stratigraphy model provides the structure of downhole permeability and sheds new light on crustal construction processes (Tominaga et al., 2009; Tominaga and Umino, 2010). Hole 1256D logging analyses demonstrate that unrecovered intervals in drilled basement are permeable structures such as highly fractured sections and breccias. FMS logging in Hole 1256D revealed that nearly 50% of the in situ architecture is composed of these lithologies; most of them were not recovered and hence were never recognized in the shipboard lithostratigraphy. This discrepancy between shipboard lithostratigraphy and FMS logging results makes it clear that a shipboard lithostratigraphy in a drilled hole with very low core recovery rates can lead to erroneous conclusions in critical elements for understanding of the evolution of the oceanic crust and the mechanism of global chemical fluxes.

Core-based lithostratigraphy indicates that the crustal architecture in Hole 504B includes a 274.5 m pelagic sediment section (cased), a 571.5 m volcanic section, a 209 m extrusive–intrusive transition zone, and a 1056 m sheeted dike complex. A full suite of wireline logging operations was conducted during the last visit to this site in 1993 (Ayadi et al., 1996, 1998a, 1998b). Although FMS logging was used to characterize physical and electrical properties in Hole 504B (Pezard et al., 1996), the existing FMS data have only 15% lateral coverage at best because only one FMS run was made and one of the four pads failed at the beginning of the logging operation (Figure **F2**). The overall quality of the existing FMS logging data only provides piecemeal intervals of lithofacies imagery and therefore little detailed crustal architectural resolution. Likewise, the collection of new FMS logs from nearby Hole 896A allows assessment of the lateral extension of lithostratigraphic units in upper ocean crust in this archetype intermediate-spreading crust. Moreover, additional FMS logs also enable comparison of the in situ crustal architecture to interpretations of fluid flow units in Hole 896A from prior temperature and resistivity logging (Figure **F3**), which are inferred to connect with various lithostratigraphic units (Becker et al., 2004; Haggas et al., 2002).

With the collection of more accurate downhole lithostratigraphy by multiple FMS logging runs in Hole 504B, we aimed to test fundamental hypotheses integral to priorities established in the IODP Science Plan in Challenge 9 (How are seafloor spreading and mantle melting linked to ocean crustal architecture?) and Challenge 10 (What are the mechanism, magnitude, and history of chemical exchanges between the oceanic crust and seawater?).

Motivation for fluid sampling to examine the crustal deep biosphere in Holes 504B and 896A

The best-characterized subsurface crustal deep biosphere is located on the Juan de Fuca Ridge flank (Edwards et al., 2012; Orcutt and Edwards, 2014; Ramírez et al., 2019). Over a decade of research at this site has demonstrated a dynamic and active archaeal, bacterial, and viral biosphere residing in fluids and on rock surfaces in this ridge flank crustal habitat (Cowen et al., 2003; Orcutt et al., 2011; Smith et al., 2011, 2016; Jungbluth et al., 2013, 2014, 2016, 2017; Lin et al., 2014; Robador et al., 2015, 2016; Baquiran et al., 2016; Nigro et al., 2017; Carr et al., 2019; Ramírez et al., 2019). Although fluid chemistry in this buried ridge flank system has varied little over time and space (Wheat et al., 2010; Lin et al., 2014), repeated sampling has revealed dynamic changes in microbial community structures. The parameters that drive this diversity are unknown.

Hole 896A on the Costa Rica Rift flank near Hole 504B (Figure **F1**), originally drilled in 1993 at ODP Site 678 (Shipboard Scientific Party, 1993), represents a unique parallel ridge flank environment for comparison to the Juan de Fuca Ridge flank (Table **T2**). Both sites are located on buried basement highs with inferred fluid flow on the order of hundreds of liters per hour (Becker et al., 2004), and both sites are characterized by pillow and sheet-flow plagioclase-olivine phyric basalts with alteration products (i.e., saponite and celadonite vein filling) that indicate complex hydrothermal evolution of crustal systems (Alt et al., 1996; Hunter et al., 1999). These sediment-covered basalt ridge systems experience similar upper basement fluid conditions (Table **T2**). Hole 896A has an undefined fluid circulation pathway in the upper crust compared with the Juan de Fuca Ridge flank, where fluid flow between basement outcrops on the ridge flank is well constrained (Fisher et al., 2014; Neira et al., 2016). However, both Hole 896A and the boreholes on the Juan de Fuca Ridge freely discharge formation fluid when the boreholes are open to the seafloor.

Although the Juan de Fuca Ridge flank has been sampled extensively, only one sample has ever been collected for deep biosphere analysis from Hole 896A (Becker et al., 2004; Nigro et al., 2012). In 2001, a wireline system with a camera documented substantial quantities of flocculent material in open basement deeper than 230 meters below seafloor (mbsf) (Figure **F3**). After this inspection, a wireline CORK was deployed in the hole. Fifteen months later, a submersible dive to the site collected biofilms on the borehole structure that was exposed to discharging formation fluids and bottom currents. Analysis of this sample revealed the presence of biofilm-forming microbial species such as the Gammaproteobacteria *Thiomicrospira*. This community was different from the communities observed in the Juan de Fuca Ridge flank environment (Table **T2**). It is important to note, however, that the biofilm samples previously collected from Hole 896A were collected above the sediment/water interface and represent a mixture of seawater-influenced fluids. Pristine borehole fluids or biofilms have yet to be recovered from Hole 896A. Thus, a major motivation for fluid sampling in Hole 896A is to collect pristine crustal fluids from various depths in the borehole (representing different temperatures [Figure **F3**] that span the ~64°C temperature range of fluids of the comparison site on the Juan de Fuca Ridge flank) to examine fluid chemistry, microbial biomass density, and microbial community composition and function. Collection of these samples would generate data relevant to IODP Science Plan Challenge 5 (What are the origin, composition, and global significance of subseafloor communities?).

Likewise, determining the temperature limits of the subsurface deep biosphere is a major aim of the scientific ocean drilling community (Challenge 6: what are the limits of life in the subseafloor?). Recently, IODP Expedition 370 sought to characterize the thermal limits of life in the organic-rich sediment deep biosphere (Heuer et al., 2017), but this drilling program did not cross the currently known temperature limit of life at 122°C (Kashefi and Lovley, 2003). Recent studies from Expedition 370 suggest a lower temperature of life in the subsurface, where other factors, such as nutrient availability, may depress the temperature of life (Heuer et al., 2017). Thus, Hole 504B, which reaches an estimated bottom-hole temperature of ~180°–190°C at ~2000 mbsf (Figure **F4**; Guerin et al., 1996), is an ideal setting to test fundamental hypotheses about thermal limits of life. Moreover, a repeat temperature log in Hole 504B is scientifically important in terms of verifying a no-downhole-flow condition and potentially shedding new light on the depth variation of heat flow after ~10 y of hole sealing and would generate data relevant to IODP Science Plan Challenge 14 (How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?).

Currently, the Kuster water sampling tool is the only water sampling device in the R/V *JOIDES Resolution* downhole tool portfolio that can operate at high temperatures (i.e., it is a mechanical tool with no electronics), allowing one ~600 mL fluid sample to be collected per run on the coring line. To improve the ability to collect larger volume and more frequent fluid samples, a new tool—the Multi-Temperature Fluid Sampler (MTFS)—was designed and built with funding from the US National Science Foundation (NSF) (award OC-1830087 to C. Geoff Wheat and collaborators). A technical objective of this expedition was to test the performance of this tool in furtherance of the science objectives in Hole 504B.

Scientific objectives

Determining in situ crustal architecture

Our primary crustal architecture hypothesis is that hydrothermal alteration and mineralization style are spreading-rate dependent (e.g., Hole 504B versus Hole 1256D). We aimed to test this through the following objectives:

- Improve current Hole 504B shipboard lithostratigraphy through collection of multiple FMS logs to reveal hydrogeologically important sections from which core samples were not recovered but are expected to be highly fractured and brecciated sections,
- Compare the improved FMS-based lithostratigraphy record from Hole 504B with Hole 1256D records to determine whether alteration styles and intensities correlate with differences in their volcanic architecture,
- Examine whether a new FMS-based lithostratigraphy model changes estimates of global chemical flux from rock-water reactions (e.g., the estimation of CO_2 uptake by hydrothermal alteration in upper ocean crust), and
- Determine whether fluid flow in upper oceanic crust correlates with crustal architecture by collecting additional FMS logs in Hole 896A for complementing previously assessed core-log integration based lithostratigraphy and comparing to earlier temperature and resistivity interpretations of flow units.

Documenting crustal fluid deep biosphere biogeography

Our primary crustal deep biosphere hypothesis is that microbial community structure and functional potential in upper basaltic basement is primarily influenced by fluid geochemical and thermal conditions (i.e., the same species are found everywhere, and the environment selects for them to be dominant). We aimed to examine this hypothesis with the following objectives:

- Collect pristine crustal fluid samples and temperature records from multiple depths (temperatures) in Hole 896A for microbiological and geochemical analysis and
- Compare Hole 896A crustal fluid microbiology and geochemistry with conditions at the Juan de Fuca Ridge flank sites.

A secondary crustal deep biosphere hypothesis we aimed to examine is that no microbial life exists above the currently known temperature limit for life (122°C). We aimed to examine this hypothesis through the collection of pristine crustal fluid samples and temperature records in Hole 504B for microbiological and geochemical analyses with samples collected below, at, and above the known thermal limit of life.

Principal results

Background and objectives

Expedition 385T aimed to revisit two DSDP and ODP legacy sites—Holes 504B and 896A on the Costa Rica Rift flank—to advance lithostratigraphic, hydrogeological, and deep biosphere studies of upper oceanic crust. Hole 504B has served as a standard reference site for upper oceanic crust for decades despite low core recovery during drilling operations and incomplete understanding of downhole lithostratigraphy. Hole 896A serves as an analog site of crustal alteration for examining biogeography in the crustal deep biosphere, and fluid sampling in Hole 504B would allow for examination of the thermal limits of life in deep oceanic crust. We aimed to advance lithostratigraphic records of in situ crustal architecture through FMS logging, with priority for these operations in Hole 504B. The new logs from Hole 504B would reveal whether unrecovered intervals are highly fractured and/or brecciated and whether alteration style and intensity are correlated to volcanic architecture, which would allow for assessment of the hypothesis that hydrothermal alteration and mineralization style are spreading-rate dependent. We also aimed to advance crustal hydrogeological and deep biosphere research through temperature logging and water sampling in both holes, with priority for these operations in Hole 896A. The new FMS-based lithostratigraphy coupled with new fluid assessment would also allow for improvements on the thermal limits of microbial life and seawater-basalt reactions. These operations in Holes 504B and 896A would have direct relevance to Challenges 5, 6, 9, 10, 13, and 14 of the IODP 2013–2023 Science Plan. To achieve these data and sample recoveries from these legacy sites, existing wireline observatories installed in both holes would need to be removed. The preexpedition plan was to conduct these operations as an abbreviated (10 operational days) expedition with no new coring.

Our primary crustal architecture hypothesis is that hydrothermal alteration and mineralization style are spreading-rate dependent (e.g., Hole 504B versus Hole 1256D). We aimed to test this through the following objectives:

- Improve current Hole 504B shipboard lithostratigraphy through collection of multiple FMS logs to reveal sections that were not recovered but are expected to be highly fractured and brecciated,
- Compare the improved FMS-based lithostratigraphy record from Hole 504B with Hole 1256D records to determine whether alteration styles and intensities correlate with differences in the volcanic architecture of the oceanic crust,
- Examine whether a new FMS-based lithostratigraphy model changes estimates of global chemical flux from rock-water reactions (e.g., the estimation of CO_2 uptake by hydrothermal alteration in upper ocean crust), and
- Determine whether fluid flow in upper oceanic crust correlates with lithostratigraphy by collecting additional FMS logs in Hole 896A for complementing previously assessed core-log integration based lithostratigraphy and comparing to earlier temperature and resistivity interpretations of flow units.

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Operations

All times reported in this section are in ship local time. Local time was set as follows:

- UTC – 4 h from 18 August 2019 to 1400 h on 22 August,
- UTC – 5 h from 1300 h on 22 August to 0200 h on 9 September,
- UTC – 6 h from 0100 h on 9 September to 1400 h on 13 September, and
- UTC −7 h from 1300 h on 13 September to 16 September.

After a delay in departure from Antofagasta, Chile, due to customs clearance, the ship completed the 1724 nmi transit to Hole 896A in 5.75 days at an average speed of 12.5 kt, arriving at 1254 h on 25 August 2019. During transit, the science party and *JOIDES Resolution* Science Operator (JRSO) technical staff prepared the new MTFS (Figure **F5**), the Elevated Temperature Borehole Sonde (ETBS), and two Kuster fluid sampling tools.

To conduct temperature measurements and fluid sampling in Holes 504B and 896A, we first had to remove the legacy CORKs installed during the ODP phase. The first bottom-hole assembly (BHA) was made up and deployed with an overshot tool, followed by deployment of the subsea camera system. With the drill pipe just above the seafloor at 3461 meters below rig floor (mbrf), the Hole 896A reentry system and wireline CORK frame were quickly located and surveyed before we moved 0.75 nmi to Hole 504B in dynamic positioning (DP) mode with the subsea camera deployed.

We arrived at the location of Hole 504B at 0245 h on 26 August. During the subsequent 4 h, we attempted to capture the short pipe sticking up from the wireline CORK frame with a 6.625 inch diameter overshot tool (Figure **F6A**). After three unsuccessful attempts to engage, we decided to recover the drill string. The overshot tool was removed, and a three-pronged "fishing" spear, which was fabricated by JRSO staff for this specific purpose as a backup tool, was attached to the BHA. At 1300 h, deployment of the drill string began while the ship moved back to Hole 896A in DP mode. The spear successfully penetrated into the CORK frame at 2215 h (Figure **F6B**). We pulled the spear with the Hole 896A CORK frame out of the hole, and to find out how much of the CORK cabling with packers we pulled out of the hole along with the CORK frame, we attempted to lay it all out on the seafloor. A brief investigation of the seafloor did not reveal either the packer or the lead-in package, although some of the cabling was visible. Because the next step was to move over to Hole 504B and remove the wireline CORK there, three attempts were made to release the Hole 896A CORK frame from the spear on the seafloor, but the CORK frame remained firmly attached to the fishing spear. At 0300 h on 27 August, we started to retrieve the drill string with the CORK frame attached (Figure **F6C**), and it arrived on deck at 0955 h. Portions of the CORK frame had to be cut away to remove the fishing spear. The rig crew removed the old data logger canisters from the frame, which had all flooded.

At 1100 h, we began to lower the drill string with the spear back to the seafloor to recover the Hole 504B wireline CORK while the vessel moved to Hole 504B in DP mode. The CORK frame was quickly engaged at 1905 h. Given our lack of success in getting a visual on the seafloor of the elements below the Hole 896A CORK frame, we decided to pull this CORK frame directly to the rig floor after offsetting to prevent anything falling back into the hole. The spear arrived on deck at 0400 h on 28 August with one bent barb and without the Hole 504B CORK frame, which must have fallen to the seafloor after the subsea camera was retrieved.

Operating under the assumption that the Hole 504B wireline CORK had been successfully removed from the hole, we decided to proceed with the logging and hydrogeologic objectives of the expedition. A logging BHA was deployed to allow deployment of fluid sampling and temperature measurement tools with the coring line and the FMS tool with the wireline logging line. An initial seafloor survey did not locate the lost CORK frame from Hole 504B. We reentered Hole 504B at 1815 h and soon tagged an obstacle at 19 mbsf, which was the expected depth of the top packer that was deployed in 2001 (Figure **F7**). We were not able to push the packer downhole with the logging BHA, so we pulled out of the hole, clearing the seafloor at 1905 h. We then moved over to Hole 896A in DP mode and reentered Hole 896A at 2130 h. As in the previous hole, we tagged an obstacle at 57 mbsf that was presumed to be a stuck packer (Figure **F8**). Because we were able to push the packer only ~9 m downhole in 0.5 h with 10,000 lb of force, we decided that a milling job was needed and retrieved the drill string.

A new BHA was made up with additional drill collars and a milling bit to remove the packers left in both holes. At 0800 h on 29 August, we began lowering the drill pipe while moving the vessel to Hole 504B in DP mode. After deploying the subsea camera and installing the top drive, we reentered Hole 504B for the second time at 1550 h. The packer was again encountered at 19 mbsf. After recovering the subsea camera, we milled and worked the junk baskets with a maximum weight of 20,000 lb and pumped sweeps of high-viscosity mud to remove the debris. At 0630 h on 30 August, with the milling bit at 70 mbsf and a lack of advance for several hours, we pulled out of the hole after lowering the subsea camera.

We thought it was prudent to have a try in Hole 896A while the milling BHA was in place. We moved over to Hole 896A in DP mode to see if the packer in that hole could be milled and pushed down more easily. We located Hole 896A and reentered it for the second time at 1252 h. The packer was tagged at 66 mbsf. After retrieving the subsea camera, we milled with as much as 20,000 lb of weight on the packer, which slid from 72 to 88 mbsf. We continued to mill until 1700 h when we reached 95 mbsf with a diminishing rate of advance. With ~15 h of time on the mill, we decided it was time to retrieve and inspect the milling bit and junk baskets. We retrieved the drill string while moving the vessel to Hole 504B in DP mode. The milling bit arrived at the rig floor at 0005 h on 31 August with an estimated 95% of the tungsten carbide missing from the mill's face (Figure **F9**). The junk baskets were emptied, and ~35 lb of packer debris was removed from the two boot-type junk baskets. The debris consisted of a mixture of the Swagelok connectors from the top of the packers, steel baffling slats, rubber, and copper threads from the cabling, presumably mostly from Hole 504B (Figure **F9**).

We made up and deployed a new milling bit assembly and reentered Hole 504B for the third time at 1042 h. After installing the top drive and retrieving the subsea camera, we tagged the packer at 70 mbsf and began milling, pumping 25 bbl mud sweeps and applying a maximum weight of 22,000 lb. At 2330 h, we had advanced to 110 mbsf and decided to retrieve the drill string because of the diminishing advance, and the bit arrived on deck at 0615 h on 1 September. The junk baskets were disassembled, emptied, and cleaned, yielding ~34 lb of metal debris mostly made up of steel baffling slats that were part of the central packer.

We made up and deployed the third milling bit assembly and reentered Hole 504B for the fourth time at 1537 h. Milling resumed from 110 mbsf, and at 0200 h on 2 September, the bit had advanced to 134 mbsf in the casing. With ~8 h on the bit, we retrieved the drill string, and the bit cleared the rig floor at 0900 h. The junk baskets were disassembled, emptied, and cleaned, again yielding ~35 lb of packer debris mostly made up of steel slats.

We made up and deployed the fourth milling bit assembly, this time with an additional stand of drill collars for additional weight instead of the junk baskets, and Hole 504B was reentered for the fifth time at 2042 h. Milling resumed from 133 mbsf. Rotation was stopped several times, and additional weight (as much as 40,000 lb) was applied in an effort to move the packer down the casing. At 1200 h on 3 September, we had advanced to 141 mbsf. With ~13 h on the bit, we retrieved the drill string, and the milling bit cleared the rig floor at 1910 h. The bit face showed severe wear with three concentric patterns thought to be caused by the packer's lower end cap (1.5 inch central hole), remains of its casing (4.75–5.75 inch ring groove), and metal debris outside the bit (honed edge).

At this point, obtaining downhole temperature measurements, fluid samples, or FMS logs had become impossible in the remaining time. The only goal left was to keep trying to open Hole 504B for potential future use. We made up and deployed the fifth milling bit, this time again with the junk baskets. At 2015 h, we began to lower the drill string to the seafloor, and we deployed the subsea camera at 0200 h on 4 September. As the camera was lowered, a shorted circuit in the camera system's slip ring prevented it from being powered, and the camera was retrieved. The milling bit was deployed to 3425 mbrf, and the top drive was installed in anticipation of a successful and timely camera system repair. At 1245 h, we determined that the camera could not be repaired in time to allow for reentry into Hole 504B and continue milling operations. The rig crew started performing rig maintenance and breaking down the 5.5 inch drill pipe stands for storing on board and offloading in port for inspection. The rig floor was secured for the transit to San Diego, California, which began at 1318 h on 5 September.

In summary, we spent 48 h actively milling the packer in Hole 504B plus associated pipe trips for the five milling runs and succeeded in removing a significant amount of packer material, 104 lb of which was captured in the BHA junk baskets, and pushing the packer from 19 to 141 mbsf (Figures **F7**, **F9**). Likewise, we spent 2 h on the same activities in Hole 896A and managed to move the packer from 57 to 95 mbsf (Figure **F8**).

Principal scientific results

To achieve the science objectives, the Expedition 385T operational plan required removing previously installed wireline CORKs from Holes 504B and 896A, ensuring open hole conditions while collecting fluid samples and temperature logs, and conditioning the hole for logging with the FMS logging tool. The challenge to remove the wireline CORK packers and related cables from inside the casing in Holes 504B and 896A was a significant operational hurdle that could not be overcome during the expedition and thus prevented the collection of any samples or data. Operations in Holes 504B and 896A were concluded without accomplishing any of the scientific objectives of Expedition 385T.

Preliminary scientific assessment

The Expedition 385T operational plan required removing previously installed wireline CORKs from Holes 504B and 896A to accomplish our scientific objectives. The challenge to remove the wireline CORK packers and related cables from casing in Holes 504B and 896A was a significant operational hurdle that could not be overcome during the expedition (Table **T3**) and thus prevented any sample or data collection activities. Operations in Holes 504B and 896A were concluded without accomplishing any of the scientific objectives of the expedition. We estimate that part of the upper packer in Hole 504B remains stuck at ~141 mbsf (Figure **F7**) despite removing at least 104 lb of packer during a total of 48 h of milling operations, and it is unknown if the lower lead-in package with packer also remains stuck at the presumed deployment depth or fell deeper into the hole. Likewise, we estimate that most of the upper packer in Hole 896A remains stuck at 95 mbsf (Figure **F8**). If future attempts are made to try to reenter these holes, we recommend budgeting several days for milling and including more junk baskets on each milling run.

Education and outreach

Outreach team

Expedition 385T had a team of three Outreach Officers on board *JOIDES Resolution*, including one Outreach Manager for the US Science Support Program (USSSP) from New York, one formal educator from Hawaii, and one science communicator from California. The Outreach team took advantage of berth availability; their primary objective was to analyze the status of the Onboard Outreach Program under NSF's revised Memorandum of Understanding (MOU).

The Outreach team's assessment is based on (1) dialogue with the Expedition 385T science party, (2) an examination of JRSO education and outreach evaluations from previous expeditions, and (3) an analysis of the *JOIDES Resolution* social media accounts, including insights for the development of a social media strategy and content plan for the Onboard Outreach position and USSSP-managed social media accounts as a whole. The Outreach team will make this assessment publicly accessible after review. Furthermore, the formal educator of the Outreach team will use the qualitative metrics from evaluations and surveys from JRSO and the USSSP office as part of her doctoral thesis project, which will continue post-expedition. The expected outcome from this project will include guidelines and expectations for the Outreach Officers.

In addition to the program assessment, the Outreach team also assisted the JR Academy students' science communication coursework. The students were divided into three groups focusing on different methods of science communication: ship-to-shore broadcasts, video editing, and 2-D illustration (see **JR Academy**). The Outreach team also led a number of seminars on visual communication techniques to improve clarifying messaging and identifying the audience for conference posters and presentations, including a 2-D poster design, publication-ready scientific illustrations, and resources for selecting a target audience and conveying a science message appropriate for that audience.

The Outreach team also conducted the typical duties for outreach officers during a *JOIDES Resolution* expedition, including communicating the goals of the expedition to students and the general public through broadcasts (led by the JR Academy students), social media posts, and blogs via **http://joidesresolution.org**. The Outreach team maintained four social media platforms during the expedition, Facebook, Twitter, Instagram, and a web page on the *JOIDES Resolution* website, each of which focused on the JR Academy experience, the importance of science communication, and the diversity of career pathways into the geosciences. In total, three ship-to-shore broadcasts took place as part of the JR Academy science communication projects.

Finally, the science communicator from the Outreach team completed a first draft of a book on the history of IODP specific to Hole 504B. This product will be provided as an introductory companion piece published by USSSP about ocean drilling research and challenges. Postexpedition, the book draft will be reviewed by the science party and the Education and Outreach subcommittee of the US Advisory Committee for Scientific Ocean Drilling (USAC).

JR Academy

The goal of the JR Academy during Expedition 385T was to utilize available berths and the relatively short expedition time (~1 month) as an opportunity to introduce undergraduate students from diverse backgrounds to IODP-relevant science programs. The JR Academy had two instructors, professors from Whatcom Community College (Bellingham, Washington) and Ursinus College (Collegeville, Pennsylvania). Twelve undergraduate students were selected to participate from across the United States through a competitive application process. The students were eligible to receive as many as 10 (potentially transferable) course credits through Whatcom Community College upon successful completion of two of the following courses: GEOL 100 Introduction to Earth Science, OCEA& 101 Introduction to Oceanography, and/or a learning contract in OCEA 289E Marine Geology with Concentration in Ocean Processes or OCEA 289E Marine Geology with Concentration in Geologic Processes.

JR Academy classes met formally for 6 h a day, 7 days a week, with an occasional required evening activity or late start. During the expedition, students were exposed to many shipboard resources, including interactions with the shipboard science party, JRSO staff, vessel and drilling operations personnel, and the Outreach team. A significant part of the JR Academy learning experience was for the students to engage and develop a research question to investigate, learn strategies to navigate the literature, and apply methods and equipment available on *JOIDES Resolution*. The student projects included investigations of petrological, sedimentological, ocean water, and magnetic and physical properties of samples or data. The JRSO technicians supported the work of the students in the laboratories by helping the students with the equipment and providing expertise. The students also received feedback from other shipboard scientists and staff members. Each of the 12 students completed their research project and presented it at a shipboard poster session at the end of the expedition to which all shipboard personnel was invited. More than 30 people attended, including all of the shipboard scientists, JRSO technical staff, the captain, and a number of ship crew members.

To learn science communication skills, the JR Academy students worked closely with the Outreach team through team and individual projects. The final projects included the creation of a ~5 min video about *JOIDES Resolution*, three ship-to-shore broadcasts, and several 2-D design products, including two posters and two illustrated children's books. All students wrote a blog related to science and their shipboard experience, and three students took the opportunity to work with the Outreach team to publish their blogs online.

References

Alt, J.C., and Bach, W., 2004. *Alteration of Oceanic Crust: Subsurface Rock-Water Interactions:* Berlin (Dahlem University Press).

Alt, J.C., and Teagle, D.A.H., 1999. The uptake of carbon during alteration of ocean crust. *Geochimica et Cosmochimica Acta,* 63(10):1527–1535. **https://doi.org/10.1016/S0016-7037(99)00123-4**

Alt, J.C., Teagle, D.A.H., Laverne, C., Vanko, D.A., Bach, W., Honnorez, J., Becker, K., Ayadi, M., and Pezard, P.A., 1996. Ridge-flank alteration of upper ocean crust in the eastern Pacific: synthesis of results for volcanic rocks of Holes 504B and 896A. *In* Alt, J.C., Kinoshita, H., Stokking, L.B., and Michael, P.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results,* 148: College Station, TX (Ocean Drilling Program), 435–450. **https://doi.org/10.2973/odp.proc.sr.148.150.1996**

Ayadi, M., Pezard, P.A., Bronner, G., Tartarotti, P., and Laverne, C., 1998a. Multi-scalar structure at DSDP/ODP Site 504, Costa Rica Rift, III: faulting and fluid circulation. Constraints from integration of FMS images, geophysical logs and core data. *Geological Society Special Publication,* 136:311–326. **https://doi.org/10.1144/GSL.SP.1998.136.01.26**

Ayadi, M., Pezard, P.A., Laverne, C., and Bronner, G., 1998b. Multi-scalar structure at DSDP/ODP Site 504, Costa Rica Rift, I: stratigraphy of eruptive products and accretion processes. *Geological Society Special Publication,* 136:297–310. **https://doi.org/10.1144/GSL.SP.1998.136.01.25**

Ayadi, M., Pezard, P.A., and de Larouzière, F.D., 1996. Fracture distribution from downhole electrical images at the base of the sheeted dike complex in Hole 504B. *In* Alt, J.C., Kinoshita, H., Stokking, L.B., and Michael, P.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results,* 148: College Station, TX (Ocean Drilling Program), 307–315. **https://doi.org/10.2973/odp.proc.sr.148.152.1996**

Bach, W., and Edwards, K.J., 2003. Iron and sulfide oxidation within the basaltic ocean crust: implications for chemolithoautotrophic microbial biomass production. *Geochimica et Cosmochimica Acta,* 67(20):3871–3887. **https://doi.org/10.1016/S0016-7037(03)00304-1**

Bach, W., Humphris, S.E., and Fisher, A.T., 2004. Fluid flow and fluid-rock interaction within ocean crust: reconciling geochemical, geological, and geophysical observations. *In* Wilcock, W.S.D., Delong, E.F., Kelley, D.S., Baross, J.A., and Cary, C.S. (Eds.), *The Subseafloor Biosphere at Mid-Ocean Ridges.* Geophysical Monograph, 144:99–117. **https://agupubs.onlinelibrary.wiley.com/doi/10.1029/144GM07**

Baquiran, J.-P.M., Ramírez, G.A., Haddad, A.G., Toner, B.M., Hulme, S., Wheat, C.G., Edwards, J.K., and Orcutt, B.N., 2016. Temperature and redox effect on mineral colonization in Juan de Fuca Ridge flank subsurface crustal fluids. *Frontiers in Microbiology,* 7:396. **https://doi.org/10.3389/fmicb.2016.00396**

Becker, K., 1989. Measurements of the permeability of the sheeted dikes in Hole 504B, ODP Leg 111. *In* Becker, K., Sakai, H., et al., *Proceedings of the Ocean Drilling Program, Scientific Results,* 111: College Station, TX (Ocean Drilling Program), 317–325. **https://doi.org/10.2973/odp.proc.sr.111.156.1989**

Becker, K., Davis, E.E., Spiess, F.N., and de Moustier, C.P., 2004. Temperature and video logs from the upper oceanic crust, Holes 504B and 896A, Costa Rica Rift flank: implications for the permeability of upper oceanic crust. *Earth and Planetary Science Letters,* 222(3–4):881–896. **https://doi.org/10.1016/j.epsl.2004.03.033**

Carr, S.A., Jungbluth, S.P., Eloe-Fadrosh, E.A., Stepanauskas, R., Woyke, T., Rappé, M.S., and Orcutt, B.N., 2019. Carboxydotrophy potential of uncultivated Hydrothermarchaeota from the subseafloor crustal biosphere. *ISME Journal,* 13(6):1457–1468. **https://doi.org/10.1038/s41396-019-0352-9**

Chan, L.-H., Alt, J.C., and Teagle, D.A.H., 2002. Lithium and lithium isotope profiles through the upper oceanic crust: a study of seawater–basalt exchange at ODP Sites 504B and 896A. *Earth and Planetary Science Letters,* 201(1):187–201. **https://doi.org/10.1016/S0012-821X(02)00707-0**

Cowen, J.P., Giovannoni, S.J., Kenig, F., Johnson, H.P., Butterfield, D., Rappé, M.S., Hutnak, M., and Lam, P., 2003. Fluids from aging ocean crust that support microbial life. *Science,* 299(5603):120–123. **https://doi.org/10.1126/science.1075653**

Dilek, Y., 1998. Structure and tectonics of intermediate-spread oceanic crust drilled at DSDP/ODP Holes 504B and 896A, Costa Rica Rift. *Geological Society Special Publication,* 131:177–197. **https://doi.org/10.1144/GSL.SP.1998.131.01.12**

Edwards, K.J., Fisher, A.T., and Wheat, C.G., 2012. The deep subsurface biosphere in igneous ocean crust: frontier habitats for microbiological exploration. *Frontiers in Microbiology,* 3:8. **https://doi.org/10.3389/fmicb.2012.00008**

Fisher, A.T., 1998. Permeability within basaltic oceanic crust. *Reviews of Geophysics,* 36(2):143–182. **https://doi.org/10.1029/97RG02916**

Fisher, A.T., Neira, N.M., Wheat, C.G., Clark, J.F., Becker, K., Hsieh, C.C., and Rappe, M.S., 2014. A cross-hole, multi-year tracer injection experiment in the volcanic ocean crust [presented at the 2014 American Geophysical Union Fall Meeting, San Francisco, CA, 15–19 December 2014]. (Abstract OS52B-04) **http://abstractsearch.agu.org/meetings/2014/FM/OS52B-04.html**

Furnes, H., and Staudigel, H., 1999. Biological mediation in ocean crust alteration: how deep is the deep biosphere? *Earth and Planetary Science Letters,* 166(3–4):97–103. **https://doi.org/10.1016/S0012-821X(99)00005-9**

Guerin, G., Becker, K., Gable, R., and Pezard, P.A., 1996. Temperature measurements and heat-flow analysis in Hole 504B. *In* Alt, J.C., Kinoshita, H., Stokking, L.B., and Michael, P.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results,* 148: College Station, TX (Ocean Drilling Program), 291–296. **https://doi.org/10.2973/odp.proc.sr.148.141.1996**

Haggas, S.L., Brewer, T.S., and Harvey, P.K., 2002. Architecture of the volcanic layer from the Costa Rica Rift, constraints from core-log integration. *Journal of Geophysical Research: Solid Earth,* 107(B2):ECV2-1–ECV2-14. **https://doi.org/10.1029/2001JB000147**

Heuer, V.B., Inagaki, F., Morono, Y., Kubo, Y., Maeda, L., and the Expedition 370 Scientists, 2017. *Expedition 370 Preliminary Report: Temperature Limit of the Deep Biosphere off Muroto.* International Ocean Discovery Program. **https://doi.org/10.14379/iodp.pr.370.2017**

Hunter, A.G., Kempton, P.D., and Greenwood, P., 1999. Low-temperature fluid-rock interaction: an isotopic and mineralogical perspective of upper crustal evolution, eastern flank of the Juan de Fuca Ridge (JdFR), ODP Leg 168. *Chemical Geology,* 155:3–28. **https://doi.org/10.1016/S0009-2541(98)00138-7**

Johnson, H.P., and Pruis, M.J., 2003. Fluxes of fluid and heat from the oceanic crustal reservoir. *Earth and Planetary Science Letters*, 216(4):565–574. **https://doi.org/10.1016/S0012-821X(03)00545-4**

Jungbluth, S.P., Amend, J.P., and Rappé, M.S., 2017. Metagenome sequencing and 98 microbial genomes from Juan de Fuca Ridge flank subsurface fluids. *Scientific Data,* 4:170037. **https://doi.org/10.1038/sdata.2017.37**

Jungbluth, S.P., Bowers, R.M., Lin, H.-T., Cowen, J.P., and Rappé, M.S., 2016. Novel microbial assemblages inhabiting crustal fluids within mid-ocean ridge flank subsurface basalt. *ISME Journal,* 10:2033–2047. **https://doi.org/10.1038/ismej.2015.248**

Jungbluth, S.P., Grote, J., Lin, H.-T., Cowen, J.P., and Rappe, M.S., 2013. Microbial diversity within basement fluids of the sediment-buried Juan de Fuca Ridge flank. *ISME Journal,* 7(1):161–172. **https://doi.org/10.1038/ismej.2012.73**

Jungbluth, S.P., Lin, H.-T., Cowen, J.P., Glazer, B.T., and Rappé, M.S., 2014. Phylogenetic diversity of microorganisms in subseafloor crustal fluids from Holes 1025C and 1026B along the Juan de Fuca Ridge flank. *Frontiers in Microbiology,* 5:119. **https://doi.org/10.3389/fmicb.2014.00119**

Kashefi, K., and Lovley, D.R., 2003. Extending the upper temperature limit for life. *Science,* 301(5635):934. **https://doi.org/10.1126/science.1086823**

Lin, H.-T., Cowen, J.P., Olson, E.J., Lilley, M.D., Jungbluth, S.P., Wilson, S.T., and Rappé, M.S., 2014. Dissolved hydrogen and methane in the oceanic basaltic biosphere. *Earth and Planetary Science Letters,* 405:62–73. **https://doi.org/10.1016/j.epsl.2014.07.037**

Mottl, M.J., 1989. Hydrothermal convection, reaction, and diffusion in sediments on the Costa Rica rift flank: pore-water evidence from ODP Sites 677 and 678. *In* Becker, K., Sakai, H., et al., *Proceedings of the Ocean Drilling Program, Scientific Results,* 111: College Station, TX (Ocean Drilling Program), 195–213. **https://doi.org/10.2973/odp.proc.sr.111.125.1989**

Neira, N.M., Clark, J.F., Fisher, A.T., Wheat, C.G., Haymon, R.M., and Becker, K., 2016. Cross-hole tracer experiment reveals rapid fluid flow and low effective porosity in the upper oceanic crust. *Earth and Planetary Science Letters,* 450:355–365. **https://doi.org/10.1016/j.epsl.2016.06.048**

Nigro, L.M., Harris, K., Orcutt, B.N., Hyde, A., Clayton-Luce, S., Becker, K., and Teske, A., 2012. Microbial communities at the borehole observatory on the Costa Rica Rift flank (Ocean Drilling Program Hole 806A). *Frontiers in Microbiology,* 3:232. **https://doi.org/10.3389/fmicb.2012.00232**

Nigro, O.D., Jungbluth, S.P., Lin, H.-T., Hsieh, C.-C., Miranda, J.A., Schvarcz, C.R., Rappé, M.S., and Steward, G.F., 2017. Viruses in the oceanic basement. *mBio,* 8(2):e0219-16. **https://doi.org/10.1128/mBio.02129-16**

Orcutt, B.N., Bach, W., Becker, K., Fisher, A.T., Hentscher, M., Toner, B.M., Wheat, C.G., and Edwards, K.J., 2011. Colonization of subsurface microbial observatories deployed in young ocean crust. *ISME Journal,* 5(4):692–703. **https://doi.org/10.1038/ismej.2010.157**

Orcutt, B.N., and Edwards, K.J., 2014. Life in the ocean crust: lessons from subseafloor laboratories. *In* Stein, R., Blackman, D., Inagaki, F., and Larsen, H.-C., *Developments in Marine Geology* (Volume 7): *Earth and Life Processes Discovered from Subseafloor Environments: A Decade of Science Achieved by the Integrated Ocean Drilling Program (IODP).* R. Stein (Series Ed.): Amsterdam (Elsevier B.V.), 175–196. **https://doi.org/10.1016/B978-0-444-62617-2.00007-4**

Peucker-Ehrenbrink, B., Bach, W., Hart, S.R., Blusztajn, J.S., and Abbruzzese, T., 2003. Rhenium-osmium isotope systematics and platinum group element concentrations in oceanic crust from DSDP/ODP Sites 504 and 417/418. *Geochemistry, Geophysics, Geosystems,* 4(7):8911. **https://doi.org/10.1029/2002GC000414**

Pezard, P.A., Becker, K., Revil, A., Ayadi, M., and Harvey, P.K., 1996. Fractures, porosity, and stress in the dolorites of Hole 504B, Costa Rica rift. *In* Alt, J.C., Kinoshita, H., Stokking, L.B., and Michael, P.J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results,* 148: College Station, TX (Ocean Drilling Program), 317–329. **https://doi.org/10.2973/odp.proc.sr.148.137.1996**

Ramírez, G.A., Garber, A.I., Lecoeuvre, A., D'Angelo, T., Wheat, C.G., and Orcutt, B.N., 2019. Ecology of subseafloor crustal biofilms. *Frontiers in Microbiology,* 10:1983. **https://doi.org/10.3389/fmicb.2019.01983**

Robador, A., Jungbluth, S.P., LaRowe, D.E., Bowers, R.M., Rappé, M.S., Amend, J.P., and Cowen, J.P., 2015. Activity and phylogenetic diversity of sulfate-reducing microorganisms in low-temperature subsurface fluids within the upper oceanic crust. *Frontiers in Microbiology,* 5:748. **https://doi.org/10.3389/fmicb.2014.00748**

Robador, A., LaRowe, D.E., Jungbluth, S.P., Lin, H.-T., Rappé, M.S., Nealson, K.H., and Amend, J.P., 2016. Nanocalorimetric characterization of microbial activity in deep subsurface oceanic crustal fluids. *Frontiers in Microbiology,* 7:454. **https://doi.org/10.3389/fmicb.2016.00454**

Schouten, H., and Denham, C.R., 2000. Comparison of volcanic construction in the Troodos Ophiolite and oceanic crust using paleomagnetic inclinations from Cyprus Crustal Study Project (CCSP) CY-1 and CY-1A and Ocean Drilling Program (ODP) 504B drill cores. *In* Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A. (Eds.), *Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program.* Special Paper - Geological Society of America, 349:181–194. **https://doi.org/10.1130/0-8137-2349-3.181**

Shipboard Scientific Party, 1993. Site 896. *In* Alt, J.C., Kinoshita, H., Stokking, L.B., et al., *Proceedings of the Ocean Drilling Program, Initial Reports,* 148: College Station, TX (Ocean Drilling Program), 123–192. **https://doi.org/10.2973/odp.proc.ir.148.103.1993**

Smith, A., Popa, R., Fisk, M., Nielsen, M., Wheat, C.G., Jannasch, H.W., Fisher, A.T., Becker, K., Sievert, S.M., and Flores, G., 2011. In situ enrichment of ocean crust microbes on igneous minerals and glasses using an osmotic flow-through device. *Geochemistry, Geophysics, Geosystems,* 12(6):Q06007. **https://doi.org/10.1029/2010GC003424**

Smith, A.R., Fisk, M.R., Thurber, A.R., Flores, G.E., Mason, O.U., Popa, R., and Colwell, F.S., 2016. Deep crustal communities of the Juan de Fuca Ridge are governed by mineralogy. *Geomicrobiology Journal,* 34(2):147–156. **https://doi.org/10.1080/01490451.2016.1155001**

Tominaga, M., Teagle, D.A.H., Alt, J.C., and Umino, S., 2009. Determination of the volcanostratigraphy of the oceanic crust formed at superfast spreading ridge: electrofacies analyses of ODP/IODP Hole 1256D. *Geochemistry, Geophysics, Geosystems,* 10(1):Q01003. **https://doi.org/10.1029/2008GC002143**

Tominaga, M., and Umino, S., 2010. Lava deposition history in ODP Hole 1256D: insights from log-based volcanostratigraphy. *Geochemistry, Geophysics, Geosystems,* 11(5):Q05003. **https://doi.org/10.1029/2009GC002933**

Wheat, C.G., Feely, R.A., and Mottl, M.J., 1996. Phosphate removal by oceanic hydrothermal processes: an update of the phosphorus budget in the oceans. *Geochimica et Cosmochimica Acta,* 60(19):3593–3608. **https://doi.org/10.1016/0016-7037(96)00189-5**

Wheat, C.G., Jannasch, H.W., Fisher, A.T., Becker, K., Sharkey, J., and Hulme, S., 2010. Subseafloor seawater-basalt-microbe reactions: continuous sampling of borehole fluids in a ridge flank environment. *Geochemistry, Geophysics, Geosystems*, 11(7):Q07011. **https://doi.org/10.1029/2010GC003057**

Table T1. Hole information, Holes 504B and 896A.

	Hole 504B	Hole 896A
Latitude	1°13.6144′N	1°13.0187′N
Longitude	83°43.8135′W	83°43.3976′W
Water depth (m)	3463	3448

Table T2. Upper basement conditions in Hole 896A compared to Hole U1301A on the Juan de Fuca Ridge flank. Data from Mottl (1989), Wheat et al. (2010), and Nigro et al. (2012).

Condition	Hole 896A	Hole U1301A
Temperature (°C)	58	64
Calcium (mM)	51	55
Magnesium (mM)	8.5	2
Sulfate (mM)	18.5	17.7
Alkalinity (mM)	0.6	0.4
Crustal age (Ma)	6–7	3–4
Dominant bacterial groups	Proteobacteria	Firmicutes

Table T3. Overview of major scientific operations, Expedition 385T. No shading = seafloor/subseafloor scientific operations, shading = all other scientific operations. DP = dynamic positioning, BHA = bottom-hole assembly, TD = total depth, VIT = vibration isolated television. (Continued on next page.)

	Hole 896A			Activity while in DP transit			Hole 504B			
Date (2019)	Start (h)	End (h)	Activity	Start (h)	End (h)	Activity	Start (h)	End (h)	Activity	Total time (h)
25 Aug	1300	2400	Lower drill pipe with overshot tool; survey reentry system							11
26 Aug				0000	0300	Survey of reentry systems				3
							0300	0700	Unable to engage overshot	4
							0700	1200	Retrieve drill string	5
							1200	1300	Make up spear assembly	1
				1300	2200	Deploy drill string with spear				9
	2200	2400	Engage CORK with spear; pull drill string 390 m out of hole							2
27 Aug	0000	0300	Lay out CORK and cabling on seafloor; cannot release spear							3
	0300	1000	Retrieve drill string + CORK							7
	1000	1100	Remove CORK							1
				1100	1800	Deploy drill string with spear				7
							1800	1900	Engage CORK with spear	1
							1900	2400	Retrieve drill string	5
28 Aug							0000	0400	Retrieve drill string	4
							0400	0700	Recover spear without CORK; install logging bit BHA	3
							0700	1400	Deploy drill string	7
							1400	1800	Search for CORK on seafloor	4
							1800	1900	Reentry 1, tag packer at 19 mbsf, pull out of hole	1
				1900	2100	Transit with logging bit near seafloor				2
	2100	2300	Reentry 1, tag packer at 57 mbsf							2
	2300	2400	Retrieve drill string							1
29 Aug	0000	0600	Retrieve drill string							6
	0600	0800	Make up BHA with milling bit 1 with junk basket subs							2
				0800	1300	Lower drill string with mill				5
							1300	1700	Reentry 2	4
							1700	2400	Mill and work junk baskets; TD = 70 mbsf	7
30 Aug							0000	0700	Continue milling	7
							0700	0900	Pull out of hole	2
				0900	1200	Transit with milling bit near seafloor				3
	1200	1500	Reentry 2							3
	1500	1700	Mill and work junk baskets; TD = 95 mbsf							2
				1700	2400	Retrieve drill string				7

Table T3 (continued).

Date (2019)	Hole 896A Start (h)	Hole 896A End (h)	Hole 896A Activity	Activity while in DP transit Start (h)	Activity while in DP transit End (h)	Activity while in DP transit Activity	Hole 504B Start (h)	Hole 504B End (h)	Hole 504B Activity	Total time (h)
31 Aug							0000	0300	Take milling bit and junk baskets apart, recover junk, make up milling bit 2 BHA	3
							0300	1000	Deploy drill string	7
							1000	1200	Reentry 3	2
							1200	2400	Mill and work junk baskets; TD = 110 mbsf	12
1 Sep							0000	0600	Retrieve drill string	6
							0600	0800	Take milling bit and junk baskets apart, recover junk, make up milling bit 3 BHA	2
							0800	1500	Deploy drill string	7
							1500	1700	Reentry 4	2
							1700	2400	Mill and work junk baskets; TD = 133 mbsf	7
2 Sep							0000	0200	Continue milling	2
							0200	0900	Retrieve drill string	7
							0900	1300	Take milling bit and junk baskets apart, recover junk, make up milling bit 4 BHA without junk baskets	4
							1300	2000	Deploy drill string	7
							2000	2300	Reentry 5	3
							2300	2400	Mill the packer; TD = 141 mbsf	1
3 Sep							0000	1200	Continue milling	12
							1200	1900	Retrieve drill string	7
							1900	2000	Take milling bit apart, make up milling bit 5 BHA	1
							2000	2400	Deploy drill string, VIT	4
4 Sep							0000	0300	Continue deploying drill string	3
							0300	0400	Camera retrieved due to slip ring problem, no reentry	1
							0400	1200	Troubleshooting, running out of time for science operations in hole	8
							1200	2400	Rig equipment maintenance	12
5 Sep							0000	1200	Rig equipment maintenance	12
							1300		Departure	
									Hole 504B total milling time:	48
									Hole 896A total milling time:	2

Figure F1. Location of Holes 504B and 896A on the Costa Rica Rift flank in the Panama Basin. Base map is from Global Multi-Resolution Topography (**https://www.ldeo.columbia.edu/research/marine-geology-geophysics/mgds-global-multi-resolution-topography-gmrt-create-maps-and-grid**).

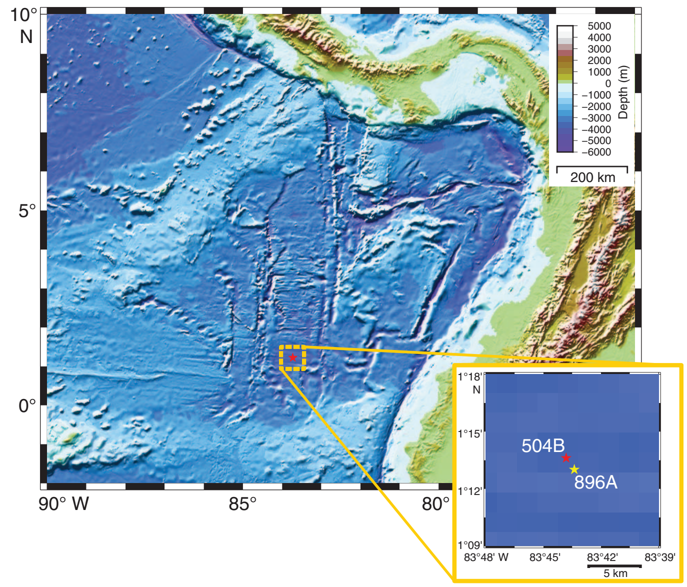

Figure F2. Summary of Hole 504B logging data available from ODP Legs 140 and 148.

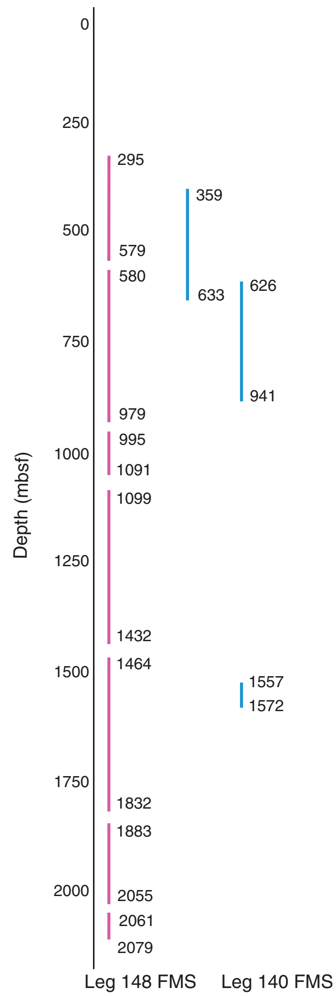

Figure F3. Caliper, resistivity, temperature, and visual logs, Hole 896A. Arrows = interpreted positions of independent sources of fluids entering the hole from the formation: 1 = cooler fluids (*), 2 = warmer fluids (**), 3 = warmest fluids (***). Flocculent material was observed in images from deeper than 230 mbsf. Reprinted with permission from Becker et al. (2004).

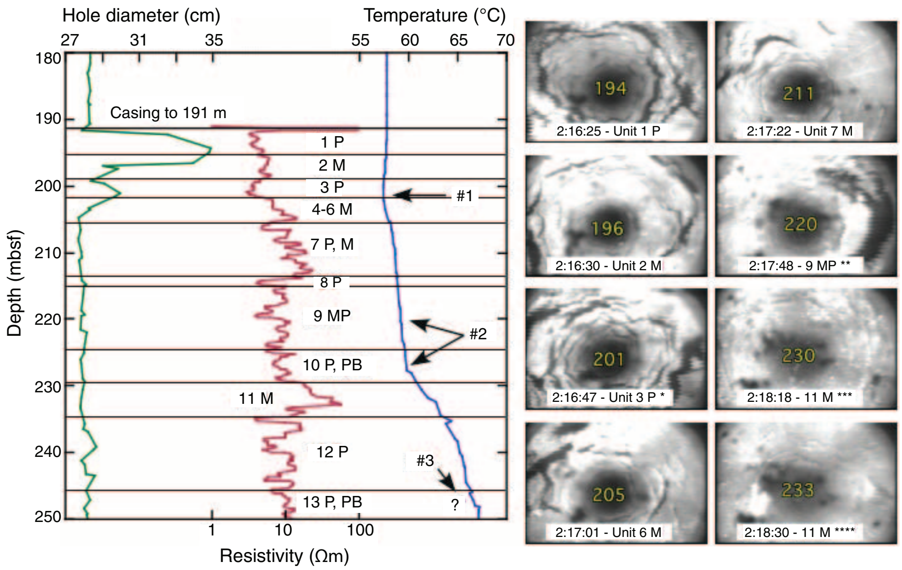

Figure F4. Hole 504B temperatures measured during several ODP and DSDP legs. The current thermal limit of life (122°C) is at ~900 mbsf.

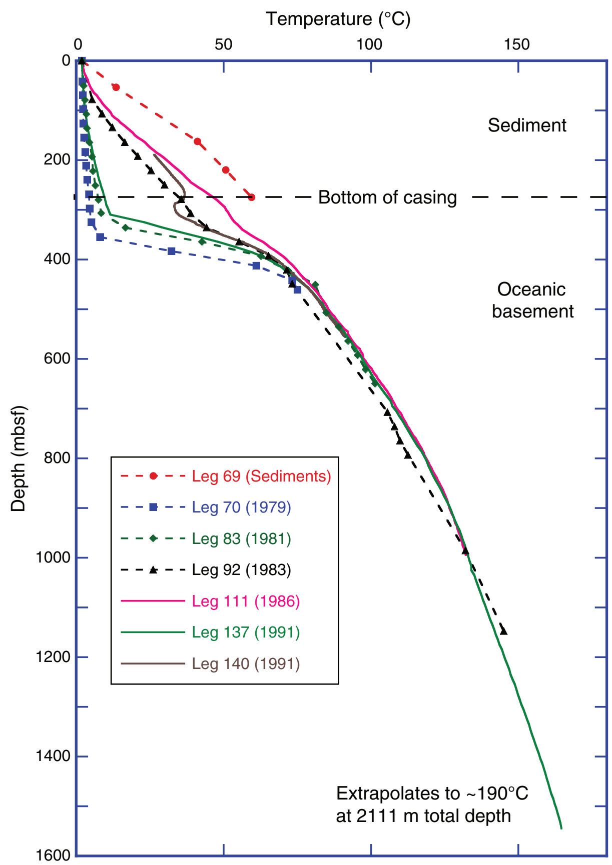

Figure F5. MTFS assembled and ready for deployment on the catwalk, Expedition 385T. Photograph by C. Geoff Wheat.

Figure F6. Wireline CORK recovery operations, Expedition 385T. A. Subsea camera footage during attempts to engage Hole 504B wireline CORK with overshot tool. B. Hole 896A wireline CORK frame engaged with fishing spear. C. Recovered Hole 896A wireline CORK frame in the moonpool. Photographs in A and B by Beth Orcutt/Bigelow Laboratory for Ocean Sciences. Photograph in C by Doug Cummings/Texas A&M University (TAMU)/IODP.

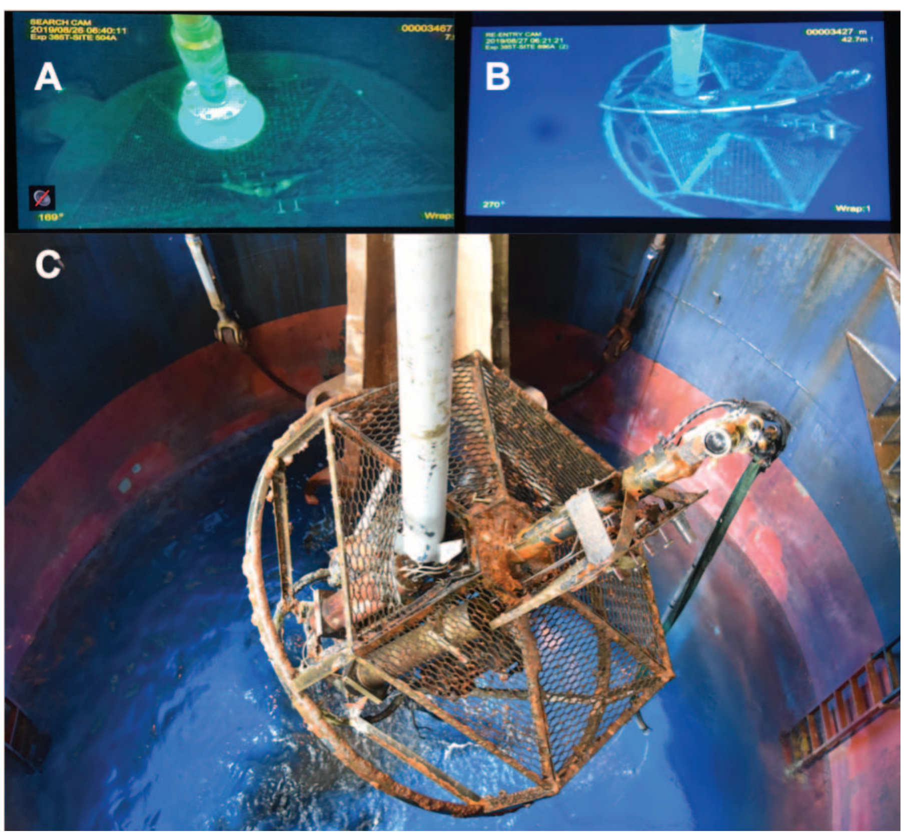

Figure F7. Hole 504B status following operations, Expedition 385T. CSG = casing, LEN = length. Figure prepared by Bill Rhinehart/TAMU/IODP.

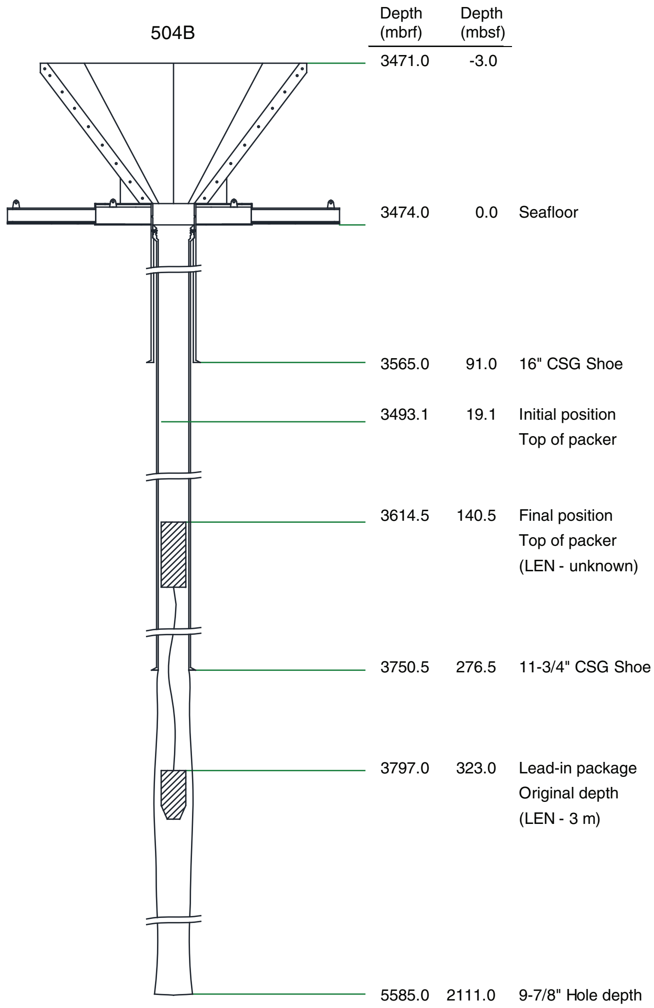

Figure F8. Hole 896A status following operations, Expedition 385T. CSG = casing, LEN = length. Figure prepared by Bill Rhinehart/TAMU/IODP.

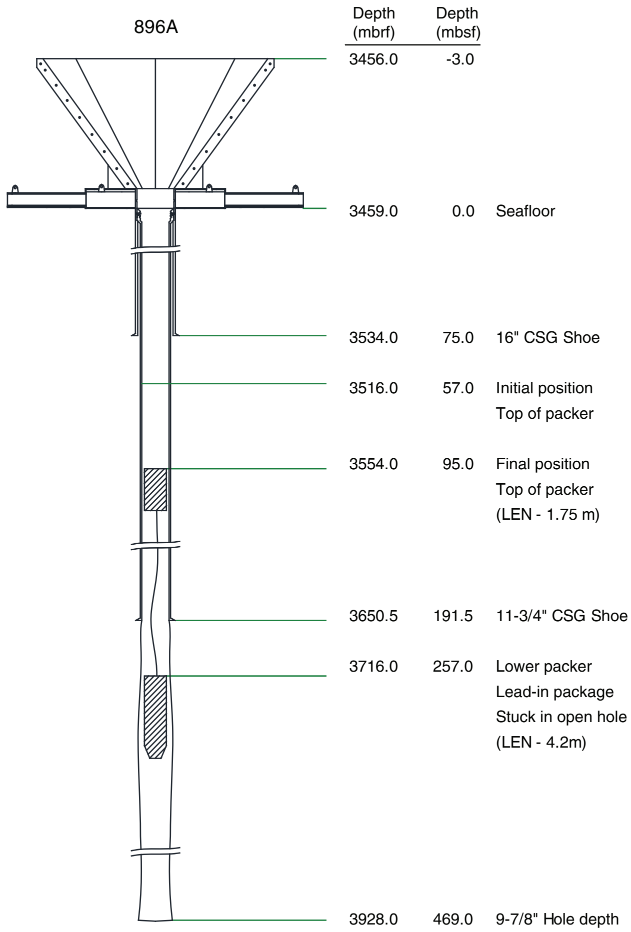

Figure F9. Used mills and recovered wireline CORK materials (i.e., Hole 896A wireline CORK frame on pallets in back, three buckets with junk basket returns), Expedition 385T. Photograph by Beth Orcutt.