Hydrogeologic properties, processes and alteration in the igneous ocean crust

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Abstract

The igneous ocean crust is a dynamic water-rock system. Scientific ocean drilling has been an essential tool for accessing, sampling, monitoring and testing basement rocks below the seafloor, to assess past and present hydrogeologic conditions. Core samples recovered from ocean crustal boreholes, most within the uppermost basaltic crust, reveal complex and heterogeneous histories, with strong lithologic and hydrogeologic control on the extent of rock alteration. There appears to be a spreading rate dependence of basic patterns of rock alteration in the upper ocean crust, with more variable and extensive alteration observed in crust created at slow and medium-rate spreading centers, compared to patterns of alteration seen in seafloor formed at faster-rate spreading centers. Geophysical logs and permeability tests in the ocean crust indicate heterogeneity in the distribution of physical properties, and ongoing active experiments are exploring rates of tracer transport and the extent of anisotropy in crustal hydrogeologic properties.

Keywords: Ocean crust, hydrogeology, fluid flow, alteration, permeability

I. Introduction

A. Motivation

Fluid flow within volcanic ocean crust influences the thermal and chemical evolution of oceanic lithosphere and seawater; subseafloor microbial ecosystems; diagenetic, seismic, and magmatic activity along plate-boundary faults; and the creation of ore deposits on and below the seafloor [e.g., Coggon et al., 2010; Huber et al., 2006; Parsons and Sclater, 1977]. The global hydrothermal fluid mass flux through the upper oceanic crust rivals the global riverine fluid flux.
to the ocean, passing the volume of the oceans through the crust once every $10^5$–$10^6$ y [e.g., Johnson and Pruis, 2003; Mottl, 2003; Wheat et al., 2003]. Much of this flow occurs at relatively low temperatures, far from volcanically active seafloor-spreading centers where new ocean floor is created. This “ridge flank” circulation can be influenced by off-axis volcanic or tectonic activity, and by exothermic reactions that occur with the volcanic crust during fluid transport, but most of the flow driven lithospheric heating from below the crust.

Fluid flow in the volcanic oceanic crust appears in several sections of the Initial Science Plan for IODP, including those focusing on solid earth cycles and alteration, ocean chemistry, and the deep biosphere. Many of the expeditions completed in the first decade of IODP operations included components of volcanic crustal hydrogeology and alteration, and several focused specifically on this topic. In this section, we summarize selected results from IODP drilling and associated studies, including borehole sampling, logging, monitoring and active experiments, and analyses completed with geological and biological materials recovered from IODP boreholes. We begin with a brief overview of motivating questions and the physical structure of the volcanic crust (a topic explored in greater detail in other parts of this chapter), then review results from a series of IODP expeditions, both direct measurements of fluid conditions and processes, and inferences involving the present day and geological history of fluid-rock interactions expressed as alteration.

B. Drilling, Coring, and Measurement Methods for the Igneous Ocean Crust

Boreholes were made in the igneous ocean crust during IODP using a variety of drilling systems, depending on operational and scientific goals. Selection of appropriate approaches depends on anticipated crustal conditions, goals for sampling versus measurements or

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instrumentation, and available time. Most crustal holes are drilled with a coring bit, but some are
drilled without coring to improve hole stability and ease installation of casing. Interested readers
are directed to individual IODP Expedition Reports for information on operational strategies.

In addition to being cored, some crustal holes have been logged with wireline geophysical
tools, to generate long records of properties related to hydrogeology, lithostratigraphy and rock
alteration. Both core samples and geophysical logs provide information on the current physical
and chemical state of the formation surrounding a borehole. This state is likely to result from a
combination of primary crustal construction processes, and subsequent tectonic, magmatic and
alteration (especially, hydrothermal) processes that occur as the lithosphere ages.

Some of the most common logging tools run in the ocean crust include caliper (hole
diameter), bulk density, porosity, resistivity, seismic velocity, and borehole temperature (we use
generic logging tool descriptions throughout this chapter, rather than specific tool names and
acronyms). Some basement holes have also been logged with tools that create higher-resolution
images of the borehole wall, including resistivity and sonic instruments, and tools that detect the
paleomagnetic orientation and/or magnetic susceptibility of formation rocks. In general, wireline
geophysical logs are the most accurate, and tools are least likely to get stuck, in holes that are "to
gauge" (having a relatively uniform diameter that is slightly larger than the drill bit diameter).

Good hole conditions also can contribute to higher core recovery. But many of the zones inferred
to be of greatest hydrogeologic interest, where rocks are the most fractured, porous and
permeable, are weak and unstable, resulting in both core poor recovery and challenging logging
conditions.

Hydrogeologic tests of individual holes drilling into the volcanic crust during IODP have
been conducted using a drillstring packer system [e.g., Becker, 1986; Becker and Fisher, 2000;
The packer is a hydraulic and mechanical system incorporated into the bottom-hole assembly of a drillstring, which isolates part of a borehole so that pressure and fluid flow conditions can be perturbed and the response can be monitored. A packer can be inflated in casing to test the entire open-hole interval or in open hole if the hole is small enough in diameter and the formation sufficiently massive to hold the inflated packer element and form a seal against the borehole wall. Interpretation of single-hole packer tests is based on fitting pressure-time observations to an equation of the form: \( \Delta P = f(Q, t, T) \), where \( Q \) is fluid pumping rate, \( t \) is time, and \( T \) is formation transmissivity (dimensions of \( L^2/T \)). Transmissivity is the product of aquifer thickness and hydraulic conductivity, \( K \) (dimensions of \( L/T \)), within a horizontal, tabular aquifer, where the latter is related to permeability, \( k \) (dimensions of \( L^2 \)) as \( k = K \mu/\rho g \), \( \mu \) being dynamic viscosity and \( \rho g \) being a unit weight of fluid.

Temperature logs in cased, crustal boreholes have quantified downflow and upflow conditions, and used these observations and estimated or measured differential pressures to infer near-borehole hydrogeologic properties [Becker and Davis, 2003; Becker et al., 1983; Fisher et al., 1997]. Flow down crustal boreholes is initiated by the imposition during drilling and other operations of a tall column of cold (dense) seawater in the borehole adjacent to warmer ambient (less dense) formation fluid. This creates a positive differential pressure that can drive borehole fluid into the formation, even where the formation is naturally overpressured, a process that can continue for days to years [e.g., Becker et al., 2001; Gable et al., 1992]. Downflow can be recognized based on curvature of borehole temperature-depth logs and modeled based on heat balance considerations to estimate the flow rate [e.g., Becker et al., 1983; Lesem et al., 1957]. If a natural formation overpressure exceeds the differential pressure created during downflow, the flow direction can reverse [Becker and Davis, 2004; Fisher et al., 1997]. In this case, rising
borehole fluids lose heat to the sediments surrounding casing during ascent towards the seafloor. The resulting borehole thermal profile has curvature opposite to that caused by downward flow, and can be modeled to estimate the flow rate.

Additional hydrogeologic measurements and sampling have been accomplished within IODP using long-term borehole observatory systems (CORKs) [e.g., Becker and Davis, 2005; Davis and Becker, 2004; Davis et al., 1992a; Wheat et al., 2011]. CORKs are designed (a) to seal one or more depth intervals of a borehole so that thermal, pressure, chemical, and microbiological conditions can equilibrate following the dissipation of drilling and other operational disturbances; (b) to facilitate collection of fluid and microbiological samples and temperature and pressure data using autonomous samplers and data logging systems; and (c) to allow long-term monitoring and large-scale active testing, including the formation response to perturbation experiments.

The CORKs developed for hydrogeologic monitoring and experiments in basement during IODP (deployed on and after Expeditions 301, 327, and 336) share features with systems deployed during earlier drilling expeditions, but include several notable differences. IODP basement CORKs are built around concentric casing strings, with the innermost casing including one or more sets of inflatable packer elements. Later IODP expeditions (327 and 336) were fitted with additional packer elements designed to expand over time through chemical interaction with seawater [Edwards et al., 2012b; Fisher et al., 2011]. Pressure measurement in these CORKs is accomplished with high-resolution sensors and loggers, deployed on the wellhead and connected at depth using small diameter stainless steel tubing. Data from these systems is accessible using an underwater mateable connector with a submersible or remotely-operated vehicle (ROV); pressure data from one IODP CORK (in Hole 1026B) is available through the Neptune Canada
cabled network (http://www.oceannetworks.ca). Temperatures in most CORKs are recorded at multiple depth using autonomous sensor-logger systems that are attached to a cable suspended inside the inner CORK casing. These instruments must be recovered from the CORKs in order to download data. The CORK in Hole 1026B provides downhole temperature data in real time.

IODP CORKs were the first designed to collect relatively pristine samples of basement fluids and microbial materials, using nonreactive casing and coatings, Teflon tubing that extended from seafloor fittings to depth, and titanium valves and sampling screens. Continuous Osmosampling systems were deployed with these CORKs both on the outside of seafloor wellheads (drawing samples up from depth) and within isolated basement intervals. Osmosampling systems were designed specifically for gas sampling (using copper tubing), microbiological incubation, tracer injection, and acid addition [Wheat et al., 2011].

In addition to providing individual monitoring and sampling points in the ocean crust, CORKs provide opportunities for active experiments and monitoring between boreholes. The experiments associated with IODP work on the eastern flank of the Juan de Fuca Ridge were designed with this as a primary project goal, and cross-hole pressure and geochemical perturbations are being used to assess crustal scale properties and processes, including differences with depth and direction(s) of flow. Several modeling studies have also been completed using samples and data from IODP boreholes.

C. IODP Sites and Results Discussed

The locations of IODP sites discussed in the section are shown in Figure 1, and key characteristics of individual holes are listed in Table 1. In several cases, boreholes started during DSDP or ODP operations were occupied as part of IODP for additional measurements, drilling,
coring, or observatory emplacement. Some of the sites discussed later in this chapter are not listed in Table 1, because they involve work primarily in the sedimentary section, although results (mainly geochemical and/or microbiological) relate to hydrogeologic and alteration conditions in underlying basement. The sites discussed are located mainly on the flanks of mid-ocean ridges, beyond the direct magmatic and tectonic influence of seafloor creation, where the integrated impacts of crustal construction and subsequent modification can be elucidated by drilling, sampling and testing. Several sites are located where additional characteristics of subseafloor hydrogeology are apparent, including an exposed section of the deep crust and upper mantle near an active spreading center, crust that is about to undergo subduction, and extrusive and intrusive material associated with mid-plate volcanism. Figure 2 shows penetration depths and general lithologies of basement holes drilled during IODP, and holes drilled during DSDP and ODP having ≥100 m of basement penetration.

The next part of this chapter presents IODP drilling and related results from ocean crustal drillholes. Within each subsection, the presentation is separated into a brief introduction, analyses of rocks and alteration, geophysical logging and thermal data, and results of hydrogeologic testing and modeling studies. Space limitations preclude discussion of drilling results from Shatsky Rise (Expedition 324) and the Louisville Seamounts (Expedition 330), settings of mid-plate volcanism, although there was significant basement penetration, coring, and geophysical logging on these expeditions.

II. Crustal Hydrogeology and Alteration

A. Eastern flank of the Juan de Fuca Ridge, northeastern Pacific Ocean, ~3.5 M.y. old

upper crust (IODP Expeditions 301 and 327)
1. Background and context

IODP Expeditions 301 and 327 were part of a series of expeditions and experiments to resolve hydrogeologic, lithologic, biogeochemical, and microbiological properties, processes, and linkages within a young ridge flank formed at a medium-rate spreading center. Ocean Drilling Program (ODP) Leg 168 completed a drilling transect across 0.9 to 3.6 Ma seafloor in this region, collecting sediment, rock, and fluid samples; determining thermal, geochemical, and hydrogeologic conditions in basement; and installing CORKs in the upper crust [Shipboard Scientific Party, 1997b]. Two Leg 168 CORKs were placed at the eastern end of the drilling transect, in Holes 1026B and 1027C. IODP Expedition 301 drilled deeper into basement at Site U1301, located 1 km south of Hole 1026B; sampled sediment, basalt, and microbiological materials; logged upper basement and conducted hydrogeologic tests in Hole U1301B; replaced the borehole observatory in Hole 1026B; and established two new CORK observatories (in Holes U1301A and U1301B). IODP Expedition 327 added two basement holes at Site U1362, between Hole 1026B and Site U1301; collected sediment, rock, and microbial samples; logged upper basement and conducted hydrogeologic tests in Hole U1362A; installed two CORK observatories; and recovered/replaced part of a CORK instrument string that had previously been deployed in Hole U1301B. As of the end of Expedition 327, there was a network of six CORK observatories operating in this area, two of which were completed across multiple basement depths (Holes U1301B, U1362A) and one of which was connected to the Neptune Canada cabled network (Hole 1026B). Addition post-drilling expeditions have used a submersible or remotely operated vehicle to download data, manipulate values, collect fluid samples, and install and recover instruments and samplers from the CORK wellheads and boreholes.
2. Crustal petrology and alteration

Basement coring on Expeditions 301 and 327 occurred in Holes U1301B and U1362A, both of which were drilled about 300 meters into the upper volcanic crust [Expedition 301 Scientists, 2005a; Expedition 327 Scientists, 2011a]. Additional holes at these sites (U1301A and U1362B) were drilled to establish borehole observatories but were not cored, and small amounts of basement material were also recovered at Site U1363, adjacent to a seamount through which regional hydrothermal recharge occurs [Expedition 327 Scientists, 2011c]. Sites U1301 and U1362 are located above a local basement high that is buried below ~235-265 m of turbidites and hemipelagic sediment, and volcanic basement rocks outcrop 4–7 km to the north and south.

The uppermost 85 m of basement at Site U1301 was not cored [Expedition 301 Scientists, 2005a], and recovery was poor (5%) in the upper ~40 m of basement cored in nearby Hole 1026B [Shipboard Scientific Party, 1997a]. Variations in drilling rates at Sites U1301 and U1362 [Expedition 301 Scientists, 2005b; Expedition 327 Scientists, 2011b] may indicate massive basalt at 55-60 m, and breccias or highly altered pillow basalts at 65-80 m. Basement in Hole U1301B was cored from 351 to 583 mbsf (86 to 317.6 mbsf), with core recovery of 30%, and consists of mainly pillow basalt with minor massive basalt and one basalt-hyaloclastite breccia unit [Expedition 301 Scientists, 2005a].

The basalts are sparsely to highly plagioclase ± clinopyroxene ± olivine phyric, and are variably fractionated normal depleted mid-ocean-ridge basalt (N-MORB), containing 6.5-8.1 wt% MgO [Expedition 301 Scientists, 2005a]. The uniform trace element ratios such as TiO$_2$/Zr suggest that all the basalts came from the same magmatic source. The basalts from Hole U1301B exhibit low-temperature alteration effects typical of upper oceanic basement [e.g., Alt, 2004]. The rocks are slightly to moderately altered, and alteration styles include a pervasive background
alteration characterized by saponite replacing olivine and mesostasis and filling vesicles,

[Expedition 301 Scientists, 2005a; Lever et al., 2013; Ono et al., 2012]. Centimeter-scale dark to brownish alteration halos along veins and fractures also contain celadonite and Fe-oxyhydroxide. Alteration intensities range between 5 and 25%, but can be as high as 60% in the brecciated intervals (Figure 3). Veins and vesicles are filled mainly with saponite, but also with celadonite, Fe-oxyhydroxide, carbonate and pyrite, and are more abundant in the pillowed than in the massive flows. Oxygen isotope analyses of carbonate indicate temperatures of 30-40°C [Coggon et al., 2010]. Secondary pyrite and bulk rocks range to strongly negative δ34S values, indicating the effects of microbial sulfate reduction in the basement (Ono et al., 2012; Lever et al., 2013). These rocks also contain organic carbon having low δ13C values and yield functional genes for methanogens, methane oxidizers, and sulfate reducing bacteria, providing further evidence for microbial activity in the basement (Lever et al., 2013).

Hole U1362A is located 800 m N of Hole 1301B, on the same buried basement ridge [Expedition 327 Scientists, 2011a]. The upper 110 m of basement was drilled without coring in Hole U1362A (236-346 mbsf), then was cored from 346 to 496 mbsf to 528 mbsf (110 to 292 mbsf), with ~30% recovery. Approximately half of the cored basement section consists of pillow basalts, with the remainder comprising subequal amounts of sheet flows and basalt flows [Expedition 327 Scientists, 2011a]. The sheet flows are thick (up to >10 m) and could be classified as massive flows, as were similar units in nearby Hole 1301B. The basalts are aphyric to highly phryic with varying olivine, clinopyroxene, and plagioclase phenocrysts. Geochemically, all basalts are normal depleted mid-ocean-ridge basalt (N-MORB), and once again their uniform ratios of immobile elements suggest a common magmatic source. Breccias
are limited to a 2-cm fragment of hyaloclastite at 430 mbsf, and a 15 cm thick cataclastic zone at 401 mbsf.

The extent of alteration in the lava flows is minor to high and comprises saponitic background alteration and cm-scale alteration halos along veins and fractures. Halos, ranging from black to green to red in color, flank about 15% of the veins (Figure 3). The two hyaloclastite layers are characterized by moderately to highly altered angular clasts in a matrix composed of saponite and altered glass (palagonite). The cataclastic zone is moderately altered, with the matrix more altered than the clasts. Veins contain mainly saponite, lesser celadonite and Fe-oxyhydroxide, and minor carbonate and pyrite, as well as rare celadonite, phillipsite, and anhydrite. Veins average 27/meter, and are more common in pillowed than in massive flows.

3. Geophysical measurements and short-term hydrogeologic experiments

Holes U1301B and U1362A were geophysically logged to assess borehole diameter and formation electrical resistivity, bulk density, porosity, and sonic velocity [Expedition 301 Scientists, 2005a; Expedition 327 Scientists, 2011a]. Caliper logs from these holes show oversized intervals with thicknesses of tens of meters, particularly in the upper 100-200 mbsf, and more massive formation conditions at greater depth. In general, oversized zones correspond to lithologies of pillow basalt, breccia and hyaloclastite, but core recovery within these intervals is typically low, so resolving of lithologic and alteration conditions in these intervals is challenging.

Bulk density measurements show similar trends in these two holes, with the highest values of 2900 to 3000 kg/m$^3$, consistent with measurements made on core samples, and the lowest values closer to 1500 kg/m$^3$ [Bartetzko and Fisher, 2008; Becker et al., 2013]. Thin intervals within
sections of both boreholes that are to gauge have bulk density of 1800 to 2200 kg/m$^3$. These are interpreted to indicate more fractured and/or porous conditions, and more broadly to indicate lithologic layering at a scale of meters to tens of meters.

Hydrogeologic tests were run in Holes U1301B and U1362A with a drillstring packer [Becker and Fisher, 2008; Becker et al., 2013], with the packer set where basement rocks were relatively massive and the hole diameter could support the inflated packer element. The deepest packer setting depth in Hole U1301B corresponds to an abrupt change in the character of basement geophysical logs (near 470 mbsf, 200 msb), with more variable borehole diameter and physical properties (bulk density, resistivity, sonic velocity) at shallower depths. Below this depth, logs indicate more massive conditions, but there are thin zones that could be brecciated or fractured [Bartetzko and Fisher, 2008; Expedition 301 Scientists, 2005a].

Packer tests deep in Hole U1301B indicate bulk permeability of $k = 1.7 \times 10^{-12}$ m$^2$, whereas shallower tests indicate higher permeability, $k = 3.2 \times 10^{-12}$ m$^2$. If the properties determined at shallower setting depths are applied to the uppermost ~200 m of basement, permeability within this interval is closer to $k = 5 \times 10^{-12}$ m$^2$. The consistency of properties determined with two shallow setting depths suggests that most of the formation transmissivity may be concentrated between ~150-180 msb; if so, the bulk permeability of this 30-m-thick zone would be $k = 2 \times 10^{-11}$ m$^2$ [Becker and Fisher, 2008].

The single packer setting depth in Hole U1362A was near 190 msb, within in a 20-m-thick massive zone that separates two oversized zones [Becker et al., 2013]. Results from testing at this depth indicate bulk permeability of $k = 1$ to $2 \times 10^{-12}$ m$^2$, essentially the same as determined at the deepest setting depth in Hole U1301B. Bulk permeability values deeper than ~150 msb in both holes are higher by roughly an order of magnitude than those obtained by Becker and
Fisher [2000] in the shallowest basement sections in nearby Holes 1026B and 1027C. This suggests considerable heterogeneity and/or that the highest upper crustal permeabilities in this area are not found immediately adjacent to the sediment-basement interface, but are deeper in the extrusive section [Becker and Fisher, 2008; Becker et al., 2013; Fisher et al., 2008].

4. Long-term observatory measurements and samples

Single-level CORKs were installed in Holes U1301A and U1362B, and two-level CORKs were installed in Holes U1301B and U1362A [Fisher et al., 2005; Fisher et al., 2011]. The first generation CORK installed in Hole 1026B on ODP Leg 168 [Shipboard Scientific Party, 1997a] was also replaced with a new system on IODP Expedition 301 to monitor uppermost basement. The CORKs installed in Holes U1301A and U1301B lacked casing seals between two of the four concentric casing strings, and as a result, these CORKs were not fully sealed during deployment. Incomplete sealing and the imposition of a cold column of water in the boreholes during drilling, casing, and other operations led to self-sustained flow of cold ocean-bottom water down these holes and into the formation. The Hole U1301B CORK was partly sealed in Summer 2007 with cement deployed by submersible, and was fully sealed in Summer 2009 by cementing with the drillship, finally stopping the downflow of cold bottom water after five years [Expedition 327 Scientists, 2011d; Fisher, 2010]. The Hole 1301A CORK was also cemented with the drillship in Summer 2009, but much of that cement drained away within a few hours to days, so that CORK has remained unsealed. However, the downflow into Hole 1301A that began in 2004 when the hole was drilled, varied in rate and slowed over several years, then reversed abruptly in September 2007 [Wheat et al., 2010]. Since this time, Hole U1301A has been a site of warm (~64°C) hydrothermal discharge.
The CORK in Hole 1027C was intended to be replaced during Expedition 327, after the hole was deepened, but the old CORK could not be removed. Instead, the Hole 1027C CORK was modified a year later using an ROV by recovering the old data logger and installing a pressure monitoring manifold and a new data logger [Fisher et al., 2012]. The other five CORKs installed in this area are installed above a buried basement high, along a transect 1 km long that is oriented parallel to the active spreading center and the trend of abyssal hill topography. Hole 1027C is located about 2.4 km to the east, above a thicker sediment section where the top of basement is >300 m deeper below the seafloor.

Pressure records recovered from these CORKs show that upper basement is overpressured at Sites 1301 and 1362 sites by tens of kPa with respect to an ambient hydrostatic column, and the upper basement interval monitored in Hole 1027C is underpressed by tens of kPa, consistent with earlier measurements [Davis and Becker, 2004; Davis et al., 2010]. Pressure data recovered from Hole 1362A, which monitors two distinct basement intervals, show that the overpressure is greater with greater depth in the hole, consistent with net upward transport of fluid below the buried basement high, as inferred from coupled fluid-heat modeling [Spinelli and Fisher, 2004].

Temperature loggers were recovered from near the top of basement in CORKs in Holes U1301A and U1301B in 2009 (by submersible) and 2010 (by drillship), respectively, following 4 to 5 years of deployment [Expedition 327 Scientists, 2011d; Wheat et al., 2010]. These loggers recorded thermal conditions during a long period of fluid downflow. These thermal data and additional information (borehole geometry, completion details, and basement stratigraphy) was used to assess upper basement hydrogeologic properties using linked analytical models and a statistical analysis using a wide range of borehole parameters [Winslow et al., 2013]. These
analyses suggest that the initial flow rate down Hole U1301A was ~2 L/s, whereas ~20 L/s flowed down Hole U1301B.

Flow may have been more rapid flow down Hole U1301B, relative to Hole U1301A, because of its greater depth into basement (which imposes a taller column of cold, dense bottom water), and because of greater formation permeability around Hole U1301B. These analyses of thermal records provide a range of possible properties and borehole parameters, based on generating statistical distributions rather than single values for variables such as hole diameter and aquifer thickness [Winslow et al., 2013].

Wheat et al. [2010] evaluated the thermal and geochemical response of Hole 1301A before, during, and after the reversal from downflow to upflow, following recovery of a downhole instrument string in 2008. In addition to a thermal response associated with changes in flow rate and direction, two single-hole tracer experiments elucidate the geochemical composition and nature of mixing of borehole and formation fluids. Osmosamplers deployed within slotted casing near the base of the CORK, surrounded by basaltic upper crust, collected fluids throughout the deployment. Major ion chemistry shows relatively consistent concentrations of solutes such as Mg, close to bottom water values, until the flow reversal occurred. After the flow reversal, when reacted crustal fluid flowed rapidly from the formation into and up the borehole, the sampled fluid composition was similar to that seen in fluids sampled from nearby Baby Bare outcrop and ODP Hole 1026B [Shipboard Scientific Party, 1997a; Wheat et al., 2004; Wheat et al., 2010].

One of the Osmosampler packages deployed in Hole U1301A also injected a tracer solution (containing Cs, Yb, and Tm). Evaluation of tracer concentrations in sampled fluids suggests that the rates of mixing and flow resulted in a volume exchange rate (for the sampled interval) of ~60%/week during the initially rapid period of downflow, 1 to 15%/week during the slowdown in
down flow that preceded reversal, and ~99%/week after upflow of formation fluids was initiated in 2007 [Wheat et al., 2010].

A large-scale assessment of basement hydrogeologic properties was made from the long-term pressure perturbation observed in Hole 1027B that resulted from leakage of cold bottom seawater into the crust around Hole U1301B following Expedition 301 [Fisher et al., 2008]. Both IODP Expedition 301 basement operations and subsequent downflow into the crust influenced pressures in sealed Hole 1027C. Although basement operations in Hole U1301B caused a direct pressure response in Hole 1027C, operations in nearby Holes U1301A and 1026B had little or no influence. The packer experiments in Hole U1301B caused the greatest immediate perturbation, despite modest pumping rates, because pumped fluids during this test were forced to enter basement (the hole being sealed by the packer element), rather than being allowed to flow back up the borehole to the overlying ocean. These observations suggest that shallow basement surrounding Holes U1301A and 1026B may be less well connected hydrologically to the uppermost oceanic crust around Hole 1027C than is deeper basement in Hole U1301B.

A comparison of pressure conditions in these holes, and correlation with drillship and later borehole operations, suggest a flow rate into Hole U1301B during the 13 months following Expedition 301 of \( Q = 2-5 \text{ L/s} \) [Fisher et al., 2008]. This flow rate and the observed 13-month pressure change in Hole 1027C (~1.5 kPa in total) suggest a bulk basement permeability of \( k = 0.7 \) to \( 2 \times 10^{-12} \text{ m}^2 \) (Figure 4). This inadvertent cross-hole experiment also provided a direct measurement of the storativity of the upper volcanic crust, a term that depends on a combination of crustal and fluid compressibility, and can't be determined with single hole pumping experiments. Upper crustal compressibility was calculated to be \( \alpha = \sim 3 \) to \( 9 \times 10^{-10} \text{ Pa}^{-1} \), a value
close to or somewhat greater than that of seawater under ambient thermal and pressure conditions. Davis et al. [2010] completed additional analyses of the cross-hole response between Sites 1301 and 1027C, and explored the properties required to sustain downflow into an open basement hole. Their analytical and numerical calculations indicate a minimum basement permeability of $k = 3 - 4 \times 10^{-13}$ m$^2$, consistent with earlier analytical calculations. Modeling also showed how the time required for a flow reversal (if one occurs) depends on formation permeability and the depth of the flowing borehole.

These CORKs were last serviced in Summer 2013, and an additional expedition is planned for Summer 2014. Downhole instrumentation will be recovered from Holes U1362A and U1362B, and data and samples will be collected from wellhead instruments of all CORK systems in this area.

5. Hydrogeologic modeling

Numerical models were used to calculate hydrologic properties consistent with inferred rates of fluid circulation between Grizzly Bare and Baby Bare outcrops, recharge and discharge sites separated by 50 km (south and north of the Expedition 301/327 work area, respectively) [Hutnak et al., 2006]. This work followed analytical calculations of basement permeability needed to maintain a self-sustaining, hydrothermal siphon [Fisher et al., 2003]. Two dimensional, transient numerical models suggest that outcrop-to-outcrop circulation can be sustained across this distance when basement permeability between outcrops is $\geq 10^{-12}$ m$^2$ [Hutnak et al., 2006]. At lower permeabilities, too much energy is lost during lateral fluid transport for circulation to continue without forcing, given the limited driving pressure difference at the base of recharging and discharging fluid columns in the crust.
These models also showed that fluid temperatures in upper basement are highly sensitive to modeled permeability. Observed upper basement temperatures in this area are generally 60–65 °C [Davis et al., 1992b; Expedition 301 Scientists, 2005a; Hutnak et al., 2006; Shipboard Scientific Party, 1997a], little changed from conductive conditions. This means that, whatever the flow rate between Grizzly Bare and Baby Bare outcrops (and across Sites U1301 and U1362), there is little advective heat extraction on a regional basis. Modeling showed that, when crustal permeability is too high (10^{-10} to 10^{-9} m^2), fluid circulation between outcrops is so rapid that basement is chilled to temperatures below those observed (modeled values of 20°–50°C). A better match is achieved to observed upper basement temperatures of 60°–65°C when lateral basement permeability is 10^{-11} m^2 [Hutnak et al., 2006].

Separate models were used to assess the significance of "background" heat flow around the Expedition 301/327 work area. Thermal data collected during regional studies showed that heat flow along a 100-km-long swath of 3.4–3.6 M.y. old seafloor is lower by 15%–20% than predicted by conductive lithospheric cooling models, even after correcting for rapid sedimentation rates (an additional 12%–18% correction) [Davis et al., 1999; Hutnak et al., 2006; Zühlsdorff et al., 2005]. Observations show no regional recharge-to-discharge trend in heat flow [e.g., Langseth and Herman, 1981; Stein and Fisher, 2003], and no low-heat flow "moat" around Grizzly Bare outcrop [Hutnak et al., 2006; Zühlsdorff et al., 2005], as might be expected if fluid flow were responsible for the regional anomaly.

Modeling shows that the Expedition 301/327 work area (and much of the surrounding region) could be undergoing "thermal rebound" following the cessation of a long period of efficient, advective heat extraction from the crust [Hutnak and Fisher, 2007]. Maps of basement relief and sediment thickness in this area show numerous shallowly buried basement high...
[Hutnak et al., 2006; Züllsdorff et al., 2005]; basement in many of these areas would have been exposed at the seafloor prior to the last several hundred thousand years of rapid sedimentation, and areas of current basement exposure (e.g., Baby Bare outcrop) would have been larger [Hutnak and Fisher, 2007]. Larger areas of basement exposure, and the greater spatial distribution of these areas, would have been permitted more efficient regional advective heat loss, as is currently seen at the western end of the Leg 168 transect [Davis et al., 1992b; Hutnak et al., 2006], where measured heat flow is ~20% of lithospheric predictions, and on other ridge flanks where basement outcrops are more common [e.g., Hutnak et al., 2008; Lucazeau et al., 2006; Villinger et al., 2002].

B. Western flank of the Mid-Atlantic Ridge, northern Atlantic Ocean, 7–8 M.y. old upper crust (IODP Expedition 336)

1. Background and context

IODP Expedition 336 was designed to explore the subseafloor biosphere, and related geology, geochemistry, and hydrogeology, within a young ridge-flank site known as North Pond. In contrast to the Expedition 301/327 work area, where the seafloor is mostly blanketed by thick sediments penetrated by isolated outcrops of volcanic rock, North Pond is characterized by large regions of basement exposure within which basement depressions (kilometers to tens of kilometers across) are covered by tens to several hundreds of meters of sediment. North Pond is a northeast-trending sediment pond bounded by basement ridges as tall as 2 km and covered by ≤300 m of sediment. This area was drilled during Deep Sea Drilling Project (DSDP) Leg 45 (Site 395) [Shipboard Scientific Party, 1979] to characterize the geology and properties of young oceanic crust. Rapid fluid flow is though to occur in the volcanic crust below North Pond,
limiting upper basement temperatures to $\leq 20$ °C [Langseth et al., 1992; Langseth et al., 1984]. Site 395 has been revisited multiple times for logging, hydrogeological studies, and other survey work (mapping, seismics, shallow coring, and heat flow) [e.g., Becker et al., 1984; Becker et al., 2001; Morin et al., 1992a; Morin et al., 1992b].

Samples and data collected during a heat flow and sediment coring expedition in 2009 suggest a crustal fluid having considerable dissolved oxygen and seawater-like concentrations for most major and trace ions and nutrients, indicating a short residence time for fluids within basaltic basement [Ziebis et al., 2012]. Processes and conditions at North Pond are likely to be typical of ridge-flank hydrothermal circulation through young crust: rapid flow of cool fluids that have limited opportunity to react with basement rocks and overlying sediments before being discharged to the overlying ocean. Determining the geometry and rates of flow below North Pond will be challenging because there are numerous locations where basement rocks are exposed at the seafloor (in contrast to Sites U1301 and U1362 on the eastern flank of the Juan de Fuca Ridge).

The principal objectives of IODP Expedition 336 to North Pond were to elucidate the nature of the subseafloor deep biosphere with respect to hydrological, geological, and bio-geochemical processes, through coring, testing, and use of CORKs for monitoring and sampling [Expedition 336 Scientists, 2012d]. Basement was cored in two holes on Expedition 336 discussed in this section: Hole U1382A and Hole U1383C (Table 1).

2. Crustal petrology and alteration

Drilling at DSDP Hole 395A penetrated 92 m of sediment and 576.5 msb, near the SE margin of North Pond, recovering mainly pillows and massive basalt units [Shipboard Scientific
Party, 1979]. The pillow units are typically tens of meters thick and separated by a sedimentary
breccia unit that contains cobbles of gabbro and serpentinized peridotite derived from the
surrounding basement peaks [Bartetzko et al., 2001; Matthews et al., 1984]. Nearby Hole 395
also contains a peridotite-gabbro complex that is several meters thick with brecciated contacts
[Shipboard Scientific Party, 1979]. Oxygen isotope data for carbonate and clay veins in the
volcanic basement from these holes are consistent with low temperatures, around 30°C for
phylllosilicates and 0-15°C for carbonates [Lawrence and Gieskes, 1981].

Basement was encountered in Hole U1382A at 90 mbsf, and the hole was cased to 102 mbsf
and cored from 110 to 210 mbsf with 32% recovery [Expedition 336 Scientists, 2012a]. The
uppermost 20 m of basement was not cored, but variations in drilling rates suggest 3 m of basalt
underlain by 6 m of sediment and 11 m basalt. Within the underlying upper crust, pillow lavas
are slightly more abundant than massive lavas. Fragments of hyaloclastite are present in a few
pillow units, and there is sedimentary breccia that contains clasts of gabbroic rocks and weakly
serpentinized harzburgite and lherzolite. The basalts range from aphyric to highly plagioclase-
olivine phyric, and are all N-MORB. Ratios of immobile trace elements (Zr/Y and Ti/Zr)
indicate that basalts above and below the sedimentary unit are derived from different parental
magmas.

Basalt recovered from Hole U1382A, like core from nearby DSDP Site 395, shows evidence
for low-temperature alteration by seawater: pervasive saponitic background alteration, and vein
formation with adjacent brown alteration halos that comprise ~15-20% of the core [Expedition
336 Scientists, 2012a]. Glassy margins are commonly palagonitized, and alteration occurs in
≤20% of some recovered intervals. Phyllosilicates (smectite > celadonite) are the most abundant
secondary phases, followed by Fe oxyhydroxides and minor zeolites and carbonates. Veins are
abundant (13 - 20 veins/m) but narrow (usually <0.2 mm in width). Common carbonate-filled vein networks are associated with intense oxidative alteration of olivine to clay, oxide, and carbonate [ Expedition 336 Scientists, 2012a].

Alteration of basalts from Hole U1383C is generally similar to that for Hole U1382A, but Hole U1383C features a greater proportion of thin flows with glassy margins, leading to an overall greater extent of palagonitization and higher average vein density (33 veins/m) [ Expedition 336 Scientists, 2012b]. Background alteration of the basalts is ≤40% in the shallower sections and decreases down hole (Figure 3). Vesicle fills of clay, phillipsite, calcium carbonate, and Fe oxyhydroxide are common. Around 20% of the recovered core consists of brownish alteration halos that flank veins. Veins fills are dominantly clay and Fe-oxyhydroxide with only minor carbonate in the uppermost 150 m of basement. The lowermost 100 m of Hole U1383C feature mixed zeolite/carbonate veins with variable, but usually small, proportions of clay. Vein frequency in this lowermost section peak at 50 veins/m and veins can make up as much as 2% of the core. Despite the higher abundance of veins, background alteration in this deeper section is less pronounced than in the uppermost basement where veins are less frequent [ Expedition 336 Scientists, 2012b].

3. Geophysical measurements

Wireline logging data collected in Hole 395A during Expedition 336 included natural gamma ray, temperature, and induced fluorescence to identify microbial material ("DEBI-t" tool) [ Expedition 336 Scientists, 2012c]. Natural gamma ray and resistivity data are consistent with results from earlier logging [e.g., Bartetzko et al., 2001; Matthews et al., 1984; Moos, 1990], which helped to define individual eruptive and flow units. The upper 300 m of basement
comprises a series of lithologic units having thicknesses of ~10 to 70 m, within which there is
generally a bottom-to-top decrease in electrical resistivity and bulk density, and an increase in
natural gamma ray emissions and sonic velocity. Some of these units are separated by thinner (1
to 10 m) layers of breccia, altered flows, or massive basalt. Fluorescence data from the DEBI-t
tool awaits quantitative interpretation, but the upper 100 m of basement is characterized by
elevated photon counts at several wavelengths, particularly at 455 nm. The excitation source
(224 nm) is intended to give peak fluorescence responses near 300 nm for spores and 320 nm for
bacteria, but variations in depth with these wavelengths are not as clear as those at 455 nm
[Expedition 336 Scientists, 2012c].

The upper 100 m of basement logged in Hole U1382A (with caliper, natural gamma ray, bulk
density, and resistivity tools) shows layering at a scale of 5 to 20 m, but without the systematic
delineation of individual eruptive units apparent in Hole 395A [Expedition 336 Scientists,
2012a]. Hole diameter is irregular within much of the logged interval, which impacts the
response of geophysical tools. In contrast to results from Hole 395, logging revealed no trends in
downhole fluorescence [Expedition 336 Scientists, 2012a]. Wireline logs penetrated almost 300
msb in Hole U1363C, generating results that were somewhat between those seen in Holes 395A
and U1382A [Expedition 336 Scientists, 2012b]. The upper 30–110 msb is characterized by
highly variable natural gamma ray emission, bulk density, electrical resistivity, and sonic
velocity. Electrofacies (geophysical logging units) defined on the basis of log response are finer
than those identified from recovered core, and once again there was no strong fluorescence
interpreted to resolve microbial biomass [Expedition 336 Scientists, 2012b].

4. Long-term observatory measurements and samples
Expedition 336 CORKs included multiple nested casing strings and packer systems (inflateable and swellable), casing seals, and non-reactive components deployed at depth [Edwards et al., 2012b]. Expedition 336 CORKs were the first to use fiberglass inner casing, along with resin-coated steel casing and collars introduced in earlier CORKs, in an effort to allow collection of near-pristine samples of basement fluids and microbial materials. Downhole pressure, temperature, and dissolved oxygen are being monitored for short-term and long-term variability, and a variety of downhole and wellhead sampling systems are collecting fluids at a range of rates in different storage media, and providing substrate for microbial incubation.

A three-level CORK was deployed in Hole 395A, after removal of an earlier generation of borehole observatory, but the wellhead was severed from the rest of the system during deployment [Expedition 336 Scientists, 2012c]. Downhole instruments should be functioning as intended, and provided the borehole is sealed, may provide long-term samples and data indicative of conditions in the upper ocean crust. A single-level CORK was deployed in Hole U1382A, containing a suite of measurement, logging and sampling systems, to monitor conditions in the upper 120 m of volcanic crust [Expedition 336 Scientists, 2012a]. A three-level CORK that isolates distinct basement levels, similar in design to that deployed in Hole 395A, was installed in Hole U1383C. Hole U1382B was drilled and cased during Expedition 336, then left for later instrumentation [Expedition 336 Scientists, 2012b]. This required rapid development and construction of a novel "CORK-lite" system, which was installed three months post-drilling using an ROV [Wheat et al., 2012]. Pressure data downloaded immediately after installation of this system showed a significant differential pressure below the CORK, indicating that the borehole was successfully sealed.
Samples and pressure data were collected from Expedition 336 CORK systems during the same expedition that deployed the CORK-lite, and preliminary evaluation suggests that the Hole U1382A and U1383C CORKs are sealed and operating as planned. Additional insight as to hydrogeologic, geochemical, and microbiological conditions in basement below North Pond awaits additional analyses and the next CORK servicing expedition planned for 2014.

C. Eastern flank of the East Pacific Rise, eastern Pacific Ocean, ~15 M.y. old upper to middle crust (IODP Expeditions 309, 312, and 335)

1. Background and context

Site 1256 was drilled to test models for the structure and origin of seismic layering of oceanic crust and the origin of melt lenses at fast spreading ridges, in crust that formed at a superfast spreading rate at the East Pacific Rise (EPR) ~15 m.y. ago [Expedition 309/312 Scientists, 2006a; Expedition 335 Scientists, 2012; Shipboard Scientific Party, 2003]. Drilling, coring, and measurements were initiated on ODP Leg 206 and continued on IODP Expeditions 309, 312, and 335. Hole 1256C penetrates 250 m of sediment extends 72 m into basement. Reentry Hole 1256D, ~30 m to the south, was cased though the sediments and ~20 m into basement. Coring started 276 mbsf (26 msb) and currently extends to 1522 mbsf (1246 msb) [Expedition 309/312 Scientists, 2006a; Expedition 335 Scientists, 2012; Shipboard Scientific Party, 2003]. Hole 1256D is currently the fourth deepest penetration into oceanic basement, through lavas, dikes, and into gabbros (Figure 2).
2. Crustal petrology and alteration

The uppermost basement in Hole 1256D comprises a ~100 m thick sequence dominated by a ponded flow >75-m thick; the same massive flow is only 32 m thick in nearby Hole 1256C [Expedition 309/312 Scientists, 2006a]. The immediately underlying lavas include sheet and massive flows and minor pillow flows. The amount of basement relief indicated by variation in the thickness of the ponded flow, plus the presence of flow lobe inflation features, indicate that the upper 284 m of the volcanic section crystallized off-axis [Expedition 309/312 Scientists, 2006a; Tominaga et al., 2009]. Sheet flows and massive lavas erupted at the ridge axis, plus two thin (1-2 m) hyaloclastite intervals (at 397 and 595 mbsf), make up the remaining extrusive section (Figure 5). At 1004 mbsf, the beginning of a lithologic transition is marked by subvertical intrusive dike contacts and sulfide-mineralized breccias. Below 1061 mbsf, subvertical intrusive contacts indicate a ~350 m-thick sheeted dike complex. Some rocks have doleritic textures, and many are cut by subvertical dikes with common brecciated and mineralized chilled margins. The lowermost ~60 m of the sheeted dike complex is characterized by recrystallization to granoblastic textures by contact metamorphism.

The plutonic complex begins at 1407 mbsf (Figure 5), and consists of a 52-m-thick upper gabbro, a 24-m thick interval of recrystallized granoblastic dikes with minor gabbroic and felsic veins, and a 24-m-thick lower gabbro. The upper gabbro comprises gabbros, oxide gabbros, quartz-rich oxide diorites and small trondjhemite dikelets. The lower gabbro consists of gabbro, oxide gabbro, and lesser orthopyroxene bearing gabbro and trondjhemite. Contacts of the gabbros with the intervening dike interval are intrusive, with partly resorbed, stoped dike clasts within the gabbros. The lowermost rock recovered from the hole is a highly altered actinolite-bearing basaltic dike that postdates the intrusion of the lower gabbro. The plutonic section has...
been interpreted in two ways: as two separate gabbro units intrusive into the sheeted dikes, with
an intervening screen of dikes [Expedition 309/312 Scientists, 2006a; Koepke et al., 2008]; and
as a single lens of gabbro containing stoped dike clasts, with the poorly recovered intermediate
dike interval representing stoped dike fragments within gabbro [France et al., 2009; Koepke et
al., 2011].

Flows and dikes are aphyic to sparsely phyrich, containing olivine, plagioclase, and
clinopyroxene phenocrysts in decreasing abundance. The rocks are variably fractionated, with
MgO contents of ~10 wt% to ~4.5 wt% [Expedition 309/312 Scientists, 2006a; Shipboard
Scientific Party, 2003]. The ranges of most major and many minor element concentrations are
similar to those of the northern EPR, indicating similar processes at the superfast spreading ridge
that formed Site 1256 and the modern EPR. Gabbro compositions span a range similar to the
flows and dikes, but are on average more primitive (mean MgO ~8 wt% vs 7.2 wt% for flows
and dikes [Expedition 309/312 Scientists, 2006a; Koepke et al., 2011].

Hole 1256D sampled the transition between low-temperature and high-temperature
hydrothermal alteration in a continuous section of oceanic crust [Alt et al., 2010] (Figure 5).
Extrusives exhibit typical low temperature alteration, with a pervasive saponitic background
alteration, with dark and brownish alteration halos that contain celadonite and Fe-oxyhydroxide
along veins. This vein-related alteration affects a few percent of the core but is concentrated in
two zones, at 350–450 and 635–750 mbsf, (Figure 3). Veins average 30 /meter, and vein
minerals include saponite, Fe-oxyhydroxide, celadonite minor pyrite, and rare carbonate.
Alteration temperatures in the lavas, estimated from oxygen isotope analyses of secondary
minerals, were ~50-125°C, generally increasing downward [Alt et al., 2010]. Sulfur isotope data
indicate widespread effects of microbial sulfate reduction in the volcanic sequence (Alt and
Shanks, 2011), as in other oceanic basement sections [Lever et al., 2013; Ono et al., 2012; Rouxel et al., 2008]. The basal lava section features intervals with pyrite-rich alteration halos, mixed-layer chlorite-smectite, and anhydrite, and oxygen isotope analyses of secondary minerals indicate higher temperatures (150°–200°C) than shallower in the crust [Alt et al., 2010].

The appearance of chlorite, albite, actinolite, anhydrite, epidote, and laumontite at around 1000 mbsf and the presence of an intensely altered and mineralized hyaloclastite breccia at 1022 mbsf indicate a stepwise increase in alteration temperatures downward across the top of the transition from lavas to dikes, and reaction with high temperature hydrothermal fluids (Figure 5). Rocks are typically more intensely altered in cm-scale halos along veins in dike margin breccias. This secondary mineral assemblage continues downward in the upper dikes, but below ~1300 mbsf the alteration intensity increases and actinolite becomes more abundant than chlorite. Circulating hydrothermal fluids had temperatures (~320-450°C), salinities, and oxygen isotope compositions similar to black smoker fluids [Alt et al., 2010]. Chlorite is the most common vein filling in the dikes, but quartz, sulfide, actinolite, prehnite, laumontite, and calcite are also present, and anhydrite veins are common to ~1200 mbsf. Hydrothermal veins composed of quartz, epidote, and sulfide postdate the chlorite-dominated veins. Crosscutting vein assemblages of anhydrite, prehnite, laumontite, and calcite formed even later at temperatures < 250°C. Below ~1350 mbsf secondary plagioclase and hornblende are common, and formed at temperatures >480°C. In the lower portion of the sheeted dikes (1370-1397 mbsf), the rocks are recrystallized to granoblastic textures in patches. These granoblastic dikes feature secondary clinopyroxene, orthopyroxene, actinolitic hornblende, plagioclase, and blebs of oxide (ilmenite and magnetite). The pyroxene-rich assemblage and the granoblastic textures indicate
recrystallization of previously hydrothermally altered rocks at temperatures >800°C, related to underlying gabbroic intrusions [Alt et al., 2010; Koepke et al., 2008].

The plutonic section comprises highly altered gabbro and felsic veins with amphibole, chlorite, plagioclase, titanite, and minor laumontite and epidote. The dike screen separating the two gabbro units is recrystallized to granoblastic textures at temperatures similar to those in the basal granoblastic sheeted dikes. The intensity of gabbro alteration is variable, with intrusive margins and dike screen contacts being most extensively hydrothermal altered [Teagle and Wilson, 2007]. Alteration temperatures and hydrothermal fluid compositions were similar to those in the overlying lower dikes.

The overall alteration scenario involves cooler seawater fluids circulating in the volcanic section, and high-temperature hydrothermal fluids in the underlying dikes and gabbros. The stepwise increase in temperature downward across the top of the lava-dike transition and the presence of a mineralized breccia here reflect a mixing zone between these two fluid and alteration regimes [Alt et al., 2010]. Evidence for black smoker like fluid compositions and the presence of mineralized dike margins at greater depths indicate upwelling hydrothermal fluids in the dike section. Profiles of oxygen and lithium isotopes reflect these thermal regimes as well as variations within the dikes [Gao et al., 2012]. Contact metamorphism of the lowermost hydrothermally altered dikes resulted in a second thermal step at this depth, which was eliminated as the section cooled back to hydrothermal conditions [Alt et al., 2010].

3. Geophysical measurements

Borehole geophysical logs were collected in Hole 1256D during IODP Expeditions 309, 312, and 335, including natural gamma ray, bulk density, porosity, sonic velocity, and electrical
resistivity and borehole imaging instruments [Expedition 309/312 Scientists, 2006a; Expedition 335 Scientists, 2012]. Borehole temperatures were also measured using several tools before and during collection of other wireline data.

Wireline logs from the upper crust show variable borehole diameter, particularly within the interval 350-460 mbsf (100 to 210 msb), with corresponding decreases in electrical resistivity, bulk density, and sonic velocity, and increases in neutron porosity. The correlation of these parameters with borehole diameter could suggest that local anomalies result in part from poor borehole conditions, but the elevated natural gamma ray values suggest that there may be more extensive alteration in the inflated flows of this interval. The overlying, more massive, lava pond interval generally shows lower natural gamma radioactivity, and higher resistivity, bulk density, and sonic velocity, despite having a relatively large diameter. There are additional zones of elevated natural gamma ray emissions within the basalt sheets and massive flows between 780 and 900 mbsf (530 to 650 msb), despite having a borehole diameter that is mostly to gauge. Borehole imaging provides clear views of formation lithologic changes, for example showing thin flow and pillow shapes in the upper volcanic crust, and allows assessment of fracture occurrence and orientation [Expedition 309/312 Scientists, 2006a; Expedition 335 Scientists, 2012].

An analysis of core-sample and downhole velocity data from Expeditions 309 and 312 suggests that the core samples yielded P wave velocity values that are consistent with both wireline borehole logs and a vertical seismic profile experiment, down to a depth of ~1000 msb, indicating a lack of larger-scale porosity (fractures) beyond those measured with cores and logs [Swift et al., 2008]. Below this depth, wireline logs indicate velocities higher than those
measured with core samples, which may indicate a stress response associated with unloading of
samples during coring and recovery.

Thermal measurements using memory tools and wireline logging tools indicate that borehole
conditions were conductive prior to the start of Expedition 309, and that heat flow through the
basement section is essentially the same as that determined for the overlying sediments
[Expedition 309/312 Scientists, 2006a; Shipboard Scientific Party, 2003]. The lack of curvature
in the temperature profile through the cased sedimentary section suggests that there little or no
fluid flow down the borehole, despite imposition of a cold column of fluid during drilling and
other operations. Heat flow determined during drilling of the sedimentary section at this site, 113
mW/m², is close to the 120-130 mW/m² that is predicted by standard lithospheric cooling curves
for seafloor that is 15 M.y. old. This is unusual in comparison to the global heat flow data set for
seafloor of this age, which typically shows evidence for advective extraction of ~40% of
lithospheric heat. Collectively these results suggest that the basement rocks around Hole
U1256D may not be as hydrothermally active as is common for crust of this age.

D. Western flank of the East Pacific Rise, seaward of Nankai Subduction Zone, 20 M.y. old
upper crust (IODP Expeditions 322 and 333)

1. Background and context

Site C0012 was cored during Exp 322 and 333 to understand inputs to the Nankai subduction
zone [Expedition 322 Scientists, 2010]. The site is located near the crest of a prominent
bathymetric high (the Kashinosaki Knoll) on the incoming oceanic plate. Hole C0012A
penetrated 538 m of sediment and 38 msb, whereas nearby Hole C0012G cored across the
sediment-basement interface and reached a total depth of 104.8 msb.
2. Crustal petrology and alteration

Sedimentary units at Site C0012 comprised silty clay with ash layers, clayey to sandy volcanic turbidites, hemipelagic silty claystone (some with coarser interbeds), and claystone with manganese oxides overlying basement [Expedition 322 Scientists, 2010]. Upper basement rocks from Hole C0012G (represented by ~20% recovery) are moderately to highly plagioclase + pyroxene ± olivine phyric basalt. Approximately 36 m of pillow basalt overlies sheet flows with pillow basalt interlayers.

The style of alteration in basement rocks recovered from Site C0012 is generally similar to that seen in other oceanic basement sites, but the C0012 rocks appear somewhat more altered [Expedition 322 Scientists, 2010]. Alteration effects include background alteration, and formation of veins and associated Fe-oxyhydroxide bearing alteration halos. Secondary mineral in the basalts include saponite, celadonite, Fe-oxyhydroxides and analcimem with other zeolites and pyrite as minor components. Glassy pillow margins are commonly completely altered to these phases.

3. Geophysical measurements

No downhole geophysical logs were collected in basement at Site C0012, but heat flow data collected during site surveys and on Expedition 333 provide insights as to thermal conditions and the potential importance of fluid flow in the upper volcanic crust of the incoming plate at the Nankai subduction zone [Expedition 333 Scientists, 2012a]. Heat flow data collected with shallow probes 20 km seaward of the deformation front (around Site C0011) generally indicate values close to 100–120 mW/m², and values of 120–150 mW/m² are apparent above and seaward
of Kashinozaki knoll (close to Site C0012, located ~12 km to the east) [Hamamoto et al., 2011; Marcaillou et al., 2013], consistent with the 20 M.y. old age of the incoming plate. Heat flow tends to decrease landward of the deformation front, as seen at many convergent margins worldwide [e.g., Stein, 2003], with areas having higher values on the accretionary wedge that are thought to be associated with deformation, friction across the décollement, and fluid flow within the sedimentary section. Higher heat flow was found during site surveys in the Shikoku Basin southwest of the Expedition 322 and 333 drilling transect [Yamano et al., 2003].

Deeper thermal data collected during Expedition 333 at Sites C0011 and C0012 suggest heat flow values that are somewhat lower than determined with shallow probes, around 90 and 140 mW/m², respectively [Expedition 333 Scientists, 2012a; b]. Modeled values are close to those observed near Site C0011, whereas modeled values are ~40% lower than measured at Site C0012 [Marcaillou et al., 2013]. The latter observation could be explained by the common correlation between heat flow and basement relief. This can occur when a basement high is buried below relatively flat-lying sediments, resulting from relative isothermality of the sediment-basement interface as a result of conductive refraction and local convection in basement [e.g., Davis et al., 1989; Fisher and Harris, 2010; Fisher et al., 1990]. In addition, it has been suggested that alteration of saponite-chlorite in the volcanic upper crust during subduction can lead to significant fluid production (perhaps in excess of that associated with the smectite-illite transition within overlying sediments) [Kameda et al., 2011]. Whether transport of resulting fluids could contribute to elevated heat flow seaward of parts of the Nankai subduction zone remains to be determined.
E. Western flank of the East Pacific Rise, southern Pacific Ocean, ~13 to 100 M.y. upper crust (IODP Expedition 329)

1. Background and context

IODP Expedition 329 was planned to understand microbial activity in sediment and (to a lesser extent) basement rocks beneath the center of the south Pacific gyre, where sediment and organic carbon input are very low [Expedition 329 Scientists, 2011b]. Sediment cover is thin to absent in this area, so basement has remained open to cold seawater for much of its lifetime, maintaining cold temperatures in the basement [D'Hondt et al., 2011]. Basement was cored in an E-W age transect across the center of the gyre near ~25°S (Figure 1).

Most sites where subseafloor sedimentary life has been explored are on ocean margins or in the equatorial ocean where there is higher productivity. Gyres cover a large fraction of ocean area, but they tend to be far from convenient ports (requiring long transits) and often have been avoided specifically because they lack a continuous and detailed sedimentary record. The South Pacific Gyre is the largest of the ocean gyres and its center is farther from continents than the center of any other gyre. Surface chlorophyll concentrations and primary photosynthetic productivity in the seawater are lower in this gyre than in other regions of the world ocean [Behrenfeld and Falkowski, 1997]. Drilling of upper basement within the South Pacific Gyre allows testing of hypotheses related to factors that limit hydrothermal circulation and chemical habitability in aging oceanic crust, and contains a continuous swath of oceanic crust with thin (1–100 m) sedimentary cover spanning thousands of kilometers and >100 M.y. of seafloor age [Expedition 329 Scientists, 2011b].
2. Crustal petrology and alteration

Site U1365 lies at the western edge of the age transect, on ~100 Ma crust [Expedition 329 Scientists, 2011a]. The 75 m thick sediment section consists of zeolitic metalliferous pelagic clay, porcellanite and chert, and dark brown metalliferous clay. Basement section was cored to 53.5 mbsf 74.6% recovery, and consists of aphyric to highly phric basalts with plagioclase, clinopyroxene and olivine phenocrysts. The upper volcanic crust comprises mainly massive lavas and a few thin flows. Breccias and hyaloclastite occur in interflow zones. K$_2$O/TiO$_2$ ratios of basalts range from 0.02 to 0.42, indicating a range from depleted to enriched compositions or possibly resulting from alteration.

Low-temperature hydrothermal alteration at Site U1365 is highly variable in extent and ranges from <2% in the centers of massive flows to 95% in brecciated units and near flow margins (Figure 3). Alteration products comprise saponite, celadonite, iron oxyhydroxides, and carbonate, as well as rare zeolite, sulfides (chalcopyrite and pyrite), and quartz, with both background alteration and halos alongside veins. The halos are variably dark green to black, green/brown, or red, and are more altered than the host rock. Some "mixed" halos are exceptionally wide (1-4 cm), indicating multiple episodes of fluid flow. Veins average 14/meter, with late calcite veins being the most common, and with fewer veins of celadonite, Fe-oxyhydroxide, and saponite.

The upper igneous crust at Site U1367 is 33.5 M.y. old [Expedition 329 Scientists, 2011c]. Sediment consists of pelagic clay overlying carbonate ooze. Thirty six meters of basement were drilled below 20 m of sediment, with 11.2% recovery. Basement consists of aphyric to sparsely plagioclase phric depleted N-MORB, and comprises fractured pillow fragments and a thin flow. Basalt from Site U1367 exhibits typical alteration effects, similar to rocks from Site U1368.
(described below), although the extent of alteration is lower at Site U1367 and >75% of the core appears fresh. [Expedition 329 Scientists, 2011c]. The most pronounced alteration at Site U1367 occurs in alteration halos along veins. Veins average 20/meter and contain saponite, celadonite, Fe-oxyhydroxides, and rare carbonate and pyrite.

Site U1368 is located on 13.5 M.y. old crust near the gyre center [Expedition 329 Scientists, 2011d]. Sediment (mainly pelagic clay and calcareous ooze) was cored in Holes U1368B–U1368E, with basalt fragments in the basal cores of Holes U1368B and U1368D. Hole U1368F penetrated 103.3 m of basement with 27.6% recovery. Basement comprises aphyric to sparsely plagioclase ± clinopyroxene ± olivine phryic massive and sheet flows and fractured pillow basalts, all having N-MORB compositions. The deepest unit is a >1 m thick volcanioclastic breccia [Expedition 329 Scientists, 2011d].

The extent of low-temperature alteration in basement from Site U1368 ranges from <2% in the interior of massive flows to 60% in breccia and at flow margins. Alteration is similar to that in other Leg 329 basement, with pervasive saponitic background alteration and dark celadonite-bearing alteration halos along veins. Carbonate, zeolites, and sulfide are rare. Apart from the shallowest core, Fe-oxyhydroxide are rare in Hole U1368F basalts. Veins are less frequent (10/meter) than in at Sites U1365 and U1367, and contain, Fe-oxyhydroxide, saponite, celadonite, minor late calcite, quartz and rare zeolite and pyrite [Expedition 329 Scientists, 2011d].

3. Geophysical measurements

Geophysical logs from U1368F included caliper, gamma ray emission, bulk density, electrical resistivity, and formation microscanner, with data collected in the upper 80 msb
[Expedition 329 Scientists, 2011d]. The borehole diameter is irregular, with over-gauge zones 1 to 5 m thick occurring every 5 to 10 m. These zones tend to be the least electrically resistive, likely because of the enlarged borehole and because these intervals correspond to regions of higher porosity. Several of the large diameter zones also have elevated natural gamma ray emissions, a characteristic that is commonly attributed to alteration in the upper crust.

A site survey prior to Expedition 329 included heat flow measurements to assess the extent of hydrothermal heat extraction across a broad area of common basement exposure [D’Hondt et al., 2011]. Measurements were made with outrigger probes attached to gravity and piston core barrels, on seafloor aged ~15 to 100 M.y. Of seven sites where heat flow measurements were made during the site survey, six yielded values within one standard deviation of the global mean on the basis of seafloor age and standard lithospheric cooling curves (including locations close to Sites U1366, U1367, and U1368). Close to Site U1369, measured heat flow was anomalously low (only ~25 mW/m²), suggesting that there may be unusually efficient extraction of lithospheric heat by fluid flow in this setting. In fact, data collected using surface probes across the South Pacific Gyre show considerable scatter [D’Hondt et al., 2011], suggesting that local redistribution of heat may occur along with advective extraction.

Heat flow measured during Expedition 329 at Sites U1365 and U1370, on 100 M.y. old and 75 M.y. old seafloor, respectively, is consistent with conductive cooling of the lithosphere [Expedition 329 Scientists, 2011a; e]. In contrast, heat flow measured during Expedition 329 at Site U1371 is somewhat lower than the global mean for 75 M.y. old seafloor [Expedition 329 Scientists, 2011f], but still within one standard deviation of global data binned by age.
F. Adjacent to the Mid-Atlantic Ridge and Atlantis Transform Fault, northern Atlantic Ocean, ~1.5 to 2.0 M.y. old upper and lower crust and upper mantle (IODP Expeditions 304 and 305)

1. Background and context

The main objective of Expeditions 304 and 305 was to understand the formation of oceanic core complexes and exposure of upper mantle rocks at the Atlantis Massif on the 1.5-2.0 Ma western flank of the Mid-Atlantic Ridge (MAR) at 30°N [Expedition 304/305 Scientists, 2006d]. The "corrugated" central massif is inferred to have been formed by detachment faulting during or soon after crustal formation [e.g., Blackman et al., 1998; Cann et al., 1997]. The detachment fault at this dome-shaped massif is exposed over an area 8–10 km wide and 15 km long. There is an adjacent basaltic block (to the east) interpreted to be the hanging wall of the detachment fault, and seafloor is covered by a thin drape of variably lithified sediment, volcanic deposits, and rubble.

2. Petrology and Alteration

Hole U1309D was drilled 14-15 km west of the MAR axis, penetrating the central dome of the Atlantis massif to 1415.5 meters below seafloor (with a thin sediment cover of 2 m), and recovering 75% of the cored interval [Expedition 304/305 Scientists, 2006b]. The basement is divided into 770 units comprising dominantly crustal rock types, including basalt (~3%) and gabbroic rocks (~91%). Interlayered with these are several olivine-rich rock types (~5%; dunites, wehrlites, troctolites), which may be in part primitive cumulates. Also present in the upper 180 m are a few thin mantle peridotite intervals [Expedition 304/305 Scientists, 2006b].
The gabbroic rocks are mainly gabros, including gabbnorite and orthopyroxene-bearing gabbro, making up 55.7% of the core. Olivine gabbro (25.5%) is the second most abundant rock type, followed by oxide gabbro (7%). Contact relations suggest that gabbro is generally intrusive into the more olivine rich rocks (olivine gabbro and troctolite), and that the gabbroic rocks are intruded by felsic dikes and oxide gabbro. Subhorizontal sheets or sills of diabase intruded other rocks at several depths late in the intrusive history of the site. The gabbroic rocks are primitive, having Mg numbers of 67–87, and may be cumulates related through crystal fractionation to the diabases, which are tholeiitic basalt and minor basaltic andesite.

The fault zone of the detachment is restricted to within tens of meters of the seafloor, as indicated by fragments of brecciated talc-tremolite fault schist and fractured metadiabase in several short drill holes at Site U1309, and lack of core recovery in the uppermost 20 m of Hole 1309D [Expedition 304/305 Scientists, 2006b]. Paleomagnetic data reveal variable rotations between several distinct, few-hundred meter thick sections and less rotation in the upper 180 m, indicating more complicated structural evolution than simple models for detachment faults. Logging data, low core recovery and cataclasis at 108-126 mbsf and 685-785 mbsf indicate fault zones. The core is divided into three structural units based on these and another zone of cataclasis and crystal-plastic deformation.

Site U1310 lies in the hanging wall ~10 km west of the rift valley axis and ~600 m east of the termination of the detachment fault exposed on the central dome [Expedition 304/305 Scientists, 2006a]. Hole U1310B penetrated 5 m of sediment, and recovered pillow basalt fragments from the uppermost 13.5 m of basement. The sparsely olivine + plagioclase phryic basalts have N-MORB compositions. Site U1311 is located near the termination of the detachment fault and may lie either in the hanging wall or in a klippe atop the footwall [Expedition 304/305 Scientists,
Drilling in Hole U1311A penetrated 12 mbsf, through 3.5 m of unconsolidated mud and into moderately plagioclase-olivine phryic pillow basalt (with 13% recovery), which is similar in composition to rocks recovered from Site U1310.

Seawater-rock interactions manifest in core from Hole U1309D range from granulite to zeolite facies and alteration assemblages and vein fillings record the unroofing and uplift of the Atlantis Massif [Blackman et al., 2011; Nozaka et al., 2008]. Alteration intensity is highly variable, but generally decreases down hole. Commonly, sections of core reveal retrograde overprinting of earlier high-temperature metamorphism by later low-grade conditions. Alteration intensity is a function of time-integrated fluid flow, but also dependents on the nature of the rocks. For instance, olivine gabbros and troctolites are more reactive that gabbro, because of the strong contrast in chemical potentials between olivine and plagioclase [e.g., Frost et al., 2008].

Given the lithological heterogeneity of the basement at Site 1309, it is difficult to link the extent of alteration to the intensity of flow of seawater-derived fluids.

The history of alteration began with the dynamic recrystallization of olivine, clinopyroxene, plagioclase, and brown hornblende under granulite to upper amphibolite-facies conditions during mylonitic deformation [Blackman et al., 2011]. Breakdown of clinopyroxene to hornblende under amphibolite-facies conditions is localized in and around mylonitic deformation zones. The continued inflow of seawater-derived fluids led to increasing background alteration facilitated by the generation of microcracks, which helped to distribute fluids across a large volume of rock. This static background alteration is most pronounced in the uppermost 300 m of the basement and decreases in intensity down hole. Actinolitic hornblende and secondary plagioclase (± epidote) formed in the gabbros and oxide gabbros, whereas olivine-rich lithologies grew chlorite-tremolite(±talc) coronas along olivine-plagioclase grain boundaries. When the system
had cooled to lower greenschist-facies temperatures, olivine underwent serpentinization, driving
alteration of plagioclase to prehnite and hydrogrossular in olivine-rich lithologies [Frost et al.,
2008]. This rootingitization reaction also affected the contacts between gabbro and peridotite
screens, where talc-tremolite±talc veins developed in the ultramafic rocks. The same talc-
tremolite±talc assemblage is developed in the uppermost 25 m of the basement, where strain
localization took place along the detachment. Late-stage prehnite to zeolite-facies veins have
saponite+zeolite, zeolite, carbonate, and occasional anhydrite. These veins do not show a
systematic relation to high-temperature deformation, lithology or depth in the hole. They are
likely related to the recent and rapid uplift of Atlantis Massif [e.g., Nozaka and Fryer, 2011;
Nozaka et al., 2008]. Carbonate±sulfide veins are abundant in the uppermost 700 m of the
basement at Site 1309. Below 700 mbsf, zeolite-prehnite and saponite-zeolite veins dominate.
Vein density is highly variable and peaks at >30 veins/meter.

3. Geophysical Measurements
The upper 94 m of basement penetration was logged in Hole U1309B, and measurements
extended to >1400 msb in Hole U1309D [Expedition 304/305 Scientists, 2006b]. Hole U1309D
was revisited for additional logging during Expedition 340T [Expedition 340T Scientists, 2012].
Wireline tools deployed in these holes included natural gamma ray emission, bulk density,
electrical resistivity, neutron porosity, sonic velocity, borehole temperature and formation
imaging. In addition, detailed vertical seismic profile experiments were completed to assist with
correlation between regional and borehole geophysical data.
Hole conditions were generally very good to excellent throughout the cored interval, and core
recovery was high, allowing direct interpretation of differences in log response in terms or
primary or secondary lithology and structure [Expedition 304/305 Scientists, 2006b]. Natural
gamma ray emissions are generally low in the rocks of Site U1309, but there are thin zones of
elevated values. One of these natural gamma anomalies (near 750 mbsf) corresponds to an abrupt
increase in formation electrical resistivity, and an increase (and reduction of variability) in bulk
density. That change in geophysical properties is associated with an interval containing up to
20% of basalt diabase, in contrast to overlying and underlying intervals comprising mainly
gabbro and gabbronorite. Formation resistivity decreases again at 1100 mbsf. Sonic velocities
generally increase with depth into the crust, although there are local excursions where lower
velocities generally correlate with lower bulk density and electrical resistivity.

   Borehole imaging data (electrical and sonic) suggests that small intervals of borehole
enlargement often correspond to open faults and fractures. Comparison of core and geophysical
logging data shows a strong correlation between deviations in logging parameters (e.g., lower
bulk density and sonic velocity) and the intensity and pervasiveness of alteration. There are also
good correlations between physical properties determined in the borehole, on recovered core, and
inferred from seismic reflection studies.

   Logging data collected in Hole U1309D during Expedition 340T is generally consistent with
data collected during earlier expeditions, except for the temperature log. Much of the drilled
interval had warmed towards a pre-drilling state, but there were subtle excursions in downhole
temperature near 750 and 1100 mbsf, which correspond to abrupt changes in geophysical
properties [Expedition 340T Scientists, 2012]. Larger excursions in temperature at these depths
were also apparent in Expedition 305 data [Expedition 304/305 Scientists, 2006b], but these were
superimposed on an overall profile indicative of borehole cooling. These zones could have been
more intensively invaded by cool drilling fluids when the holes were cored, and thus would have
taken longer to recover. There is no rapid flow down Hole 1309D today, as this would suppress
the borehole thermal gradient much more than observed [e.g., Winslow et al., 2013], but there
may be slow movement of water into thin zones (fractures, faults).

III. Synthesis: Method and Site Comparisons and Trends

A. Nature of Fluid-Rock Interactions in the Ocean Crust

The volcanic sections of oceanic crust cored by IODP exhibit distributions and styles of low-
temperature alteration that are generally similar to those sampled by earlier phases of scientific
ocean drilling, including presence of secondary minerals and their distribution in veins, alteration
halos, and "background" alteration, as well as the evolution of fluids and alteration processes and
their integrated chemical influences on the rock record [e.g., Alt, 2004; Bach et al., 2004]. IODP
drilling provides valuable new insights regarding lithological controls on alteration in upper
oceanic basement and the relation between alteration and crustal spreading rate.

Prior to drilling Hole 1256D it was believed that oxidation effects (as evidenced by reddish
alteration halos) should generally decrease with depth in the volcanic section of oceanic crust
(e.g., Figure 3, Hole 504B). Hole 1256D does not show this trend with depth. Instead, alteration
halos are focused in distinct zones, indicating a strong control on fluid flow by lithology and
permeability, and halos are much less abundant in this hole than in crust formed at intermediate
spreading rates (Figure 3). In some cases, oxidation and alteration effects are concentrated at the
tops of lava flows or eruptive units, which can be rubbly and permeable, allowing focused fluid
flow. IODP drilling and logging of cores by shipboard scientists has also extended this
comparison to crust generated at slow spreading ridges, showing that alteration halos there are
comparable in abundance to those in crust formed at intermediate spreading rates (Figure 3).
The oceanic crust is a significant global sink for carbon, and carbonate is more abundant in the volcanic section of crust formed at slow spreading rates than in upper crust formed at intermediate and fast spreading rates [Alt and Teagle, 1999; Gillis and Coogan, 2011]. Vein carbonates recovered from core samples of the oceanic crust are valuable recorders of fluid chemical evolution as the seafloor ages, indicating variations in both crustal and seawater composition and temperature [e.g., Expedition 301 carbonates, Coggon et al., 2004; Coggon et al., 2010; Gillis and Coogan, 2011; Rausch et al., 2013].

Analysis of samples and data from ODP/IODP Site 1256 has also shown that sheet flows are more abundant throughout the volcanic section in crust formed at fast spreading rates, whereas pillows are more abundant at intermediate and slow rates (Figure 3) [Expedition 309/312 Scientists, 2006a; Teagle and Wilson, 2007]. This interpretation is consistent with observations made of seafloor lava flows [e.g., Carbotte and Scheirer, 2004]. A thorough understanding of the distribution of rock types found in oceanic crustal sections is limited by biased and incomplete recovery of core, but careful integration with well logs can help to place core samples in context, as demonstrated by Tominaga et al. [2009] (Figure 6). Their analysis based on wireline logging data, with an emphasis on resistivity and natural gamma ray responses, suggests that breccias and fragmented flows comprise more than 50% of the borehole interval. In contrast, the vast majority (>90%) of recovered core was classified as sheet and massive basalt flows.

Data from active experiments (e.g., fluid chemistry, hydrology) in the basement do not necessarily directly correspond with alteration effects observed in the basement rocks. For example, in Holes U1301B and 1362A the highest transmissivity occurs at 150-180 mbsf, but alteration halos are abundant throughout the basement sections (Figure 3). Current upper basement temperatures are ~65°C in these holes, but carbonates in veins formed at temperatures
of 30-40°C [Coggon et al., 2004; Coggon et al., 2010]. These differences exist because active
experiments and measurements give a snapshot of the system at the time of measurement,
whereas secondary minerals in veins provide data concerning times in the past, and bulk rocks
can integrate alteration effects over millions of years, throughout the lifetime of fluid circulation.

The temperature of water-rock interaction has important controls on the composition of
crustal fluids, as shown with a global compilation of data from upper basement fluids [Fisher
and Wheat, 2010] (Figure 7), including analyses of sedimentary pore fluids recovered from
adjacent to the sediment-basement contact [e.g., Elderfield et al., 1999; Mottl, 1989; Orcutt et
al., 2013]. For major ions involved in mainly inorganic exchange, like magnesium, there is
relatively little change in fluid composition at temperatures below about 20 °C, but solutes
involved in biogeochemical cycling (such as phosphate) show evidence of reaction at essentially
all fluid temperatures (Figure 7). In some cases, reactions may occur in both basement rocks and
in overlying sediments, with diffusional exchange between crustal and sedimentary layers.

Alteration in core samples from Hole 1256D indicate an abrupt increase in the thermal
gradient with depth (Figure 5), corresponding to an increase in alteration temperature across the
transition from lavas to dikes, similar to that documented in DSDP/ODP Hole 504B and at Pito
Deep [Alt et al., 1996; Alt et al., 2010; Heft et al., 2008]. This observation indicates different
styles of fluid circulation at depth, controlled by lithology and permeability, with higher-
temperature hydrothermal fluids in the dikes and cooler seawater fluids in the volcanic section at
the spreading axis, and continued low-temperature circulation in the lavas on the ridge flank.
Cores from Hole 1256D also reveal a step in the thermal gradient at the dike-plutonic boundary,
corresponding to contact metamorphism of the lowermost dikes driven by intrusion of
underlying gabbros at the spreading axis [Alt et al., 2010; Koepke et al., 2008].
Studies of lower crustal rocks from Hole 735B, the deepest seafloor penetration into plutonic rocks, showed that metamorphism, fracturing, and fluid penetration occurred over a wide range of conditions [Bach et al., 2001; Dick et al., 2000]. Results from gabbroic rocks from Hole 1309D generally show a similar range of alteration styles, from granulite and amphibolite facies reactions down to low-temperature smectite formation [Blackman et al., 2011]. In contrast, cores from Hole U1309D differ in having a greater abundance of olivine-rich rocks, making serpentinization reactions especially important, and lacking evidence for subgreenschist conditions. Nozaka et al. [2008] interpret this to indicate rapid uplift of the Atlantis Massif (Hole U1309D) in comparison to Atlantis Bank (Hole 735B), but there could also be different fracturing histories during cooling. This would be consistent with packer testing results from Hole 735B, which suggested considerable permeability at present [Becker, 1991], but temperature logs from Hole U1309D that suggest dominantly conductive conditions [Expedition 340T Scientists, 2012].

Study of basalts recovered during scientific ocean drilling show that microbial activity in basement results in formation of trace fossils in basalt glass and affects the geochemistry of sulfur in the rocks [e.g., Alford et al., 2011; Alt et al., 2007; Fisk et al., 1998; Furnes and Staudigel, 1999; Furnes et al., 1999]. Work on IODP cores has shown that the influence of microbes in the subsurface biosphere is widespread and affects carbon geochemistry [Alt and Shanks, 2011; Lever et al., 2013; Ono et al., 2012]. In a study of Hole 1256D, Alt and Shanks [2011] show that microbial effects on sulfur in volcanic basement are mostly complete within about 15 M.y., with sulfate reduction rates comparable to those in deep sea sediments.

Lever et al. [2013] documented links between alteration halos, sulfur, organic carbon, and genetic evidence for consortia of microbes in the basalt from IODP Hole 1301B, and correlate...
these with compositions of basement fluids sampled from nearby IODP boreholes and basement outcrops [e.g., Wheat et al., 2004; Wheat et al., 2010]. Traces of organic carbon in lower crustal rocks from IODP Hole 1309D suggest the presence of a heterotrophic microbial community [Mason et al., 2010]. However, assessing the abundance and activity of microbial life in the subseafloor remains challenging. Santelli et al. [2010] noted the difficulty of detecting subcrustal life using common DNA-extraction techniques in basaltic rocks from cold and sediment-starved systems, although an earlier study found evidence for abundant and rich bacterial life on top of lava flows exposed at the seafloor using a similar approach [Santelli et al., 2008]. The mechanism and extent of microbial colonization of the subseafloor, and the metabolic and genetic diversity among different settings (basaltic vs. gabbroic vs. ultramafic; warm vs. cold, sediment-rich vs. sediment-starved) hence remain uncertain. CORKs provide opportunities for sampling and experimentation aimed at understanding subseafloor life and rock alteration under more pristine conditions [e.g., Edwards et al., 2012a; Edwards et al., 2012b; Orcutt et al., 2010a; Orcutt et al., 2010b; Smith et al., 2011].

B. Hydrologic Properties in the Oceanic Crust

There is considerable heterogeneity in the distribution, extent, and nature of physical changes to the ocean crust resulting from water-rock interaction and alteration. This heterogeneity indicates the dependence of rock alteration on local conditions, including temperature, water-rock ratio, fluid composition, and initial rock properties such as porosity and permeability. Evaluating these conditions on the basis of core samples from the upper and middle levels of volcanic ocean crust is challenging, because core recovery in these intervals tends to be both low
and biased towards more massive lithologies. In contrast, recovery tends to be much greater in
the lower crust, but there is less evidence there for rapid fluid circulation.

Geophysical logs offer advantages in providing nearly continuous data coverage in basement
boreholes, but measure conditions in the crust at larger scales. A comparison of age trends in
physical properties (from multiple DSDP, ODP and IODP holes) using core and wireline logging
data illustrates how measurements made at different scales may be related [Bartetzko and Fisher,
2008] (Figure 8). Sonic velocity, electrical resistivity, bulk density, and total gamma ray
measured with wireline tools in open boreholes in the upper basaltic crust tend to increase with
basement age, whereas sonic velocity and bulk density measured on core samples tend to
decrease. Properties determined from wireline data and core data tend to converge with
increasing crustal age. One explanation for these observations is that borehole-scale
measurements of physical properties record the infilling of small pore spaces by alteration
products of water-rock interaction. In contrast, hand samples tend to become less dense and have
lower sonic velocities as a result of the same alteration processes, as expressed in the mostly
massive samples that are recovered during coring.

Age trends in borehole permeability measurements are more difficult to assess (Figure 9).
The vast majority of packer and thermal measurements have been made in seafloor that is ≤8
M.y. old, and only a few measurements have been made along a single crustal "flow line"
produced at the same rate and by the same seafloor spreading center. Permeability data from
ODP Leg 168 and IODP Expeditions 301 and 327 [Becker and Fisher, 2000; 2008; Becker et al.,
2013] suggest that the uppermost crust of the youngest site might be the most permeable [Becker
and Davis, 2003], but there is considerable variability associated with the scale (duration), type,
and depth of measurement. An analysis of physical and hydrologic properties within the
uppermost volcanic crust suggests the permeability may remain relatively high in the largest pathways responsible for crustal-scale fluid flow, even as smaller pores and cracks become filled during water-rock interaction [Fisher and Becker, 2000]. Borehole permeability measurements are needed in moderate to older crust, produced at slow to fast spreading rates, to assess these global trends with greater confidence.

Additional insight is provided by the observation that the permeability calculated from the cross-hole response observed in Hole 1027C to long-term flow down Hole U1301B (Figure 4A) is at the lower end of estimates based on single-hole packer experiments [Fisher et al., 2008] (Figure 9). This is surprising at first, because the cross-hole test should be influenced by a much larger rock volume, extending perhaps 10–30 km from the borehole, and larger test volumes generally correspond to higher apparent permeability in heterogeneous/fractured rock systems such as the ocean crust [e.g., Clauser, 1992; Fisher, 1998; Guéguen et al., 1996]. Basement permeability estimated from this cross-hole response is also 1 to 3 orders of magnitude lower than estimates based on numerical modeling and calculations based on tidal responses and drainage following tectonic strain events, which evaluated similar crustal volumes [Davis and Becker, 2002; 2004; Davis et al., 1997; Davis et al., 2004; Wang et al., 1997].

One possible explanation for the differences in inferred properties based on these methods is that permeability in the crust around Site U1301 is anisotropic. Anisotropy in the seismic properties of oceanic basement rocks is thought to result from preferential orientation of cracks, faults, and fractures (i.e., the crustal "fabric") [e.g., Sohn et al., 1997; Stephen, 1981]. The dominant crustal fabric is generally thought to be subparallel to the orientation of the mid-ocean ridge where the crust was created. This fabric may favor fluid flow in the crust in the "along-strike" direction [Delaney et al., 1992; Haymon et al., 1991; Wilcock and Fisher, 2004], an
interpretation consistent with geochemical and thermal data from the Expedition 301/327 field area [Fisher et al., 2003; Hutnak et al., 2006; Walker et al., 2007; Wheat et al., 2000]. Azimuthal anisotropy could influence the permeability apparent from a cross-hole experiment involving a single observation borehole (Figure 4B). If the angle of measurement is oblique relative to the direction of greatest permeability (as between Holes U1301B and 1027C), the measured value will be very close to that in the lowest-permeability direction, even for a large anisotropy ratio.

Along-strike consistency of crustal hydrologic properties in this area, at a kilometer scale, is indicated from comparison of packer and wireline logging responses, and rates of drilling penetration, from Holes U1301B and U1362A [Becker et al., 2013; Expedition 301 Scientists, 2005b; Expedition 327 Scientists, 2011b]. Similar consistency is not apparent in crustal layering on the basis of core descriptions, but this may result from local heterogeneity at the hand-sample scale and/or limited recovery across upper crustal intervals.

C. Future Needs and Frontiers

The observations and interpretations presented in this chapter remain somewhat limited by the numbers and locations of boreholes that penetrate into the igneous oceanic crust (Figure 2). Although scientific ocean drilling is filling gaps across the global map, as a function of seafloor age and spreading rate, there need to be more opportunities to sample, analyze and test multiple basement holes from individual areas. This is often not done during scientific ocean drilling because of the cost and time required to establish, drill, sample, test and instrument basement holes, but results from individual holes raise questions about whether these sample points are representative, and how properties and processes may vary laterally, with age, and with proximity to features such as fracture zones and areas of basement exposure. These questions can
be addressed, in part, by drilling age transects to assess the evolution of ocean crust as a result of fluid-rock interactions.

There are ongoing experiments, results of which are currently incomplete, that were designed to test the nature of permeability and advective transport conditions in upper basement on the eastern flank of the Juan de Fuca Ridge. In 2011, after the new CORKs installed during Expedition 327 were permitted to equilibrate for a year following drilling, a large diameter ball valve was opened on the wellhead of the CORK in Hole U1362B. Downhole temperature loggers and a flowmeter attached to the discharging wellhead were deployed to help to assess the rate at which fluids discharged from the overpressured formation for the next two years, and the long-term pressure response from surrounding CORKs will help to determine both crustal-scale properties and the extent of permeability anisotropy (vertical, azimuthal). In addition, about 500 m$^3$ of fluid and tracers (gas, solute, particles) were injected into the formation around Hole U1362B in 24 hours as part of a cross-hole tracer experiment initiated during IODP Expedition 327. Multi-year records of tracer recovery are being developed from fluids collected with Osmosamplers and active pumping systems deployed on multiple CORK wellheads before and after tracer injection. Additional records will come from Osmosamplers and temperature loggers deployed below CORKs in Holes U1362A and U1362B, which will be recovered in Summer 2014.

Drilling deeper basement holes remains important for exploration of hydrothermal processes and effects in the crust. Further drilling in Hole 1256D (or elsewhere) through the uppermost gabbros will allow testing of petrological and geophysical models for melt lenses at mid-ocean ridges. Such drilling will also enable testing of how hydrothermal metamorphism, fluid fluxes, and heat transport in high-temperature axial hydrothermal systems are related to...
these bodies, and help reconcile budgets for hydrothermal heat, fluid fluxes, and chemical fluxes.

Drilling in nearby ("pilot") holes can be helpful for assessing lithologic and alteration heterogeneity, and could facilitate cross-hole tests that measure rock properties and fluid flow at the scale of crustal fluid flow.

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**Figure Captions**

**Figure 1.** Map showing locations of drilling sites at which boreholes discussed in this chapter were created or occupied during IODP. One or more holes were drilled at each of the sites shown. Table 1 provides details on hole depths, lithologies encountered, and measurements made. Continental topography and ocean bathymetry shown for reference [Ryan et al., 2009].

**Figure 2.** Plot showing total depth and general lithology for basement holes drilled during IODP (hole labels in bold italic, lithology with dark shading), and holes having ≥100 m of basement penetration from DSDP and ODP for comparison (figure modified from Shipboard Scientific Party [2006b]). Drilling, coring, and logging intervals for most IODP basement holes are listed in Table 1.

**Figure 3.** Lithology and proportion of alteration halos along veins versus depth for volcanic oceanic basement holes in crust grouped by fast, intermediate, and slow spreading rates. More abundant sheet flows and much lower proportion of alteration halos in crust generated at fast spreading rates may indicate control of fluid flow and low-temperature alteration by lithology and permeability [Alt et al., 2010]. Hole 801C contains features not typical of the upper (generally, basaltic) oceanic crust, including a low-temperature hydrothermal deposit with associated alteration, and late alkalic sills that contain abundant alteration halos at top of basement [Alt and Teagle, 2003]. Sheet flows may be more abundant than indicated [Tominaga et al., 2009]. Figure modified from Alt et al. [2010], with additional data from IODP Sites U1301 [Expedition 301 Scientists, 2005a], U1362 [Expedition 327 Scientists, 2011a], and U1382 and U1383 [Expedition 336 Scientists, 2012a; b].
Figure 4. Data from hydrogeologic experiments in the IODP Expedition 301/327 field area [plots modified from Becker and Fisher, 2008; Fisher et al., 2008]. A. Observations and calculations from crosshole test. A. Filtered pressure time record from Hole 1027C, beginning 6 months before and ending 13 months after Expedition 301. Striped vertical band indicates period of basement drilling, coring, casing, and testing operations during Expedition 301. Smooth curve shows least-squares best fit of observations to analytical calculations for the pressure response in Hole 1027C, 2.4 km away, to long-term flow into Hole U1301B. The fit of this curve indicates basement permeability of $k = 0.7 \times 10^{-12}$ m$^2$. Inset: Similar fit to short term (1-hour) packer experiment in Hole 1301B, illustrating fit of the same model. Note relatively large change in pressure during this test (up to 50 kPa) versus that seen from the cross-hole response (~1.5 kPa).

B. Calculations of the effective transmissivity ratio (apparent transmissivity/highest transmissivity) as a function of the angle of measurement. Vertical band is orientation of the Site U1301 to Site 1027 experiment, assuming that the direction of highest transmissivity is N20°E (subparallel to the crustal fabric) and the direction of lowest transmissivity is perpendicular to this, N110°E.

Figure 5. Basement lithology, distribution of secondary minerals, and estimated alteration temperatures for Hole 1256D [modified from Alt et al., 2010]. Figure illustrates stepped temperature gradient with depth. Secondary minerals and temperature estimates indicate low temperature seawater fluids in the volcanic section and upwelling high-temperature hydrothermal fluids in the dikes. Stepwise temperature increase at lavas-dikes transition results from mixing of these fluids at this lithologic boundary. Stepwise increase at~1350 mbsf indicates heating and
contact metamorphism of lowermost dikes from underlying gabbroic intrusion. Range of
temperatures in plutonic and dike sections results from retrograde reaction during cooling.
Temperatures estimated from oxygen isotope analyses of secondary minerals, mineral equilibria,
and fluid inclusions.

Figure 6. Comparison of rock types in the volcanic section indicated by shipboard core
descriptions (left) and analysis of electrofacies (geophysical logs) to identify igneous
stratigraphy (right) [modified from Tominaga et al., 2009]. Pie slices and numbers indicate the
percent of each rock type identified. Shipboard lithostratigraphic data was tabulated from visual
core descriptions from Leg 206, Expedition 309 and 312 [Expedition 309/312 Scientists, 2006a;
Shipboard Scientific Party, 2003] by calculating a total of recovered core length of each rock
type divided by a total of recovered core length. Recovery was highly variable, but was
particularly low in zones containing breccia and heavily fractured rock.

Figure 7. Concentrations of magnesium and phosphate in ridge-flank fluids from the upper
portion of basaltic basement plotted versus measured and inferred temperatures at the sediment-
basement contact [figure modified from Fisher and Wheat, 2010]. These plots are based on a
global compilation of DSDP, ODP, and IODP data, and analyses of samples collected with
traditional gravity and piston corers, and from seafloor seeps and springs. Data are classified
qualitatively to indicate quality.

Black and white version: circle = highest quality; square = moderate quality; diamond = fair
quality. Horizontal dashed lines indicate typical concentrations in bottom seawater. Solid
lines/curves show global trends based on the highest quality data.
Color version: red circle = highest quality; blue square = moderate quality; black diamond = fair quality. Green dashed lines indicate typical concentrations in bottom seawater. Pink solid lines/curves show global trends based on the highest quality data.

**Figure 8.** Comparison of geophysical logging (borehole) and physical properties (hand sample) values from the upper ocean crust as a function of basement age [updated from Bartetzko and Fisher, 2008], based on selected data from DSDP, ODP, and IODP boreholes. Data are from Holes U1301, 504B, 896A, 395A, 1256D, 1224F, 418A, and 801C, with means of logging data plotted using filled symbols and means of core data plotted using open symbols. Lines are least squares best fits based on a semi-logarithmic trend (but note log$_{10}$ scale for electrical resistivity values) with correlation coefficients shown. Solid lines are significant with >99% confidence [Bartetzko and Fisher, 2008].

**Figure 9.** Compilation of borehole measurements of permeability in the volcanic ocean crust (based on summary presented in Becker and Fisher [2008], with additional data from Fisher et al. [2008], Becker et al. [2013], and Winslow et al. [2013]. Most data are from packer experiments (P) and borehole thermal logs (T), but there is a single cross-hole test, as shown.

Black and white version: Data collected during DSDP and ODP are shown in gray with patterns. Color version: Data collected during DSDP, ODP, and IODP are coded by color and pattern, with DSDP and ODP data being partly transparent.
Table 1. Summary of characteristics for IODP holes with significant basement penetration.

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**a** TD = total depth of hole, mbsf = meters below seafloor, msb = meters sub-basement.

**b** Core top = depth of bit when first coring began, Core bot = depth of bit when final core ended.

**c** Log top = approximate depth of shallowest open hole log data collected in basement, Log bot = approximate depth of deepest open hole.

**d** RF = Ridge flank, RF-OCC = Ridge flank, oceanic core complex, RF-S = Ridge flank at subduction zone, LIP = Large igneous province, SM = Seamount.
Age as cited in expedition reports, generally based on magnetostratigraphy, radiometric dating, or paleontological analysis of basal sediments.

Hole U1309D was drilled on IODP Expeditions 304 and 305, then revisited for additional logging on Expedition 340T.

Hole 1256D was first drilled, cored and logged on ODP Leg 206.

Results from drilling on IODP Expeditions 324 (Shatsky Rise) and 330 (Louisville Seamounts) are not discussed in this chapter, although these expeditions had significant basement penetration, coring and downhole measurements.
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