IODP Expedition 327: Juan de Fuca Ridge-Flank Hydrogeology

Site U1362 Summary

31 August 2010

Background

Regional basement relief on the eastern flank of the Endeavour segment of the Juan de Fuca Ridge is dominated by linear ridges and troughs oriented subparallel to the spreading center and produced mainly by faulting, variations in magmatic supply at the ridge, and off-axis volcanism. Basement rocks are covered in most of Cascadia Basin by thick turbidites that flowed west from the continental margin, mainly during the Pleistocene sea level lowstands. The low permeability sedimentary cover limits advective heat loss across most of the ridge flank, but there is vigorous fluid circulation in basement throughout this area. Leg 168 and Expedition 301 drilled a series of sites across 0.9–3.6 Ma seafloor, collecting sediment, rock, and fluid samples; determining thermal, geochemical, and hydrogeologic conditions in basement; and installing a series of CORK observatories in the upper crust (Davis, Fisher, Firth, et al., 1997; Fisher, Urabe, Klaus, et al., 2005).

The primary scientific objectives at Site U1362 (Scientific Prospectus Site SR-2; Fisher et al., 2010) were to drill two new basement holes, ~200 m south-southwest of Hole 1026B and ~800 m north-northwest of Hole U1301B, where sediment thickness is ~250 m. Seismic coverage in this area is detailed, and holes were located along the peak of the buried basement ridge, much like Expedition 301 Holes U1301A and U1301B and Leg 168 Hole 1026B. Hole U1362A, the deepest of the two new holes, was designed to penetrate the sedimentary section and the uppermost 100 m of basement with coring planned only for ~100–260 mbsf and the final hole depth determined by hole conditions and available time. The operations plan included wireline logging with a single string, testing for permeability using the drill string packer, and instrumenting the borehole with a multilevel CORK. Hole SR-2B, the shallowest of the new holes, was designed to penetrate the sedimentary section and the uppermost ~70 m of basement with no coring or logging planned. CORK instruments are designed to monitor formation fluid pressure and temperature, sample fluids (using downhole and wellhead OsmoSamplers), and provide growth substrate for microbes inhabiting the basement aquifer. A pumping and tracer injection experiment was designed to take place for 24 h before Hole U1362B CORK was instrumented.

Operations

The *JOIDES Resolution* departed on 9 July 2010 from Victoria, B.C., and arrived at Site U1362 at 0815 hr on 10 July. Seafloor was tagged at 2672 mbrf. Two jet-in tests were conducted 15 m from the coordinates of Holes U1362A and U1362B to determine the length of the first casing string.

Hole U1362A

Drilling operations at Hole U1362A consisted of the following intermittent stages between 12 July and 11 August: (1) deploying a reentry cone with 20 inch casing to 53 m below seafloor (mbsf); (2) drilling a 21-1/2 inch hole to 235.7 mbsf (18-1/2 inch hole to 242 mbsf), deploying 16 inch casing to 230 mbsf, and cementing the bottom of the hole; (3) drilling a 14-3/4 inch hole to 346 mbsf, deploying 10-3/4 inch casing to 308.5 mbsf, and cementing the bottom of the hole; (4) coring from 346 to 496 mbsf; and (5) drilling a 9-7/8 inch hole to a total depth of 528 mbsf. Drilling was followed by wireline logging on 12 August and a packer flow test on 12–13 August (see “Science Results”). The L-CORK and instrument string were deployed on 13–17 August. The CORK assembly extends to 470 mbsf, with the entire instrument string enclosed within the 4-1/2 inch casing.

Hole U1362B
Drilling operations at Hole U1362B consisted of the following intermittent stages between 17 July and 22 August: (1) deploying a reentry cone with 20 inch casing to 53 m below seafloor (mbsf); (2) drilling a 21-1/2 inch hole to 243.7 mbsf (18-1/2 inch hole to 250 mbsf), deploying 16 inch casing to 242 mbsf, and cementing the bottom of the hole; (3) drilling a 14-3/4 inch hole to 282 mbsf, deploying 10-3/4 inch casing to 272 mbsf, and cementing the bottom of the hole; and (4) drilling a 9-7/8 inch hole to a total depth of 359 mbsf. Drilling was followed by a 24 hr flow and tracer injection experiment on 22 August (see "Science Results"). The L-CORK and instrument string were deployed on 28–29 August. The CORK assembly extends to 312 mbsf, with the entire instrument string enclosed within the 4-1/2 inch casing.

Science Results
Petrology, hard rock geochemistry, and structural geology
Basement was cored from 346.0 to 496.0 mbsf (110 to 260 m sub-basement [msb]) in Hole U1362A with 45.27 m of core recovered. The recovered core consisted of (1) aphyric to moderately phyric pillow basalts, (2) aphyric to sparsely phyric sheet flows, and (3) sparsely to highly phyric basalt flows. The above lithologies were divided into eight units based on changes in lava morphology, texture of the rock and phenocryst occurrence. Pillow lava units (Units 1, 3 and 5) were subdivided according to changes in phenocryst abundance and mineralogy. Sheet flow units (Units 4, 6 and 8) were subdivided based on the presence of chilled margins and variations in phenocryst mineralogy. No breccia units were recovered with only two centimeter-sized breccia pieces recovered in total.

Pillow basalt forms the most abundant flow morphology of Hole U1362A with Units 1, 3 and 5 accounting for 78.85 m of the stratigraphy. Pillow basalt was primarily identified by the occurrence of curved glassy chilled margins with perpendicular radial cooling cracks. They are sparsely to highly phyric with olivine, clinopyroxene and plagioclase phenocrysts present with spherulitic, hyalophitic, intersertal and glomeroporphyritic textures. Pillow basalts range from sparsely to moderately vesicular with a range of secondary minerals filling the vesicles. Alteration in the pillows is variable and ranges from slight to highly altered.

Sheet flows are the second most common lava morphology in Hole U1362A and were classified on the basis of continuous sections of the same lithology with an increase in grain size downwards through the unit. Core recovery in these units averaged 43% and was up to 119% in Core 17R. Two near continuous sheet flows were recovered in Cores 17R and 18R and were divided into two subunits based on a change in phenocryst mineralogy. The primary mineralogy of the sheet flows is very similar to the pillow basalts with a range from aphyric to moderately phyric basalt with olivine, clinopyroxene and plagioclase phenocrysts. The grain size within the sheet flows ranges from cryptocrystalline up to fine grained and textures vary from intersertal to intergranular. The sheet flows are non-vesicular to highly vesicular with some flows exhibiting similar abundance throughout and others high variability within the flow. Alteration within the sheet flows varies from slight to complete. Fracture and vein intensity within the sheets flows are lower than in the pillow basalts and resulted in improved core recovery and larger individual.

The third lithology type of basalt flows was classified based on the absence of definitive morphological features associated with either pillow lavas or sheet flows, allowing only a general "basalt flow" interpretation to be made. These units are aphyric to moderately phyric crypto- to microcrystalline basalt with the same primary mineralogy as all basalts from Hole U1362A. They are generally sparsely vesicular with secondary minerals filling vesicles and textures vary from hyalophitic to variolitic. Alteration is moderate to high and is present as groundmass replacement (mesostasis and phenocrysts), vesicle fill, vein formation and halos.

Two individual pieces of breccia were recovered, a hyaloclastite sample in Core 13R and a hydrothermal breccia vein in Core 9R. The hyaloclastite is characterized by moderately to highly altered angular clasts in a saponite and altered glass matrix. The hydrothermal breccia vein is formed of sub-angular clasts with moderate alteration similar to the host rock and exhibits evidence of clast rotation and separation with a matrix of highly altered ground up basalt.

Geochemical analyses of basalt samples indicate that they are all normal depleted mid-ocean-ridge basalt (MORB) and based on cross plots of TiO_2 vs Zr are inferred to all have the same magmatic source. Hydrothermal alteration of the basement is observed in all basalts from Hole U1362A and varies from slight to completely altered with the majority moderately altered. Alteration of the rocks manifests in four ways: (1) replacement of phenocrysts, (2) replacement of groundmass (mostly mesostasis), (3) filling veins and adjacent alteration halos, and (4) lining and filling vesicles. In thin section the alteration is observed to range from 8% to 91%. Away from vesicles and veins, background alteration is generally moderate to high in pillow lavas and predominately moderate in sheet and basalt flows, and is dominated by saponitic background alteration. Olivine is present only as completely replaced pseudomorphs.

The secondary mineralogy is dominated by clay minerals that are present in all four types of alteration. Saponite is the most abundant of the clay minerals and is present as black, dark green, greenish brown and pale blue colors and in thin section is characterized by pale brown color and mottled or fibrous form. Celadonite is also present in all four styles of alteration but is less abundant than saponite. In thin section celadonite is bright green in color and within some vesicles the color varies in intensity reflecting a mix of saponite and celadonite. Iron oxyhydroxide is the second most abundant secondary phase occuring both alone as iron oxyhydroxides and mixed with saponite and other clay phases to form iddingsite. Iron oxyhydroxides are identified by a bright orange to red color and often stain other phases present. The zeolite phillipsite was identified by XRD analysis of mixed veins and altered chilled margins in addition to montmorillonite (smectite group) and sepiolite (clay) from veins. Carbonate is present as vesicle fill, in veins and within chilled margins and predominantly occurs mixed with clays and occasionally sulfides. Anhydrite is rarely present in veins from Subunit 6B.

A total of 1230 veins were logged with an average frequency of 27 veins per meter of recovered core. Vein width ranges from <0.1 to 4 mm and vein morphology is variable. Saponite is the most abundant vein fill and is present in 76% of the veins with unidentified clay minerals filling 50% of veins. The next most abundant vein fill is iron oxyhydroxides in 32% of veins. Carbonate and pyrite are present in 10% of veins but only occasionally as a dominant component. Celadonite occurs in 2% of veins and is a larger component of the background alteration. Rare anhydrite veins are present within Subunit 6B. Alteration halos flank 15% of hydrothermal veins and are otherwise found flanking rock edges or apparently unassociated from structural features. Halos range from single color black, green or orange halos to complex multi-halos with mixed colors.

The dips of 519 veins and fractures were measured. Three types of fractures were distinguished in the cores: (1) veins flanked by alteration halos (termed haloed veins), (2) veins not flanked by alteration halos but filled with secondary minerals (termed non-haloed veins), and (3) joints sometimes flanked by alteration halos but not filled with minerals. Non-haloed veins were the most frequently observed structures. Non-haloed veins were identified mainly in the massive lavas and some pillow lava pieces. No faults or shear veins with any evidence of displacement were found.

Physical Properties
Whole-round basalt core sections were run through the whole-round multisensor track and natural gamma ray logger (NGR) prior to splitting. Gamma ray attenuation (GRA) density data vary widely due to unfilled core liners in poor recovery sections. Despite this, peak bulk density values remained

consistent at ~2.5 g/cm^3 for much of the core recovered. For the more cohesive, massive sections recovered in deeper cores, GRA results were slightly higher than 2.5 g/cm^3. Magnetic susceptibility measurements were also widely variable, ranging from 0 to 3300 x 10^{-5} SI. Total counts from the NGR were generally low (between 1 and 5 counts/sec). For all measurements, the highest values are found in massive sections, with other lithologies, namely pillow lavas and sheet flows, generally yielding much lower values.

The three samples tested for thermal conductivity came from the uppermost section of pillow basalts, yielding values of 1.63, 1.67, and 1.72 W/[m·K] at depths of 349, 354, and 355 mbsf, respectively. These values compare well with data collected at similar depths at nearby Hole U1301B (1.70 ± 0.09 W/[m·K]). Problems with the thermal conductivity half-space system prevented additional measurements.

P-wave velocities were measured on 71 discrete samples. Velocity values determined with the automated method range from a minimum of 4.7 km/s to a maximum of 6.3 km/s, with an average of ~5.6 km/s. *P*-wave velocity values determined by manual picking of the first arrival range from a minimum of 4.3 km/s to a maximum of 6.0 km/s, with an average of ~5.4 km/s. Both averages are greater than values obtained from Expedition 301 Hole U1301B. The lowest velocity was measured on a heavily altered sample (Section U1362A-14R-1, 11–13 cm). A test of nearby unaltered material yielded much higher velocity, which demonstrates the influence of rock alteration on *P*-wave velocity. We found no statistically significant overall velocity trend with depth or overall velocity anisotropy depending on sample direction.

Moisture and density properties were determined on 71 discrete samples from Hole U1362A. Bulk density values range from 2.58 to 2.89 g/cm^3, with an average of ~2.74 g/cm^3. Grain density values range from 2.66 to 3.16 g/cm^3, with a mean of ~2.88 g/cm^3. Porosity values range from 2.76% to 14.2%, with a mean of 7.9%. The highest value of porosity was obtained from a highly altered sample that also has the lowest velocity. Overall, *P*-wave velocity and porosity are inversely correlated.

Microbiology

Twenty five whole-round samples (4–20 cm length) were collected for microbiological analysis. Samples were preserved for shore-based DNA analysis, shore-based fluorescence in situ hybridization and cell counting analysis, and shipboard fluorescent microsphere analysis. One sample was also collected for shore-based analysis of particulate organic carbon and nitrogen as well as carbon and nitrogen isotopic compositions. Hard rock samples span a range of lithologic units, alteration states, presence of chilled margins, and most contain at least one vein/fracture. Additionally, a few recovered plastic bags that held the fluorescent microspheres were collected as a contamination check for DNA analysis. Colonization experiments were assembled for the Hole U1362A and U1362B CORK instrument strings. Fluid samples were collected during the 24-hour tracer injection experiment at Hole U1362B.

Paleomagnetism

Remanent magnetization measurements were made on 79 discrete pieces and on portions of 23 core sections. Samples were demagnetized at 5 or 10 mT steps from 0 to 50 mT using the cryogenic magnetometer's inline alternating field coils. Most samples display simple magnetization behavior. Principal component analyses were performed on selected samples. The majority of samples have positive inclinations, indicating the magnetization was acquired during a normal polarity period, consistent with the age of the crust at this location. Some samples have steep, positive inclinations that might be influenced by a drilling overprint. A few samples have reverse magnetizations, which are most likely the result of alteration. Inclinations are scattered around 460–470 mbsf in Unit 6. The average inclination for Hole U1362A basalts is 72°, slightly higher than the expected geocentric axial dipole direction.

Downhole Measurements

A single wireline logging string was deployed in Hole U1362A to identify suitable intervals for packer placement and to quantify formation properties. The logging string consisted of a qualitative spontaneous potential electrode and sensors for measuring natural spectral gamma ray, bulk density, borehole fluid temperature, tool orientation, tool motion, ultrasonic images, and hole diameter. Two passes were run over the entire open hole section and a third pass was run over two intervals of interest. Both the mechanical and ultrasonic calipers revealed a borehole that is highly enlarged over the upper open hole section. Near-gauge sections are identified at 417 and 447 m wireline depth below seafloor. The ultrasonic borehole images are marred by rotational and heave-induced tool motion. The density readings are impaired by poor borehole conditions because high-quality measurements depend on both a near-gauge borehole and good tool pad contact with the borehole wall. Where hole condition is good, log density compares well with laboratory measurements. Gamma ray measurements are relatively unaffected by borehole condition and are repeatable over the three passes. Borehole fluid temperature data were acquired while running into the hole and during the three logging passes.

Hydrologic Experiments

Packer experiments were completed in Hole U1362A to assess the permeability of the formation. The sealed-hole pressure baseline was recorded for an hour and two hour-long injections tests were conducted, each followed by an hour to allow the pressure to recover to baseline conditions. A preliminary data analysis indicates a bulk permeability consistent with that in nearby Hole U1301B (Becker and Fisher, 2008).

A 24-hr pumping and tracer injection experiment was conducted prior to the CORK deployment in Hole U1362B. Fast-sampling reverse osmosis pumps and pressure gauges were run to just below the casing shoe in the open hole. After waiting for an hour to allow the hole to equilibrate, sea water was pumped into the formation at a rate of 20 strokes per minute. At 2 and 20 hr into the experiment fresh water was pumped for an hour. The tracers injected included SF_6 gas (continuously throughout), CsCL and $HoCl_3$ salts, fluorescent microspheres, and stained bacteria extracted from sea water. Pumping ceased during the last hour of the experiment so the hole could equilibrate again. The composition of the injected fluid will be analyzed postcruise but the recovered pressure data provide an excellent record of hole conditions during the experiment.

Experiment Hour	Mud Pump (spm)	Cement Pump (spm)	Water Type	Tracer Injected
0:00 – 1:00	20		Salt	
1:00 – 2:00	20		Fresh	
2:00 – 3:00	20		Salt	
3:00 – 3:20	20	30	Salt	Salt (Cs, Er)
3:20 – 19:00	20		Salt	
19:00 – 19:20	20	30	Salt	Salt (Cs, Ho)
19:20 – 20:00	20		Salt	
20:00 – 20:20	20		Fresh	
20:20 – 20:40	20	30	Fresh	Microspheres
20:40 – 21:00	20		Fresh	
21:00 – 21:20	20		Salt	
21:20 – 21:40	20	30	Salt	Bacteria
21:40 – 24:00	20		Salt	

Borehole Observatories

The Hole U1362A L-CORK monitors two basement intervals: a shallow interval extending from the base of the 10-3/4 inch casing to the top of the deepest set of swellable packers (307.5 to 417.5 mbsf), and a deeper interval extending from the base of the deepest inflatable packer to the bottom of the hole (429.2 to 528.0 mbsf). Pressure in both intervals is monitored through 1/4 inch stainless steel tubing connected to miniscreens installed just below the inflatable packers at the top of the isolated intervals. Three 1/2 inch stainless steel fluid sampling lines are configured at two depths (two sampling below packers in the upper interval, one sampling below packers in the lower interval). One 1/2 inch PTFE microbiology sampling line ends in a titanium miniscreen that rests on perforated and coated 5-1/2 inch casing, 7 m below the base of the deepest inflatable packer, just above the perforated collars. The downhole instrument string includes six osmosamplers positioned within the coated perforated 5-1/2 inch casing and collars, eleven autonomous temperature probes, and a 200 lb sinker bar.

The Hole U1362B L-CORK monitors a single basement interval that extends from a single set of swellable and inflatable packers positioned just inside the base of the 10-3/4 inch casing to the bottom of the hole (272 to 359 mbsf). Pressure in this interval is monitored via a 1/4 inch stainless steel tube connected to a miniscreen installed just below the inflatable packers. The intakes of the three 1/2 inch stainless steel fluid sampling lines are installed on perforated and coated 5-1/2 inch casing, about 3 m below the packers, providing sampling redundancy. A single 1/2 inch PTFE microbiology sampling line ends in a titanium miniscreen that rests on perforated and coated 5-1/2 inch casing, 7 m below the base of the deepest inflatable packer, just above the perforated collars. The downhole instrument string comprises of six separate osmosamplers, eight autonomous temperature probes, including two installed in osmosamplers suspended inside the perforated and coated drill collars at depth in the hole, and a 200 lb sinker bar.

References

Becker, K., and Fisher, A.T., 2008. Borehole packer tests at multiple depths resolve distinct hydrologic intervals in 3.5-Ma upper oceanic crust on the eastern flank of Juan de Fuca Ridge. J. Geophys. Res., 113, B07105, doi: 10.1029/2007JB005446.

Davis, E.E., Fisher, A.T., Firth, J.V., et al., 1997. *Proc. ODP, Init. Repts.,* 168: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.168.1997

Fisher, A.T., Tsuji, T., and Gamage, K., 2010. Juan de Fuca Ridge-Flank Hydrogeology: the hydrogeologic architecture of basaltic oceanic crust: compartmentalization, anisotropy, microbiology, and crustal-scale properties on the eastern flank of Juan de Fuca Ridge, eastern Pacific Ocean. *IODP Sci. Prosp.,* 327. doi:10.2204/iodp.sp.327.2010

Fisher, A.T., Urabe, T., Klaus, A., and the Expedition 301 Scientists, 2005. *Proc. IODP,* 301: College Station, TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.301.2005