IODP Expedition 301 Installs Three Borehole Crustal Observatories, Prepares for Three-dimensional, Cross-Hole Experiments in the Northeastern Pacific Ocean

Andrew T. Fisher[1], Tetsuro Urabe[2], Adam Klaus[3], C. Geoff Wheat[4], Keir Becker[5], Earl Davis[6], Hans Jannasch[7], Sam Hulme[8], Mark Nielsen[9], Derryl Schroeder[3], Richard Dixon[3], Tom Pettigrew[10], Robert Macdonald[6], Robert Meldrum[7], Martin Fisk[9], James Cowen[11], Wolfgang Bach[12], Katrina Edwards[12], and the IODP Expedition 301 Scientific Party[13]

[1] Earth Sciences Department and Institute for Geophysics and Planetary Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA

[2] Earth and Planetary Science, University of Tokyo, 7 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan

[3] Integrated Ocean Drilling Program, Texas A&M University, 1000 Discovery Drive, College Station, TX 77845-9547, USA

[4] NURP/MLML Marine Operations, 7700 Sandholdt Road, Building D, Moss Landing, CA 95039 USA

[5] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Division of Marine Geology and Geophysics, 4600 Rickenbacker Causeway, Miami, FL 33149-1098 USA

[6] Pacific Geoscience Centre, Geological Survey of Canada, Geological Survey of Canada 9860 West Saanich Rd., North Saanich, BC Canada, V8L 3S1

[7] Natural Resources Canada, 7 Observatory Crescent, Geomagnetic Laboratory, Ottawa, ON Canada K1A 0Y3

[8] Monterey Bay Aquarium Research Institute, 770 Sandholdt Road, Moss Landing, CA 95039, USA

[9] College of Oceanic and Atmopspheric Science, Oregon State University, Ocean. Admin. Bldg. 104, Corvallis, OR 97331-5503

[10] Mohr Engineering Division of Stress Engineering Services, Inc., 13602 Westland East Blvd. Houston, Texas 77041-1205, USA

[11] Oceanography Department, University of Hawaii, 2525 Correa Road, Honolulu, HI 96822, USA

[12] Dept. of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

[13] A. Fisher, T. Urabe, A. Klaus, A. Bartetzko, K. Becker, R. Coggon, M. Dumont, B. Engelen, S. Goto, V. Heuer, S. Hulme, M. Hutnak, F. Inagaki, G. Iturrino, S. Kiyokawa, M. Lever, S. Nakagawa, M. Nielsen, T. Noguchi, W. Sager, M. Sakaguchi, B. Steinsbu, T. Tsuji, C. G. Wheat

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I. Introduction and Goals

The basaltic upper oceanic crust comprises the largest aquifer on Earth, containing a volume of water about equal to that currently stored in ice sheets and glaciers. Annual fluid fluxes through the upper oceanic crust are at least as large as the global river flux to the ocean. Much of the seafloor is hydrogeologically active, but the majority of the fluid flow within oceanic crust occurs on "ridge-flanks," regions located kilometers or more from active seafloor spreading centers. Fluid circulation in these areas is.driven mainly by lithospheric heat rising from deep within the plate, but is influenced by seafloor and basement topography, seismic and tectonic events, and tides.

Subseafloor fluid flow on ridge flanks influences a diverse array of processes and properties, including: the thermal state and evolution of oceanic plates; alteration of the lithosphere and crustal pore waters; establishment and maintenance of vast subseafloor microbial ecosystems; and diagenetic, seismic, and magmatic activity along plate-boundary faults. Although there have been numerous drilling expeditions, and surface and submersible surveys over the last several decades focused on hydrogeologic phenomena, we still know relatively little about driving forces, property distributions, scales of flow, rates of flow, extent of "compartmentalization" (isolation) of distinct fluid-rock systems, or links between hydrogeologic, geochemical, microbiological, and geophysical processes. Progress through drilling has been limited in the past by the perturbing effects of borehole creation on subseafloor thermal, pressure, chemical, and biological conditions. Subseafloor observatories address this challenge by allowing the formation to recover from drilling perturbations, and also allow scientists to run passive and active experiments for years to decades.

IODP Expedition 301 was part of a multidisciplinary program designed to evaluate the formation-scale hydrogeologic properties within oceanic crust; determine how fluid pathways are distributed within an active hydrothermal system; and elucidate relations between fluid circulation, alteration, microbiology, and seismic properties. The complete experimental program will comprise two IODP expeditions (the first having been Expedition 301, the second to be scheduled), an offset seismic experiment, and long-term monitoring and cross-hole tests facilitated with submersible and ROV expeditions extending 6-10 years after the first IODP expedition. The experimental program will also take advantage of opportunities related to a plate-scale network of long-term observatories (NEPTUNE), currently being planned.

II. Experimental Setting and Earlier Work

The Endeavour segment of the Juan de Fuca Ridge (JFR) generates lithosphere west of North America. Topographic relief produces barriers to turbidites from the continental margin, resulting in the accumulation of sediment over the eastern flank of the JFR, particularly during Pleistocene sea level low-stands. This resulted in burial of oceanic basement rocks under thick sediments at a young age. Sediment cover is sparse and oceanic basement is exposed near the active ridge at the western end of this ridge flank (Fig. 1). The sediment layer becomes thicker and more continuous to the east, with basement exposed at only a few, isolated outcrops. Basement relief 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 relief is low near the active ridge (±100–200 m) and higher (±300–700 m) to the east. Low-permeability sediment limits advective heat loss across most of the ridge flank, resulting in strong thermal, chemical, and alteration gradients in basement.

An 80-km transect comprising 10 sites was drilled on the eastern flank of the JFR during ODP Leg 168 [*Davis et al.*, 1997], including sites aged 0.9-3.6 Ma (Fig. 1). Thermal observations at the western end of the Leg 168 transect showed that basement was cooled by seawater recharging from nearby basement outcrops. Upper basement temperatures were remarkably isothermal at the eastern end of the drilling transect, despite extreme basement relief below thick sediments, evidence for vigorous convection in the oceanic crust. Upper basement temperatures generally increase from ~15°C at the western end of the transect to ~64°C at the eastern end. This overall trend in basement temperatures might suggest that the dominant direction of fluid flow is from west to east, but sedimentary and basement pore fluid samples are inconsistent with this interpretation. The western end of the transect shows increasing alteration from west to east, but fluid recovered from sites in the middle of the transect were anomalously altered [*Elderfield et al.*, 1999]. The chemistry of these fluids is most consistent that of fluids recovered from eastern Sites 1026 and 1027 and from springs on nearby Baby Bare outcrop [*Wheat and Mottl*, 2000]. Fluid ^{14}C analyses yielded some of the youngest crustal fluids at Site 1026 [*Elderfield et al.*, 1999], but it is not possible for waters recharging the basement aquifer near the western end of the Leg 168 transect to gain "youth" as they travel to the east and become increasingly altered. There is geochemical evidence for along-strike (south-to-north) fluid transport in basement [*Wheat et al.*, 2000], and thermal data and hydrogeologic calculations show that recharge of Baby Bare outcrop springs (and of basement fluid recovered from Site 1026) most likely occurs through a larger basement outcrop ~50 km to the south [*Fisher et al.*, 2003].

Borehole hydrogeologic experiments completed in several Leg 168 basement holes indicated near-borehole formation permeabilities of 10^{-14} to 10^{-10} m^2, with the highest permeabilities determined for the youngest sites [*Becker and Davis*, 2003; *Becker and Fisher*, 2000]. These data are broadly consistent with the rest of the global data set, and suggest two additional trends: a decrease in uppermost basement permeability with increasing age, and variations in permeability estimated using methods with different measurement scales. CORK observatories were installed during Leg 168 at western Sites 1024 and 1025 and eastern Sites 1026 and 1027, to monitor borehole fluid pressure and temperature, and to collect long-term fluid samples within uppermost basement. Borehole fluid responses to tidal loading and regional tectonic events indicate effective basement permeability as great as 10^{-9} m^2, similar to values inferred from numerical and analytical calculations [e.g., *Davis and Becker*, 2004; *Spinelli and Fisher*, 2004].

Hole 1026B also yielded direct observations of ridge-flank fluid microbiology. Samples collected during drilling suggested the presence of microbes, and seafloor experiments assessed microbial biomass and diversity in fluids venting from the CORK observatory [*Cowen et al.*, 2003]. Cells collected from the wellhead included bacteria and archaea, whose closest known phylogenetic neighbors comprise nitrate reducers, thermophilic sulfate reducers, and thermophilic fermentative heterotrophs, consistent with basement fluid geochemistry. These tantalizing results encourage additional study of the basement biosphere.

III. Drilling, Sampling, Testing, and Installing Borehole Observatories on IODP Expedition 301

IODP Site 1301 was positioned 1 km SSW of ODP Site 1026, above a buried basement ridge, where sediment thins to 250-265 m (Figure 1). We cored upper basement in Hole 1301B to ~580 mbsf (~320 m sub-basement, msb), with ~ 30% recovery, typical for basaltic crust. Samples were collected to study lithostratigraphy, alteration, microbiology, and paleomagnetic and physical properties. Nearly 9% of recovered basement rocks were dedicated to microbiological analysis. We also collected high-quality APC sediment cores immediately above basement to sample fluid chemistry and microbiology. Wireline logging data from the lower part of Hole 1301B indicate that the hole is to gauge and that the crust is highly layered. Comparison with other crustal holes shows that we achieved a critical basement observatory objective: isolating upper and lower parts of extrusive crust. Packer experiments completed in Holes 1301A and 1301B show that the upper crust is highly permeable, perhaps $>10^{-10}$ m^2, and there may be a slight decrease in bulk permeability with depth [*Fisher et al.*, 2005a].

We replaced the CORK observatory in Hole 1026B; created new basement Holes 1301A and 1301B, that penetrate 108 and 320 msb, respectively; and instrumented each of these holes with CORK observatories (Figs. 1 and 2). Site 1301 basement holes and observatories are separated by just 35 m. All new CORK observatories have multiple isolated intervals to monitor and sample pressure, temperature, chemistry, and microbiology, and will serve as observation points for cross-hole experiments (Fig. 2). Holes 1026B and 1301A each include one monitored zone in uppermost basement, and there are three basement zones being monitored in Hole 1301B. The uppermost basement zones in these holes are in rubbly, brecciated rock; the deepest crustal zone in Hole 1301B appears to be considerably more massive and stable, although it is also highly permeable. These CORK observatories include plumbing that allows us to monitor intervals between the two inner casing strings (Fig. 2A), to assess the quality of hydrologic seals. We also planned to replace the CORK system in Hole 1027C during IODP Expedition 301, but ran out of time and supplies. The old CORK system is currently monitoring basement fluid pressure within one interval and will be replaced with a more sophisticated system during the next drilling expedition [*Fisher et al.*, 2005b].

IODP 301 CORKs were deployed inside concentric 20", 16", and 10-3/4” casing strings, and use a 4-1/2" inner casing that includes one or more inflatable packers to seal monitoring intervals (Figure 2). Pressure measurement systems were installed at the wellhead post-drilling by ROV (described below), using tubing to monitor depths of interest. Each Expedition 301 pressure logger monitors multiple intervals and has significantly greater memory, lower power consumption, faster communication and data download rates, less temperature sensitivity, and greater pressure resolution than previous generation tools. Hydraulic connections are provided by light-weight submersible-mateable connectors, and the sensor and logger housings are smaller and more portable than earlier tools, making servicing by submersible/ROV easier.

The CORK fluid sampling program makes use of pumps placed (1) at depth below the CORK seals, and (2) at the seafloor on the CORK head. The first systems allow fluid to be collected within boreholes at *in-situ* temperature, pressure, and chemical conditions, but require removal of the plugs and other instrumentation inside 4-1/2" casing to recover the samples. The second systems use valves and small-bore tubing to draw fluids from depth, making it easier for samplers to be recovered and redeployed using a submersible/ROV. The heart of each of these sampling systems is one or more OsmoSamplers. OsmoSamplers sample fluid for a specified time using osmotic pressure across a semi-permeable membrane (created by solutions of differing salinity) to draw sample continuously through small-bore tubing. These systems have operated successfully during deployments of weeks to years in many settings, including estuaries, seamounts, seafloor spreading centers, and deep ocean boreholes. Four different kinds of OsmoSampler units were deployed during Expedition 301: gas sampling, microbiological, tracer injection, and acid addition. Subseafloor systems will run for five years, whereas seafloor systems will run for up to two years before replacement.

Microbiological colonization instrumentation deployed at depth within CORK observatories during Expedition 301 are intended to enable better characterization of the rates of microbial alteration of minerals and roles of mineralogy in controlling microbial alteration. These experiments comprised two kinds of systems: passive experiments in which fluids are allowed to pass over polished sections of various rock or mineral samples located inside a perforated HDPE sleeve between OsmoSamplers, and flow-cells in which fluids are pumped across rock samples using OsmoSamplers. The Hole 1301B CORK also includes a "clean" Tefzel microbiological sampling line extending from the wellhead to the deepest monitored basement interval.

Autonomous temperature sensors and data loggers were deployed within all three Expedition 301 CORK observatories, to assist with interpretation of osmotic pumping rates and to determine the thermal state, particularly the extent of thermal homogeneity, of upper basement. Autonomous loggers provide greater flexibility in deployment depths than do preconfigured, instrumented cables, are stable and robust during multiyear deployments, and make field-configuration (cutting, splicing) of instrument support cables faster and easier. Temperature logging systems constructed for Expedition 301 were modified versions of commercial products, with upgraded batteries, pressure cases, and other components, and are about the size of a marking pen. These instruments provide temperature resolution and absolute accuracy of 1-30 mK over a wide temperature range and will collect hourly data for up to five years.

IV. Post-Expedition 301 CORK Servicing

Expedition 301 CORKs were serviced three weeks after the drilling expedition, using the ROV *ROPOS* in September 2004. The primary goals of these operations were to (1) inspect and evaluate CORK installations, (2) install pressure loggers, (3) close unused pressure and sampling valves left open for deployment (to purge air from the lines), (4) recover short-term OsmoSampling systems, and (5) install "dust covers" on the CORK heads to prevent clogging. Additional submersible and ROV work will occur during Summers of 2005 and 2007.

All three CORKs installed during IODP Expedition 301 appear to be operating properly, but we will have more information after a planned Summer 2005 *Alvin* program, when we can examine longer borehole pressure records. The top plugs in CORKs at Holes 1026B and 1301A were found to be located outside of the CORK heads, whereas the top plug in Hole 1301B was found to be in place as intended. No shimmering water was seen exiting through or around the CORK heads of the Expedition 301 installations; shimmering water had been seen exiting the Hole 1026B CORK when it was leaking prior to Expedition 301.

Data collected for a few hours with a newly-installed data logger in Hole 1026B are noticeably "cleaner" than those collected prior to Expedition 301, probably as a result of having a better borehole seal. These data also show that the borehole fluid is overpressured relative to local hydrostatic pressure, in part as a result of the rise of warm water up the CORK casing before pressure valves were closed. Data recovered from an earlier-generation pressure logging system installed in Hole 1027C, 2400 m from Site 1301, yielded some of the most exciting results obtained during September 2004 CORK servicing. An overall increase and several abrupt changes in pressure in Hole 1027C correlate with pumping into Holes 1301A and 1301B, illustrating the extent of hydrogeologic "connection" across long distances in the crust (Fig. 2B).

V. Plans for Future Experiments

The next JFR drilling expedition will include initiation of multidisciplinary, cross-hole experiments and will be followed by several years of seafloor work for observatory servicing; hydrologic perturbation; fluid, tracer, and microbiological sampling and data recovery; analytical work and interpretation. We will replace the Hole 1027C CORK and create two new multilevel, subseafloor observatories at Site SR-2 (Figs. 1 and 2).

Hole 1027C is located 2.2 km east of Hole 1026B, and Site SR-2 will be located 200 m south of Hole 1026B (Fig. 1). The new observatories, in combination with existing systems, comprise a three-dimensional network of basement monitoring points, with borehole separation of 35 to 2500 m, for use in cross-hole experiments. Operations in Hole 1027C will begin with recovery of the existing CORK and deepening the hole by 30-40 m. This will make room to hang drill collars, provide upper-crustal samples for microbiological and other analyses, and "open up" the formation for large-scale testing. Emplacement of a two-level CORK system will optimize the configuration for the cross-hole tests and allow acquisition of long-term geochemical and microbiological samples.

Hole SR-2A will be the deeper new basement hole, and the operational approach will be similar to that used for Hole 1301B, with drilling, casing, coring, wireline logs, VSP, single-hole packer work, and emplacement of a multilevel CORK. Hole SR-2B will penetrate the upper, most permeable crustal layer(s), and will be the main perturbation well for long-term experiments. Once this hole is drilled, cased, and open sufficiently below casing, we will initiate a 24-hour pumping test with seawater and tracers, then set a multilevel CORK Observatory. Multiyear cross-hole tests will be initiated by submersible/ROV one-two years after drilling operations are complete, using the naturally-overpressured formation to test properties within an enormous crustal volume.

Figure Captions

Figure 1. A. Index map of field area, eastern flank of the Juan de Fuca Ridge, showing location of ODP Leg 168 transect and IODP Expedition 301 sites. B. Seafloor bathymetric contour map of area around IODP Expedition 301 sites showing spatial relations between CORK observatories (colored circles) in Holes 1026B, 1027C, 1301A, 1301B, planned Site SR-2, and nearby basement outcrops (gold bathymetric contours). Depth contours in meters. C. Perspective basement map of IODP expedition 301 drilling area, showing ODP and IODP hole locations [*Zühlsdorff et al.*, 2005]. Sediment has has been digitally "removed" to show basement relief below largely flat seafloor. The map is based on bathymetry shown in Fig. 1B and interpretation of ~25 seismic lines collected during the 2000 *Sonne* expedition (ImageFlux). Holes at Site SR-2 will be drilled during the next drilling expedition. Holes 1026B and 1301A/B are ~1 km apart, whereas Holes 1026B and 1027C are 2.2 km apart. Hole SR-2B will be the "perturbation" well for three-dimensional, cross-hole experiments that will last several years.

Figure 2. A. Schematics of casing and CORK system deployed during IODP Expedition 301, not drawn to scale [*Fisher et al.*, 2005b]. Primary CORK casing is 4-1/2” in diameter and is sealed with two plugs, one at depth and one at the top. Additional seals are provided by casing packers, cement at the base of the 16” and 10-3/4” casing strings, and around CORK head inside 10-3/4" casing. CORK systems include up to nine fluid, microbiological, and pressure sampling lines, with ports and screens in one or more basement or cased depth intervals, and a variety of fluid and microbiological sampling systems suspended on cable at depth. Note that total depths (TD) indicate depths into basement. B. Evidence that the upper oceanic crust is hydrogeologically "connected" from Site 1301 to Site 1027C, 2.4 km away. Rig pumping records from Site 1301 and pressure data downloaded from the CORK system in Hole 1027C. Pressure record has been corrected for tidal loading. There is a clear correlation between pumping in basement in Holes 1301A and 1301B and the pressure response in Hole 1027C (several particularly abrupt "events" marked with red arrows). As with other such "uncontrolled" cross-hole pressure signals, this one can not be interpreted quantitatively because the perturbation holes were not sealed during pumping. In fact, much of the fluid pumped probably came out of the holes at the seafloor and never entered the formation. We will monitor fluid flow volumes and rates during cross-hole experiments completed during and after the next drilling expedition, allowing quantitative interpretation of pressure response, in addition to monitoring fluid temperature, chemistry and microbiology.

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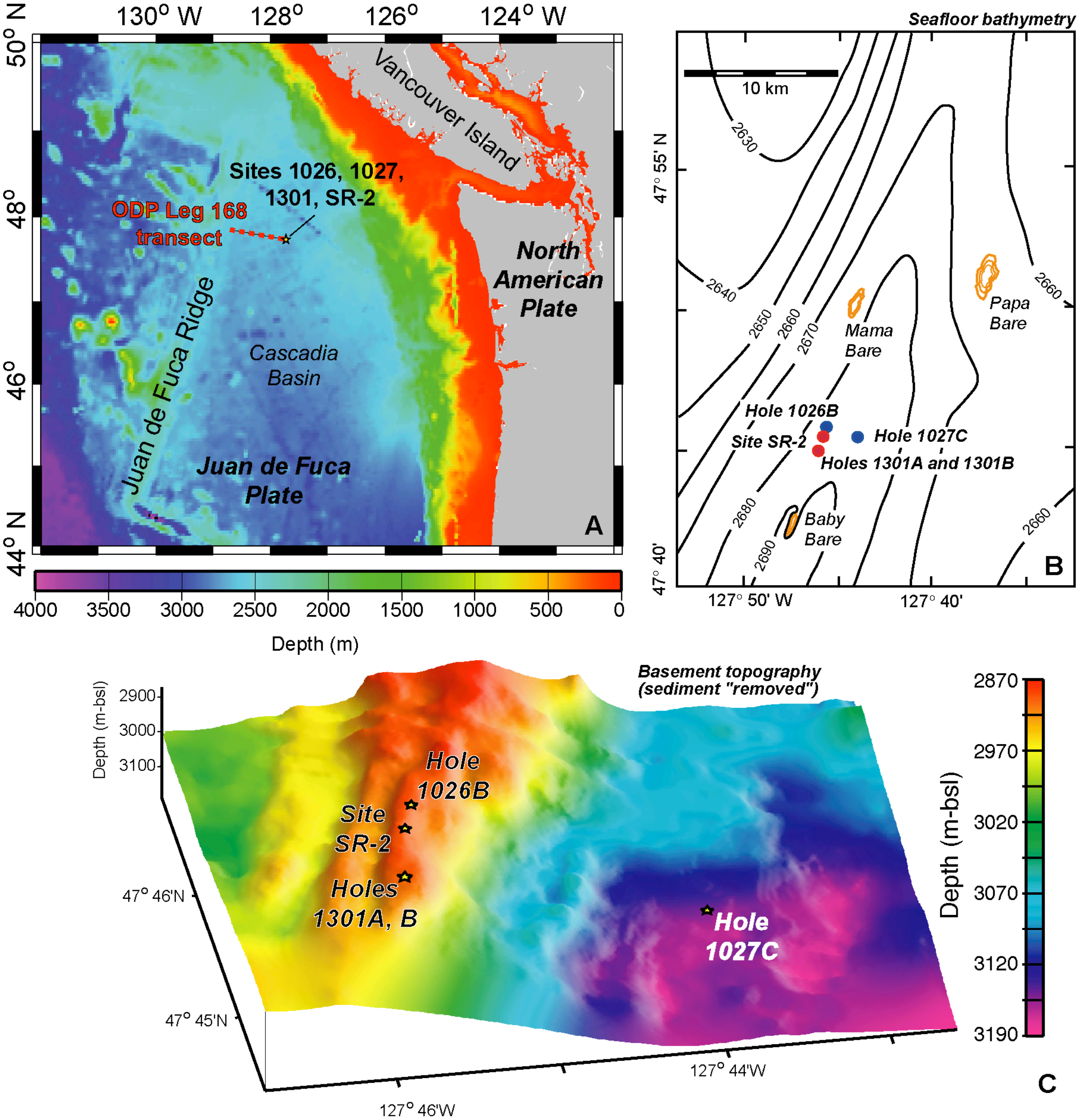

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Figure 1
IODP 301 Overview
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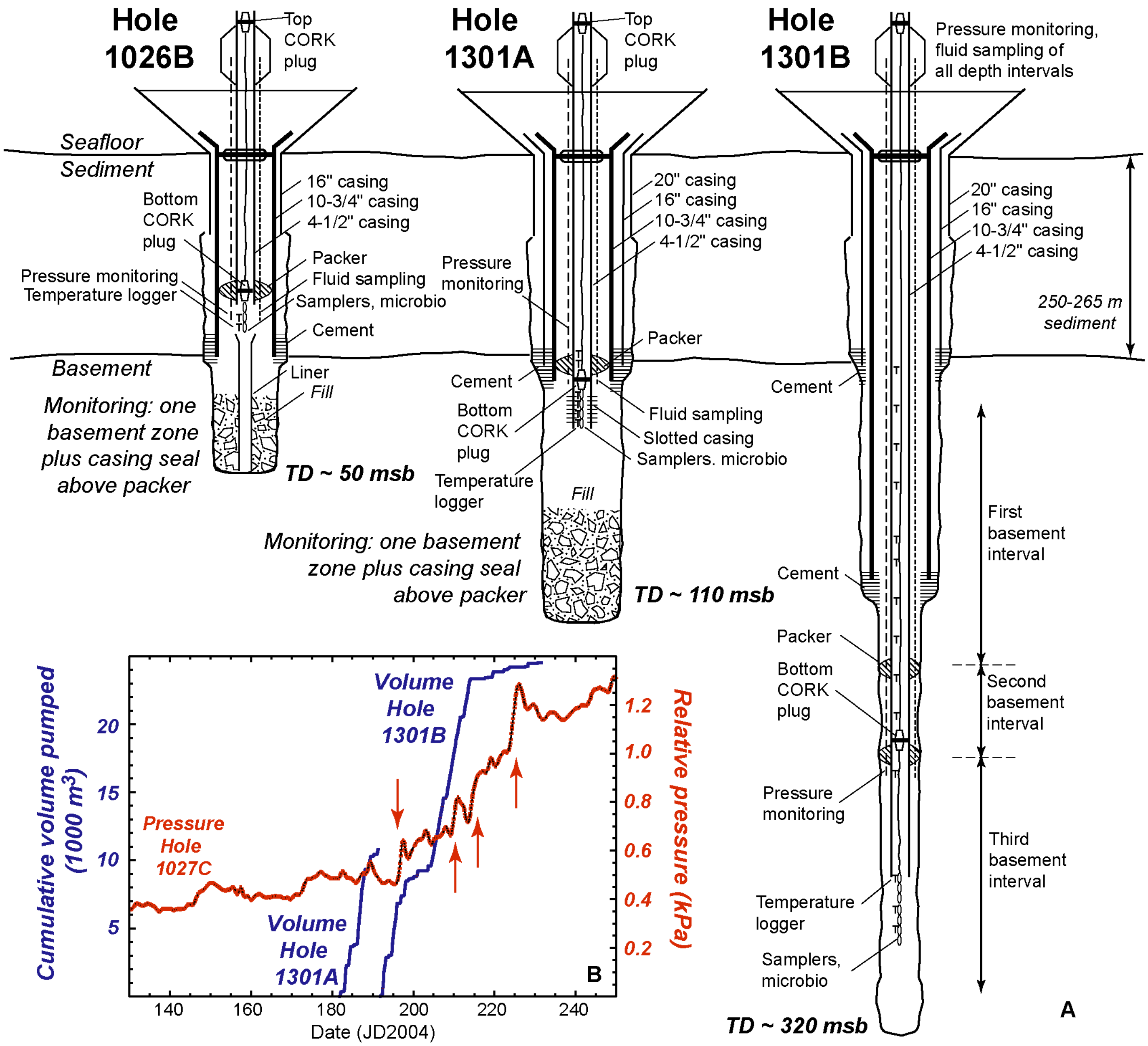

Figure 2. A. Schematics of casing and CORK system deployed during IODP Expedition 301, not drawn to scale. Primary CORK casing is 4-1/2" in diameter and is sealed with two plugs, one at depth and one at the top. Additional seals are provided by casing packers, cement at the base of the 16" and 10-3/4" casing strings, and around CORK head inside 10-3/4" casing. CORK systems include up to nine fluid, microbiological, and pressure sampling lines, with ports and screens in one or more basement or cased depth intervals, and a variety of fluid and microbiological sampling systems suspended on cable at depth. Note that total depths (TD) indicate depths into basement. **B.** Evidence that the upper oceanic crust is hydrogeologically "connected" from Site 1301 to Site 1027C, 2.4 km away. Rig pumping records from Site 1301 and pressure data downloaded from the CORK system in Hole 1027C. Pressure record has been corrected for tidal loading. There is a clear correlation between pumping in basement in Holes 1301A and 1301B and the pressure response in Hole 1027C (several particularly abrupt "events" marked with red arrows). As with other such "uncontrolled" cross-hole pressure signals, this one this one can not be interpreted quantitatively because perturbation holes were not sealed during pumping. In fact, much of the fluid pumped probably came out of the holes at the seafloor and never entered the formation. We will monitor fluid flow volumes and rates during cross-hole experiments completed during and after the next drilling expedition, allowing quantitative interpretation of pressure response, in addition to monitoring fluid temperature, chemistry and microbiology.