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Leg 174B Synopsis: Revisiting Hole 395A for Logging and Long-Term Monitoring of Off-Axis Hydrothermal Processes in Young Oceanic Crust[1]

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INTRODUCTION

During Leg 174B in midsummer of 1997, we revisited Hole 395A for a 5-day program of logging and deployment of the thirteenth Ocean Drilling Program (ODP) instrumented borehole seal (known as a "CORK" for Circulation Obviation Retrofit Kit) (Davis et al., 1992) for long-term hydrological investigations. Drilled over 21 yr earlier during Deep Sea Drilling Project (DSDP) Leg 45, Hole 395A is a classic legacy hole in young crust near the Mid-Atlantic Ridge. Prior to Leg 174B, it had been revisited four times for logging and hydrogeological studies: twice by DSDP and ODP (Legs 78B and 109) for logging and downhole experiments, once with *Nautile* for logging by wireline reentry, and once by *Atlantis* for detailed heat flow, coring, and pore-pressure surveys. The primary purpose of the Leg 174B logging and CORK installation was to further elucidate the controlling formation properties and driving forces for the vigorous off-axis, low-temperature hydrothermal circulation inferred to be active in the region from previous reentries of the hole and geothermal surveys.

It is now well accepted that off-axis hydrothermal systems account for the majority of hydrothermal heat and chemical fluxes in the oceanic crust and are a primary factor in the chemical and physical evolution of the crust. Off-axis circulation occurs at lower temperatures and slower rates over large areas of the ocean basins, commonly out to crustal ages of tens of millions of years. It only rarely produces identifiable vents and is therefore more difficult to study with measurements at

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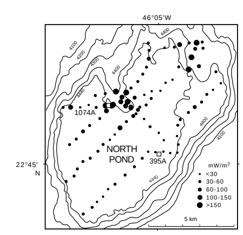
the seafloor. To date, much of our understanding of off-axis circulation is based on deductions from patterns in seafloor heat flow, analyses of pore waters in the sediments overlying oceanic basement, numerical simulations, and drilling results in a few well-studied, well-sedimented off-axis areas. Like Leg 168 a year earlier, Leg 174B was planned specifically to address the physical and chemical processes occurring in off-axis hydrothermal systems. Along with the four CORKs deployed during Leg 168 on the flank of the Juan de Fuca Ridge (Davis, Fisher, Firth, et al., 1997; Davis and Becker, 1998), the CORK deployed in Hole 395A during Leg 174B represents five active CORKs deployed in off-axis systems for the first continuous monitoring of in situ conditions and processes in such systems.

RIDGE-FLANK CIRCULATION IN SEDIMENT PONDS NEAR THE MID-ATLANTIC RIDGE: HOLE 395A

Drilled in 1975–1976 (Melson, Rabinowitz, et al., 1979), Hole 395A was one of the earliest successful reentry holes in oceanic crust and penetrated 93 m of sediments and over 500 m of predominantly extrusive basalts. It remains one of the deepest penetrations of upper oceanic crust formed at a mid-ocean ridge and is thus one of the most important reference holes for young oceanic crust. The hole is located in 7-Ma crust about 70 km west of the axis of the Mid-Atlantic Ridge, sited in an isolated sediment pond ("North Pond") about 8 km × 15 km in size and completely surrounded by exposed basement with topographic relief up to a kilometer (Fig. F1). Oceanic crust formed at slow spreading rates typically exhibits much greater bathymetric relief than crust formed at fast rates, so this kind of environment might be considered typical for off-axis circulation in the Atlantic and Indian Oceans.

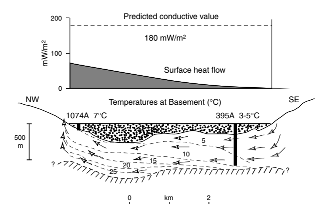
F1. Location of Hole 395A in North Pond showing the heat flow survey, p. 7.



Hole 395A was also one of the earliest and best examples of a phenomenon that is fairly common in holes drilled into young oceanic crust and dramatically illustrates the need for experiments like CORKs to understand off-axis hydrothermal circulation. In the >21 yr it was left open after initial drilling, Hole 395A was reentered four times: during Leg 78B (Hyndman, Salisbury, et al., 1984), Leg 109 (Bryan, Juteau, et al., 1988), the French wireline reentry DIANAUT expedition (Gable et al., 1992), and Leg 174B. Each time, repeat temperature logs, fluid samples, and flowmeter logs clearly demonstrated that ocean bottom water was flowing down the hole at consistent rates of ~1000 L/hr (e.g., Becker et al., 1984; Morin et al., 1992). Downhole flow in an open hole like Hole 395A requires both a pressure differential to drive the flow and sufficient formation transmissivity to accept the flux. The higher the formation transmissivity, the lower the differential pressure required to drive downhole flow. The pressure differential probably results from some combination of two effects: true formation underpressures resulting from natural fluid circulation and a drilling-induced artifact resulting from the density differential between cold drilling fluids and warmer formation fluids. Resolving the former is obviously of greater interest. However, in most cases of downhole flow in crustal holes, the formation temperatures are indeed warmer than the drilling fluid so the drilling-induced artifact must be significant and virtually precludes determining the true formation state if the hole is left open. Hole 395A is important among examples of downhole flow in that it was drilled into an area of low heat flow; thus, the density difference between drilling fluids and formation fluids was small, and a predominantly natural driving force is probably responsible for the prolonged downhole flow.

Early indications of the nature of the subsurface fluid flow system at North Pond were provided by downhole measurements during prior reentries and particularly the detailed heat flow survey conducted by Langseth et al. (1992) long after the drilling of Hole 395A. Prior downhole measurements indicate that the upper 300–400 m of basement in Hole 395A is certainly permeable enough to support a vigorous fluid flow system if there is lateral continuity of such permeability in the crust underlying North Pond. The heat flow survey indicates that heat flow is on average considerably less than the value of ~180 mW/m^2 expected for conductive cooling of 7-Ma crust, with a general increase of heat flow from southeast to northwest across North Pond (Fig. F1). Even where the heat flow is high in the northwest, pore-pressure measurements show negative gradients in the sediments, suggesting recharge through sediments everywhere in the sediment pond. These observations corroborate the model put forth earlier by Langseth et al. (1984) for one-pass lateral fluid flow in permeable upper basement beneath North Pond (Fig. F2) and indicate that this flow generally runs from southeast to northwest. In this model, permeability of uppermost basement is quite high and interconnected throughout the sediment pond and the lateral flow is vigorous enough to keep temperatures at the basement contact nearly isothermal, increasing only slightly along the flow path beneath North Pond. In this case, heat flow in North Pond would be predicted to be directly related to distance from the basement exposures to the southeast and inversely related to sediment thickness—just as observed by Langseth et al. (1992).

F2. Schematic model for fluid flow in permeable basement beneath North Pond, p. 8.



LEG 174B LOGGING RESULTS

About 2 days were devoted to logging in Hole 395A during Leg 174B, with the overall purpose of documenting the in situ physical properties of the upper oceanic crust at the site, particularly as they relate to the hydrologic properties. The hole had been logged reasonably well during Legs 78B and 109, so Leg 174B focused on deploying improved tools made available to ODP since then. These included temperature, Formation MicroScanner (FMS), and density-porosity-resistivity logs, as well as two new tools deployed in oceanic crust for the first time during Leg 174B, an azimuthal resistivity imager (ARI) and digital shear imager (DSI).

F3. Temperature and spontaneous potential logs, p. 9.

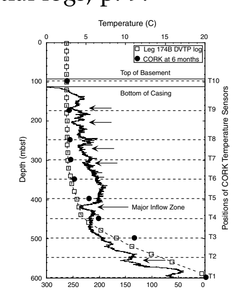
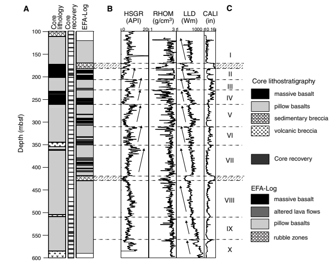


Figure F3 shows the downhole temperature log taken when Hole 395A was first reentered during Leg 174B, a log that is very similar to past temperature logs in the hole and illustrates the virtually isothermal profile in the upper 300–400 m, characteristic of downhole flow of ocean bottom water. This figure also shows the Leg 174B log of spontaneous potential (SP), which is quite sensitive to flowing fluids. The SP log suggests that the primary zone accepting downhole flow was at ~420 m below seafloor (mbsf), with several other shallower zones and possibly a deeper zone accepting lesser amounts of the flux. The resistivity log, shown in Figure F4, indicates that the inflow zones are associated with low resistivities between cyclic zones of high resistivity. Hyndman and Salisbury (1984) and Moos (1990) reported this cyclicity in earlier logging data from the hole and suggested that it represents eruptive cycles. If so, the temperature and SP logs suggest that most of

F4. Summary of log interpretation in Hole 395A, p. 10.



the considerable permeability in basement at Site 395 is concentrated in the zones between eruptive cycles.

The advanced logs collected during Leg 174B provided an overwhelming amount of high-quality data, various aspects of which are analyzed in papers submitted to or in preparation for outside journals. Bartetzko et al. (in press) analyzed the log data to interpret a volcanic stratigraphy from a synthetic "electro-facies" log (EFA) based on characteristic log responses. From this EFA log (Fig. F4), they can identify most of the lithostratigraphic types (but not the chemical stratigraphic types) originally identified by Melson, Rabinowitz, et al. (1979) from the relatively poor core recovery (average = 18%) and can present a continuous lithostratigraphic interpretation based on the continuous log data. Bartetzko et al. (in press) also clearly recognize the cyclicity in log data and further develop the interpretation of eruptive cycles in terms of the model of Smith and Cann (1992, 1999) for construction of crust formed at slow spreading rates.

SITE 1074 RESULTS

The logging and CORK installation in Hole 395A were completed ahead of schedule, allowing time to offset the ship and core the sediments of North Pond. These sediments had not been properly cored during the original drilling leg, which was well before the advent of the hydraulic piston corer. The ship was offset 4.5 km to the northwest of Hole 395A to the zone of highest measured heat flow in North Pond, where we expected results of hydrologic importance in addition to the more basic goal of properly recovering the sediments of North Pond. At Hole 1074A, a 64-m-thick section of sediments and underlying 0.6 m of basalt were recovered using the advanced hydraulic piston corer/extended core barrel assembly. The sediments are predominantly nannofossil ooze with 2 m of red clay overlying the basalts. Hirano et al. (Chap. 1, this volume) studied microtextures of sediment samples from Hole 1074B and report on the relationship between foraminifer content and consolidation state of the sediments.

During Leg 174B, sediment temperatures were measured with the Adara shoe and pore-water chemistry was analyzed throughout the core. The temperature profile is conductive and the pore-water profile diffusive with no evidence for advection through the sediments associated with relatively high heat flow in North Pond. The temperature profile extrapolates to a value of ~7°C at the top of basement near the western edge of North Pond—very close to the value predicted by the Langseth et al. (1984) model (Fig. F2). This result and the lack of evidence for advection through the sediments at the site provide further corroboration for the Langseth et al. (1984) model of fluid flow confined to basement beneath North Pond.

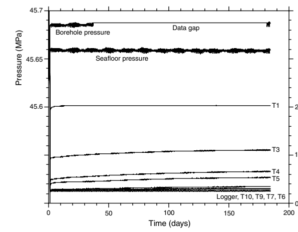
CORK RESULTS FROM HOLE 395A

The CORK experiment in Hole 395A was designed to monitor true formation pressures and temperatures in the upper basement—the zone of large-scale lateral flow—to elucidate the causes and patterns of this flow and to further test the model of Langseth et al. (1984) for off-axis circulation in sediment ponds on the flanks of slow-spreading ridges. Using *Nautile,* the first 6 months of temperature/pressure data was recovered from Hole 395A on 30 January 1998. No further data have been recovered since then, but a data recovery dive using *Alvin* is scheduled for the summer of 2001. The first 6 months of data (Fig. F5) clearly show a very slow recovery of temperatures and pressures in the hole. Full recovery will certainly take much longer than 6 mo, given the >21 yr of unabated downhole flow immediately before the installation of the CORK.

The initial 6 months of data allow only lower bounds to be estimated for in situ temperatures and pressures—but these preliminary bounds are themselves quite illuminating. First, although temperatures clearly show signs of recovery throughout the first 6-month recording period, they are not much warmer than the profile characteristic of downhole flow (Fig. F3). Second, in situ pressures appear quite close to hydrostatic under local geothermal conditions and the attenuation of the tidal signal seen in the sealed hole is small. Thus, there appears not to have been a strong formation underpressure "sucking" the pre-CORKing downhole flow into a basement reservoir; instead, it appears that the upper basement beneath North Pond is very well connected in a hydrologic sense to the ocean bottom water via the basement exposures that surround North Pond. These results clearly support the Langseth model; they indicate that much of the uppermost basement beneath the sediment pond is indeed very permeable and kept quite cool by vigorous lateral flow of fluids close to bottom-water temperature. Basement permeability and transmissivity underneath the sediment pond must be high enough that there is virtually no resistance to flow nor pressure losses along the flow path. In this context, the disturbance generated by the >21 yr of downhole flow before CORKing—a total of over 100,000,000 L of seawater flowing down the hole and into the formation—was just a relatively minor perturbation to the natural flow system!

This interpretation is further supported by analysis by Davis et al. (2000) of attenuation and phase lag of the tidal loading signal as recorded by the CORK pressure gauges, even if only 40 days of pressure data were available. Davis et al. (2000) show that the results from Hole 395A are remarkably consistent with those from the younger Juan de Fuca flank CORKs. This pair is located in 0.9 and 1.3 Ma crust under continuous sediment cover within a few kilometers of extensive basement outcrop—a comparable setting to Hole 395A, which is even closer (1 km) to extensive outcrop. Although located in different oceans in crust formed at different spreading rates, these CORKs show tidal loading behavior that remarkably can be fit to a single simple model of lateral transmission from nearby basement outcrop via permeable and transmissive upper basement (Fig. F6). Thus, the CORK results from Hole 395A as well as the Juan de Fuca flank sites strongly support other inferences that there are huge fluxes of low-temperature fluids in very transmissive upper basement in thinly sedimented young oceanic crust, regardless of whether the sediment cover is continuous or patchy and regardless of spreading rate.

F5. Pressure and temperature data; first 6 months of operation of the CORK, p. 11.



F6. Amplitude and phase of observed basement pressure variations resulting from diurnal and semidiurnal tidal loading, p. 12.

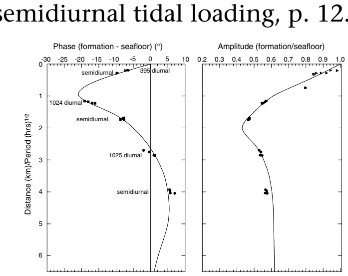


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Figure F1. Location of Hole 395A in North Pond showing the heat flow survey of Langseth et al. (1992) [N1]. Bathymetry is shown in meters, with contour intervals of 100 m except for the deepest contour at 4440 m.

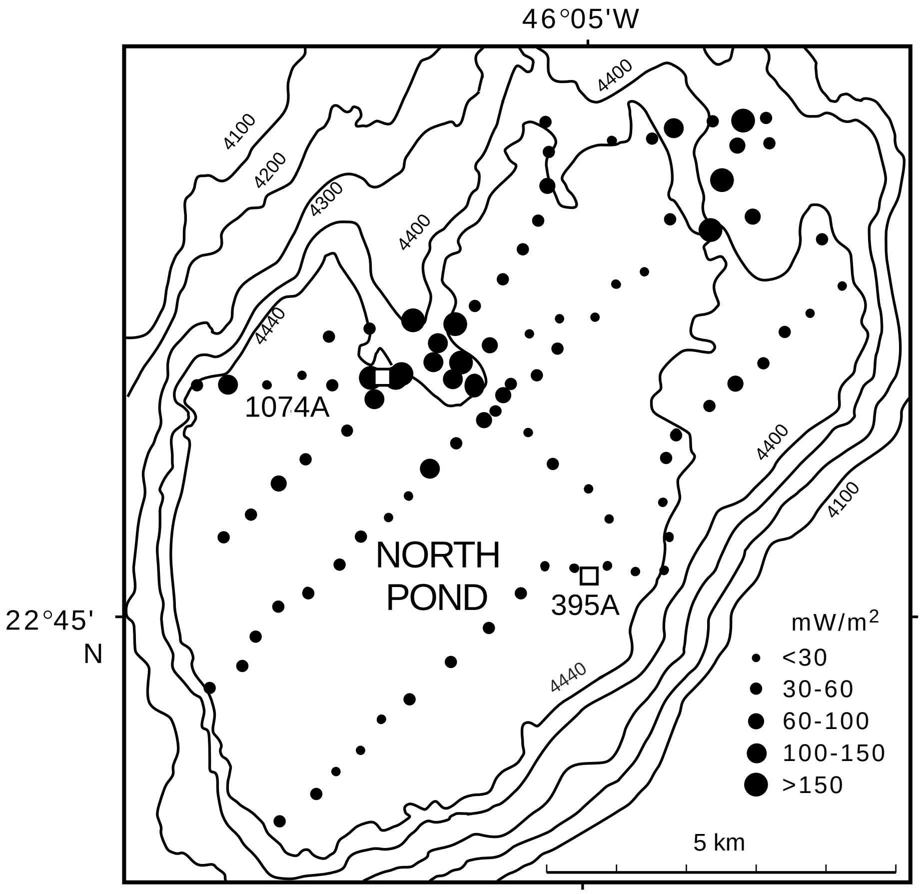


Figure F2. Schematic model of Langseth et al. (1984) for fluid flow in permeable basement beneath North Pond showing approximate relative locations of Holes 395A and 1074A.

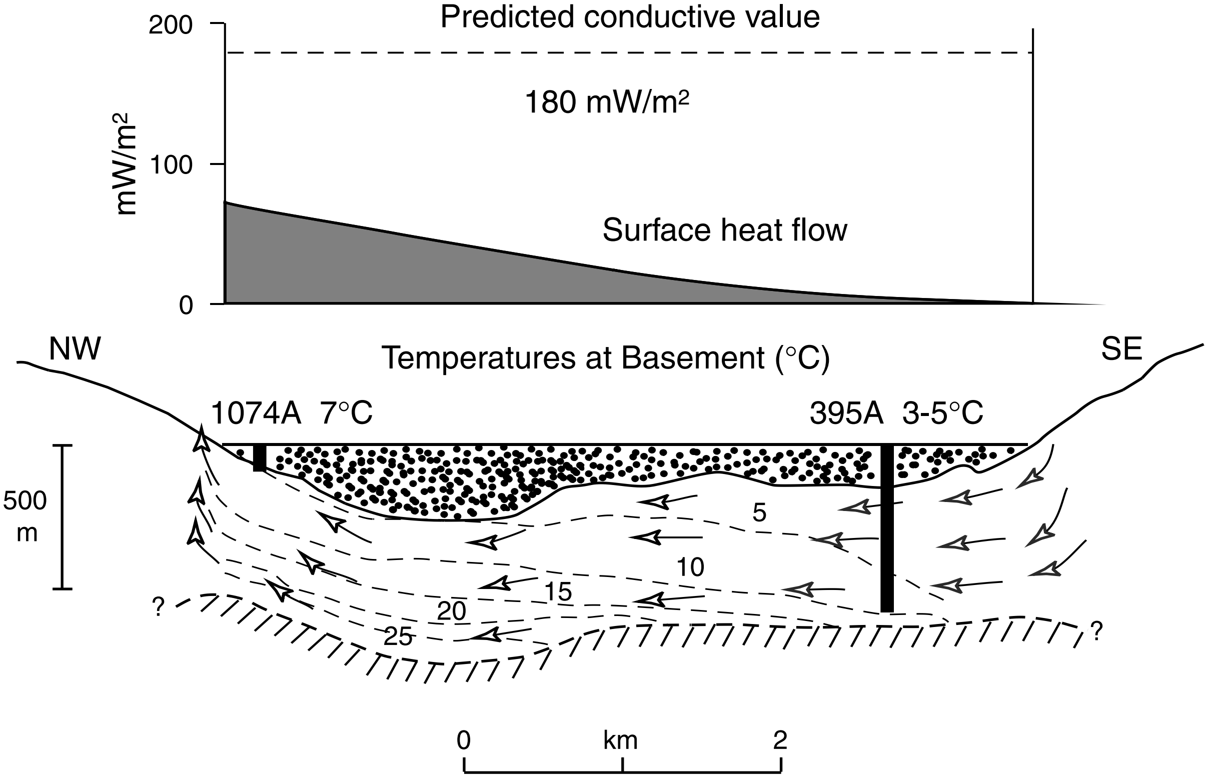


Figure F3. Leg 174B temperature (open squares) and spontaneous potential (SP) logs in Hole 395A, with still-recovering CORK temperatures (solid circles) as recorded 6 months after CORK deployment. DVTP = Davis-Villinger temperature probe.

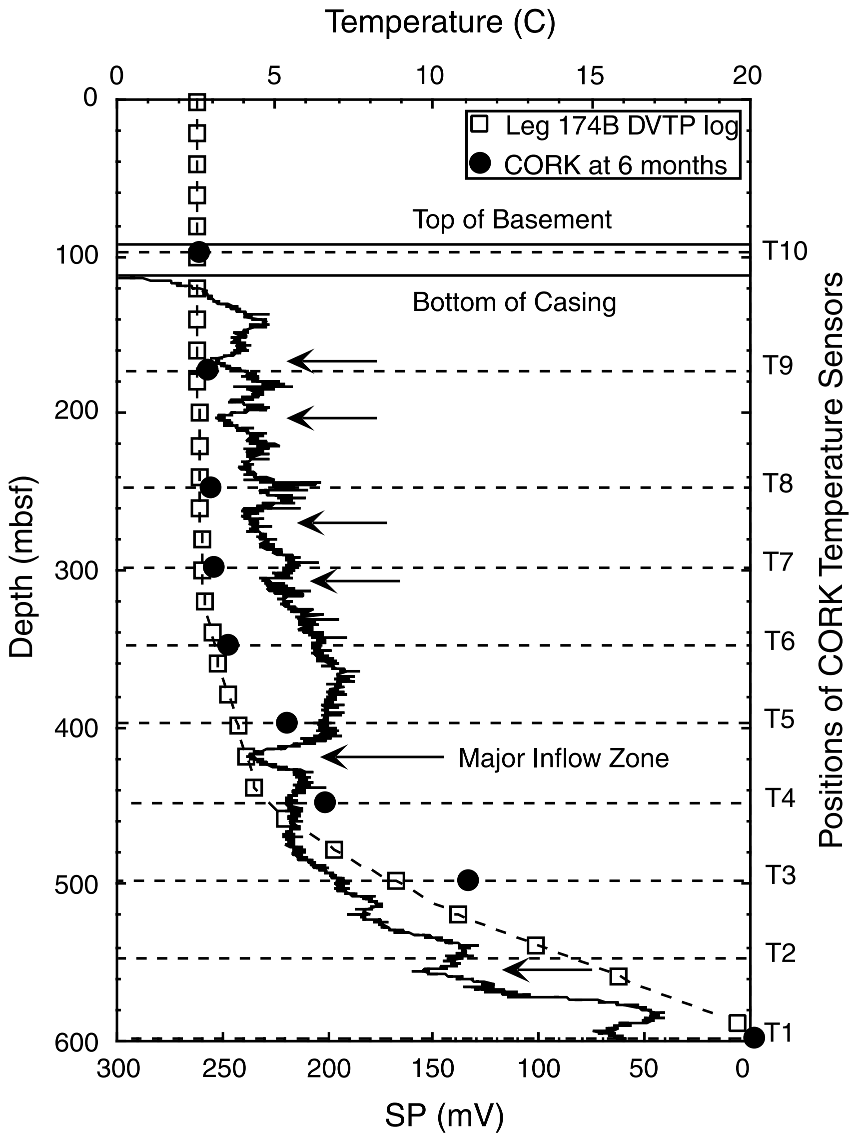


Figure F4. Summary of log interpretation in Hole 395A, after Bartetzko et al. (in press). **A.** Comparison between the core lithostratigraphy (Melson, Rabinowitz, et al., 1979) and the synthetic EFA log. The latter shows more details and yields a more precise definition of individual units than the lithostratigraphy based on cores with incomplete recovery. **B.** Many of the logs show clear cyclic trends, marked with arrows. HSGR = gamma ray log, RHOM = neutron density, LLD = deep laterolog resistivity, CAL1 = borehole diameter. **C.** The cyclic trends are interpreted to represent cycles of volcanic eruptions, labeled I through X.

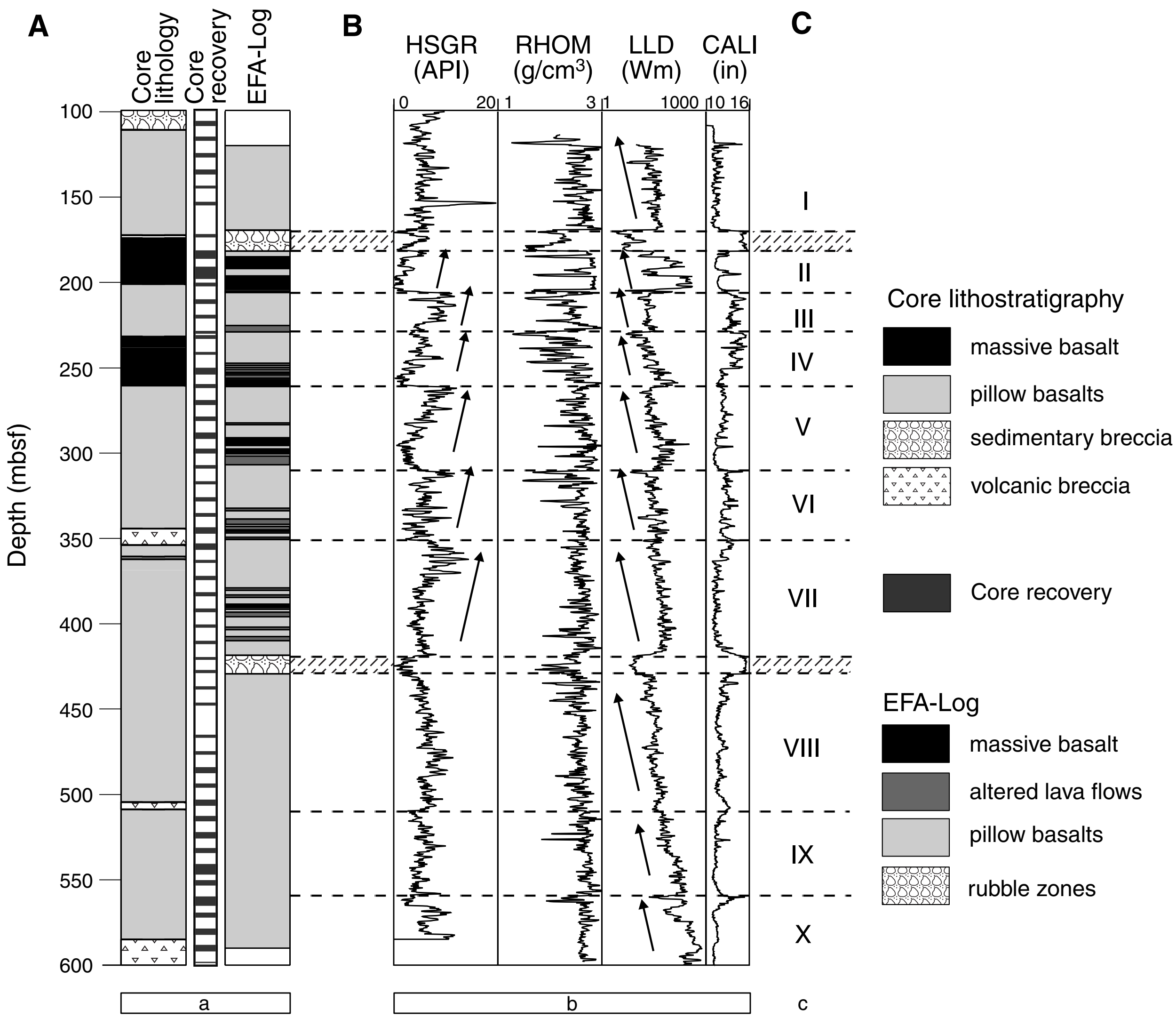


Figure F5. Pressure and temperature data recorded during the first 6 months of operation of the CORK in Hole 395A.

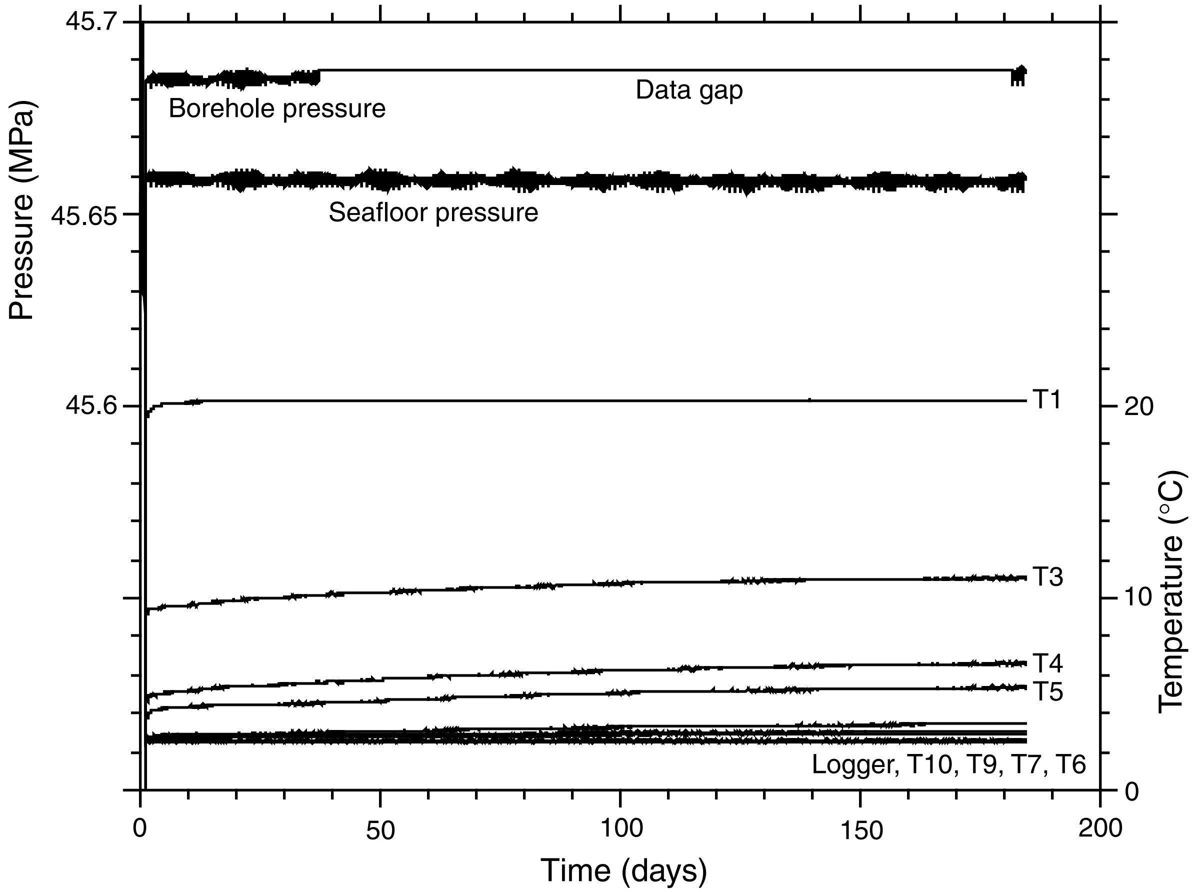
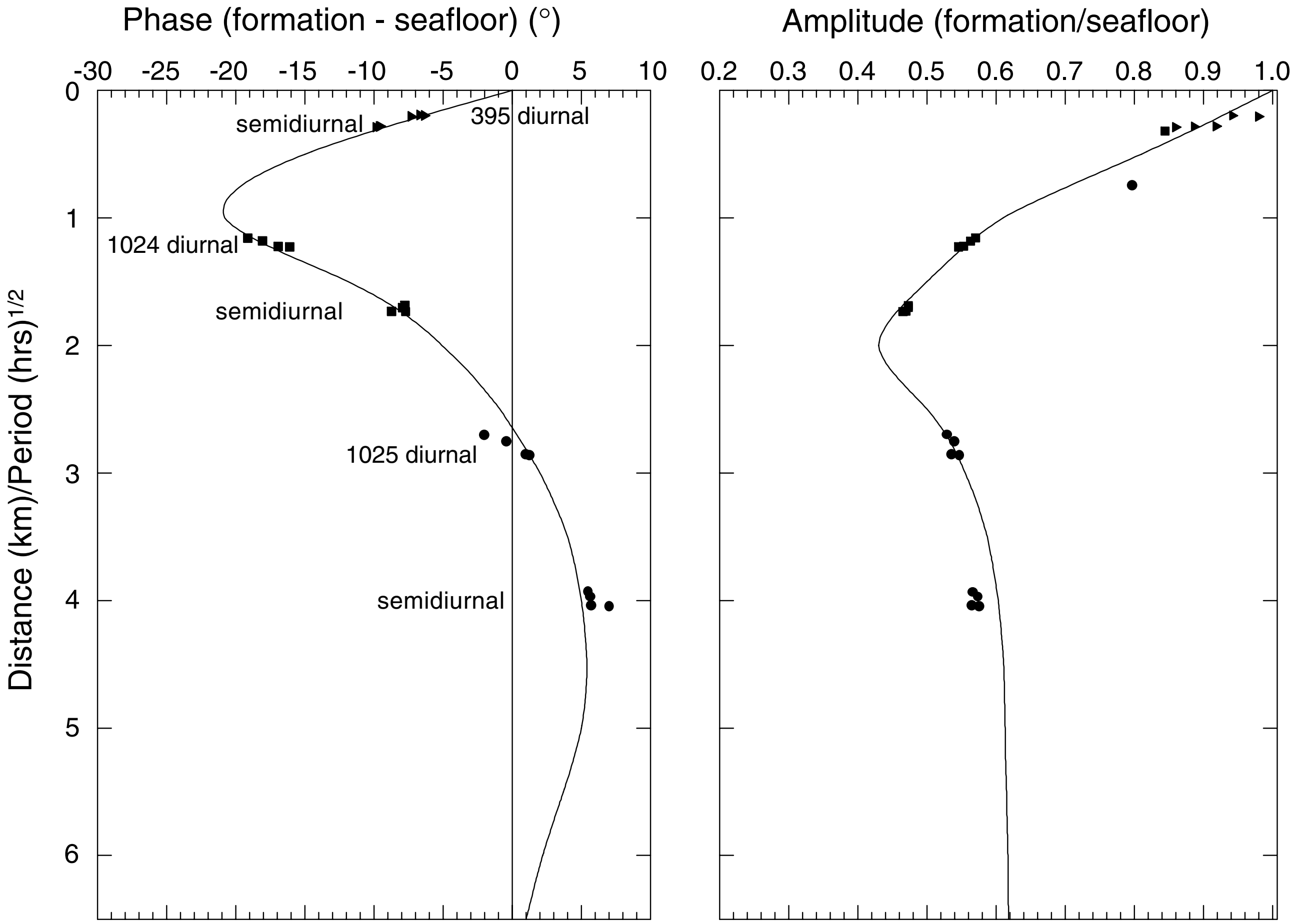


Figure F6. Amplitude and phase of observed basement pressure variations resulting from diurnal and semidiurnal tidal loading from the CORK in Hole 395A, as well as Holes 1024C and 1025C on the east flank of the Juan de Fuca Ridge (after Davis et al., 2000). The data fit well to smooth curves remarkably similar to predictions of the conceptual model for tidally driven lateral flow in a partially buried permeable basement, as described in more detail by Davis et al. (2000).



CHAPTER NOTE*

N1. 4 April 2003—The North Pond site location map (Fig. F1) was initially published with the incorrect longitude. The correct longitude appears in this version.

*Dates reflect file corrections or revisions.