Temperature and video logs from the upper oceanic crust, Holes 504B and 896A, Costa Rica Rift flank: implications for the permeability of upper oceanic crust

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Abstract

In 2001, we revisited thickly sedimented 5.9 Ma crust on the southern flank of the Costa Rica Rift for wireline re-entry of two important ocean crustal boreholes, Holes 504B and 896A, more than 8 years after they were last drilled in 1993. Here we report borehole temperatures measured in both holes within casing through the sediment sections and then into open hole in uppermost basement, as well as a video log from the upper basement section of Hole 896A. Since it first penetrated into oceanic basement in 1979, Hole 504B has been known for downhole flow of ocean bottom water into uppermost basement that was initially strong ($\sim$100 m/h) but then waned; our temperature data indicate a very slow lingering downflow at 0.4 m/h. The pressure differential driving this slow flow was determined to be 11–12 kPa from pressure data acquired when the hole was sealed by our wireline installation of a long-term hydrological observatory. The combination of the flow rate and the pressure differential constrains an estimate for the average permeability of the upper basement section in Hole 504B of 1–5 $\times$ $10^{-14}$ m$^2$, a value similar to but slightly less than past determinations. In Hole 896A, which is located $\sim$1 km away on a sediment-covered basement high, the temperature log indicated uphole flow of formation fluids at an average temperature of 57.8 $\degree$C and at a total rate of 12 m/h through casing; it also showed that at least three zones in uppermost basement produce fluids of different temperatures that contribute to this total flow. Although the associated pressure differential could not be measured in Hole 896A, estimates of average permeability of the section with the producing zones can be derived by assuming a differential of $\sim$20 kPa similar to those measured in other ridge-flank sites in basement highs also known to produce formation fluids; estimated permeability values for uppermost basement in Hole 896A are on the order of $1–4 \times 10^{-13}$ m$^2$, again consistent with past packer determinations. The video log in Hole 896A provides unprecedented visual images that document the discrete nature of the permeability of the producing zones. It also suggests an abundance of bacterial floc within the hole that may be either flushed from the formation by the producing fluids or blooming within the hole in response to nutrients advected by the producing fluids.

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1. Introduction and background

The southern flank of the Costa Rica Rift is notable because high pelagic sedimentation rates have produced a thick sediment cover at young crustal age, and average measured seafloor heat flow closely matches the conductive prediction for lithospheric cooling at only ~6 Ma [1,2]. It was inferred that the rapidly accumulating pelagic sediment cover largely isolates circulation within the permeable igneous crust at this young crustal age, and on this basis, the area was identified early as an important type location for detailed investigation of off-axis hydrothermal processes by both detailed survey methods and scientific ocean drilling [3]. Located in 5.9 Ma crust (Fig. 1), Hole 504B was designed to investigate upper crustal processes, but became, through multiple drilling revisits, the deepest DSDP/ODP (Deep Sea Drilling Project/Ocean Drilling Program) hole into oceanic crust. It penetrated to a total depth of 2111 m below seafloor (mbsf) or 1836 m into basement and is a very important reference hole for the structure and composition of upper oceanic crust [7–10]. When drilling in Hole 504B was abandoned in 1993, the companion re-entry Hole 896A was drilled on a sediment-covered basement knoll about 1 km to the south–southeast. The location was selected for reasons that included the elevated surface heat flow over the basement high [11], and this hole penetrates 469 mbsf or 290 m into igneous basement.

Permeability, porosity, and resistivity data from Holes 504B and 896A provide arguably the most complete description available of the vertical hydrogeological structure in upper oceanic crust (Fig. 2) also [7,9,19,20]. Hole 504B is also the best-studied example of a phenomenon often observed in holes.
drilled through sediment cover into young oceanic crust and left open: the flow of cold ocean bottom water down the hole and into permeable upper basement [13,14,21,22]. Repeat temperature logs at irregular intervals (Fig. 3) show that downhole flow in Hole 504B was initially quite strong (~100 m/h or 6000 l/h) when the hole first penetrated into igneous basement, waned over the next 7 years (1979–1986), and mysteriously revitalized briefly in 1991 only to wane again. A few well-documented examples [27–30] have been reported of borehole flow in the opposite sense (production of warm formation fluids or presence of superhydrostatic pressures) and they are all from settings much like that of Hole 896A–sediment-covered basement highs.

Detailed heat flow and seismic surveys [4–6] of the area around Sites 504/896 show a regional inverse correlation of surface heat flow with sediment thickness, or a positive correlation of heat flow with sediment-buried basement topography. Similar observations have been made on the sedimenterd eastern flank of the Juan de Fuca Ridge [31–34], which is comparable in terms of spreading rate, basement structures, and thick sediment cover at young crustal age. These observations can only be explained by vigorous lateral flow to produce a nearly isothermal state of uppermost basement beneath the sediment cover even in the presence of significant basement topography and sediment thickness variations [32,35–38]. The Juan de Fuca flank was also the location of the first four ridge-flank subseafloor hydrogeological observatories [39,40], in settings specifically chosen to assess the effect and role of basement topography in off-axis circulation. Surveys and borehole experiments at the Juan de Fuca Ridge have provided a wealth of results [41], including a suite of experimental determinations of the permeability of upper oceanic basement using a range of techniques that investigate at spatial scales from meters to tens of kilometers. These include packer experiments [42], analyses of borehole fluid flow [27,28], analyses of responses of subseafloor pressures to seafloor tidal loading and tectonic dislocations [43,44], and constraints from numerical models to simulate nearly isothermal upper basement indicated by heat flow measurements [32,35–38]. This suite of observations documents both an age and spatial scale-dependence of permeability of uppermost oceanic basement [28,42] that are consistent with models of upper crustal evolution through progressive sealing of porosity at smallest scales first [45,46].

In 2001, we returned to the southern flank of the Costa Rica Rift to reoccupy Holes 504B and 896A, for wireline installation of sealed-hole hydrological observatories. These holes comprise a closely spaced pair with significantly different basement topography and sediment thickness, comparable to a pair of the observatory sites in 3.5–3.6 Ma crust on the Juan de Fuca Ridge flank. In this study, we report (a) a temperature log and video images obtained in the upper part of Hole 896A prior to observatory deployment, and (b) a temperature profile plus pressure measurements obtained in Hole 504B during and after the successful installation of an observatory there. The temperature profiles in both holes indicate vertical flow of borehole fluids prior to deployment of the observatories, slow downhole flow in Hole 504B and faster uphole flow in Hole 896A. We focus on...
quantifying the rates of vertical flow in the cased sections of the holes and then assessing the permeabilities of the upper basement formations associated with either the production of formation fluids (896A) or the acceptance of ocean bottom water (504B). In combination with prior determinations of permeabilities in both holes using packers and in comparison with results at the Juan de Fuca Ridge, the results further document the age and spatial scale-dependence of permeability of the upper oceanic crust. Finally, the video from Hole 896A images the fractures and voids that contribute to overall permeability and produce the warm formation fluids that flow up that hole, advecting not only heat but apparently abundant microbiota either blooming within the hole or produced from the formation.

2. Measurement and interpretation methods

The data reported here were collected during (a) August 2001 operations from R/V Roger Revelle to install sealed-hole hydrological observatories in Holes 504B and 896A by wireline using the Control Vehicle of the Marine Physical Laboratory [47] and (b) a November 2002 revisit with R/V Atlantis and DSV Alvin to recover 15 months of data stored in observatory memory. The observatories represent an adaptation of the CORK (“Circulation Obviation Retrofit Kit”) concept as deployed from the ODP drillship in 16 sites to date [48,49], and they are termed “wireline CORKs” herein. Technical details will be presented elsewhere, but basic downhole sensor configurations are described below. In both Holes 504B and 896A, steel casings extend completely through the sedimentary sections and into uppermost basement: Hole 504B is cased to 276 mbsf, or 1.5 m into basement, and Hole 896A is cased to 191 mbsf or 12 m into basement. The wireline CORK sensor strings were configured to investigate only the shallower parts of both holes, primarily the uppermost basement that is known from prior packer experiments to be quite permeable [12,18]. The sensor strings extend in each hole through the cased-off sedimentary section and into the upper ~50 m of open-hole section in upper basement. Our operations and measurements were confined to these shallower sections, although both holes penetrate considerably deeper.

2.1. Temperature and video logging of hole 896A

We initially re-entered Hole 896A with a logging tool equipped with temperature and pressure sensors, a four-arm caliper, and a video camera with lights (Fig. 4) to assess the condition of the upper part of the basement section in which the wireline CORK sensor string was to be deployed. The logging was conducted at an average speed of 18 m/min from seafloor into uppermost basement, and the pressure, temperature, and caliper sensors were sampled ~18 times/min. Analog video was recorded in Hi-8 format that was subsequently captured digitally in DV format. Sensor depths beneath seafloor were determined from pressures calibrated using the video record of tool passage past known reference points such as the throat of the re-entry cone and the bottom of casing. A log of temperature, caliper and video images was recorded through the cased section and into upper basement, to a pressure-determined video camera depth of about...
253 mbsf. At that point, the logging operation was suspended because the zone in which the wireline CORK was to be deployed had been logged and the borehole fluid temperatures of 67°C exceeded the limitations of the internal electronics. A comparable logging run was not attempted in Hole 504B because the section of that hole in which the wireline CORK was to be deployed had been carefully logged in multiple prior drillship operations.

2.2. Temperature and pressure determination in hole 504B

Before activating the wireline CORK to seal Hole 504B, an open-hole temperature profile in the upper section was obtained from the discrete temperatures of 14 thermistors recorded during initial deployment of the sensor string. The thermistor spacing was concentrated in the open-hole basement section to assess processes and state in that section. The string included 10 thermistors spaced every 5 m from 275 to 320 mbsf, as well as five thermistors above, evenly spaced at wider intervals through the cased-off sedimentary section. The sensors also included two pressure gauges (Paroscientific Digiquartz depth gauges), one to determine a reference seafloor pressure, the other to measure pressures within the open-hole section after it was sealed off by an inflatable packer positioned within the casing. Comparison of pressures measured before and immediately after the packer was inflated allowed a determination of the differential pressure associated with any vertical flow of borehole fluids resolved by the temperature profile. A comparable determination of pressures in Hole 896A was not possible because inflation of the two packers in that sensor string was not achieved, and that hole was never sealed.

2.3. Determination of vertical flow rate and permeability

Fig. 5 shows the basic geometry used to interpret the temperature and pressure data for flow rate and permeability. It illustrates the case of downhole flow, but the calculation is equally valid for the case of uphole flow. The undisturbed temperature profile in the sediments, determined in this case with downhole sediment probes prior to drilling into basement, provides both the far-field boundary condition and the initial condition that govern borehole temperatures in the cased section after initial drilling into basement and the beginning of flow down or up the casing. By balancing the radial heat exchange between sediments and the heat advec- ted by flow in the cased section of hole, profiles for borehole fluid temperatures within the casing can be calculated for various flow rates, and the actual flow rate can be estimated by matching observed temperatures to these profiles. Two approaches to the calculation are possible: the transient method of Lesem et al. [51], which involves numerical integration of a two-dimensional Laplace Transform solution (given as eqs. A19–A21 in [13]); or, at very long times, a steady-state approximation (eq. 7 in [13]) that utilizes the heat-transfer analysis of Jaeger [52]. The temperature profiles used to estimate borehole flow in this study were collected many years (8–22) after initial drilling first opened the holes to exchange of fluids between basement and ocean, so either meth-
od would be suitable; we present flow rate calculations below using the transient method.

In the open-hole section below the casing, the flow may exit into or be produced from the formation at various transmissive intervals; if the thickness(es) of these zone(s) can be estimated from the temperature profile or other logs, then the average permeability of the zone(s) can be calculated as a function of the pressure differential driving the flow \[13,27\]. This calculation utilizes a radial form of the Darcy equation:

\[ Q = \frac{\pi a^2 v}{\mu} \left( \frac{8kh\Delta P}{\pi \mu} \right) I(\tau) \]  \hspace{1cm} (1)

Here \( Q \)=total volume flux (units: m\(^3\)/s), \( a \)=radius of cased section (m), \( v \)=linear flow rate (m/s), \( k \)=formation permeability (m\(^2\)), \( h \)=thickness of permeable zone(s) (m), \( \Delta P \)=pressure differential (Pa), \( \mu \)=fluid dynamic viscosity (Pa s), \( \tau = kt/\phi \mu C a^2 \)=dimensionless time, \( t \)=time since flow began (s), \( \phi \)=formation porosity, and \( C \)=total formation compressibility (Pa\(^{-1}\)). \( I(\tau) \) is a complicated integral function [53], for which we utilized the first three terms of a series expansion valid for large \( \tau \). The resulting determination of permeability, as in packer experiments, is a “bulk” permeability that averages transmissivities through the interval, under the assumptions of horizontal, homogeneous, and isotropic aquifer(s) with purely laminar, radial flow of uniform fluids to/from the borehole.

In earlier applications of this method, the compressibility of seawater was used for the total formation compressibility, as there was no information available about the contribution from matrix frame compressibility and the effect of rock grain compressibility is negligible \[13,27\]. More recently, in analyzing comparable borehole flow determinations in four holes on the Juan de Fuca Ridge flank at much shorter times (days) after drilling, Becker and Davis [28] utilized effective formation compressibilities obtained from analyses of the response of sealed-hole pressures to seafloor tidal loading [43]. They also demonstrated that the calculated permeability is insensitive to the compressibility value, primarily because of the way the compressibility enters mathematically into the series expansion of \( I(\tau) \) at large values of \( \tau \). The lack of sensitivity will be even more pronounced for the very long times and large values of \( \tau \) that hold in this study, so the temperature-corrected compressibility of seawater was used for the calculations reported here.

3. Results

3.1. Flow rates within the cased sections of Holes 504B and 896A

In Hole 504B, the temperatures determined with the wireline CORK sensor string minutes before the hole was sealed are essentially linear with true depth within the cased-off sediment section. However, there is a well-documented increase with depth of thermal conductivities through the sediment section at the site [54], and a “Bullard plot” [55] of temperature versus integrated thermal resistance shows a slight, consistent concave-upward curvature indicative of slow downhole flow of ocean bottom water. To apply the method described in Section 3.3, which is formulated for the constant-conductivity case, we rescaled the thermal resistance axis of the Bullard plot by the average sediment conductivity to produce a plot of temperature versus equivalent depth for a constant-conductivity analog for the true situation. This plot preserves the slight concave-upward curvature and is shown in Fig. 6a along with profiles calculated for various flow rates since the hole was first opened nearly 22 years earlier. We estimate a slow lingering downflow at a linear rate of about 0.4 m/h through the casing, equivalent to a volume flux of about 30 l/h.

In contrast, Hole 896A exhibited a convex-upward temperature profile clearly indicative of uphole flow of 57.8 °C formation fluids at a greater rate than the downhole flow in Hole 504B. Fig. 6b shows that log along with profiles calculated for various flow rates since that hole was first drilled ~8.5 years earlier. The estimated uphole linear flow rate in Hole 896A is about 12 m/h, equivalent to a volume flux of about 800 l/h. Also shown in Fig. 6b is a temperature log that was measured during the drilling expedition in 1993, after Hole 896A had been drilled into basement and a hiatus of 8 days had been spent at Hole 504B [11]. At the time, this log was difficult to understand, particularly in that it displayed both concave-upward and convex-upward inflections within the cased section where any vertical flow of borehole fluids must remain uniform with depth. Realizing now that the hole produces warm formation fluids, that 8-day profile can be understood as a snapshot during the period of rapid recovery of the borehole from the strong cooling by circulation during drilling toward a
convex-upward producing profile. The inference is that Hole 896A has been producing warm formation fluids ever since the 1993 drilling operations, but there is no information on possible temporal variations of the production rate.

3.2. Temperatures within open hole in uppermost basement

Deeper than the cased section in Hole 896A, the temperature profile displays two inflection points in the 56 m of open-hole basement section logged, at ~205 and ~230 mbsf (Fig. 6b). This indicates that at least three different zones are independently producing fluids that contribute to the overall uphole flow; there may be more producing zones below the depth at which logging was suspended. The deeper inflection point separates two sections with convex-upward profiles, indicating that parts of these zones are producing fluids warmer than the 57.8 °C mixed fluid that enters the bottom of the casing. The shallower inflection point is actually slightly cooler, indicating that the fluid that flows up the cased section is a mixture of warmer fluids from deeper in the upper basement plus some 57.4 °C fluid produced from a shallower zone in uppermost basement. These observations clearly require a heterogeneous permeability structure to maintain in-situ independence of the fluid packets that commingle in the borehole.

In Hole 504B, the discrete nature of our thermistor placement and sampling rate during deployment did not provide a continuous temperature log like that in Hole 896A, so we could not resolve comparable detail in the profile in the open-hole section in uppermost basement. After the hole was sealed with the wireline CORK, the data collected 15 months later show temperatures still equilibrating from the perturbation due to nearly 22 years of downhole flow of ocean bottom water. Pre- and post-sealing temperatures hint at a tendency to near-isothermal conditions in upper-
most basement, as has been observed more conclusively in longer-term records from CORKs on the east flank of the Juan de Fuca Ridge [40]. The results suggest a generally permeable uppermost basement, but the limited data do not resolve possible heterogeneities in the permeability structure as in Hole 896A. Therefore, in the following section, we can only assume uniformly permeable uppermost basement.

3.3. Average upper crustal permeabilities at Holes 504B and 896A

As noted in Section 2.3, determining average permeabilities from the flow rate estimates also requires knowledge of the driving pressure differential. For Hole 504B, the effective pressure differential was constrained quite accurately by the borehole pressure record obtained as and after the wireline CORK packer seal was activated (Fig. 7). The raw record shows (a) a calibration offset of \( 5.8 \) kPa between the seafloor and borehole pressure gauges immediately prior to inflation of the packer, and (b) after decay of an initial pressure spike associated with the packer inflation, a relatively stable uncorrected pressure differential of \( 5.5 \) kPa. Correcting the latter for the former yields a corrected negative pressure differential of \( 11-12 \) kPa. In this case, the downhole flow rate is so low and borehole temperatures are so close to formation temperatures that the effective pressure differential for the downhole flow and the actual formation underpressure are nearly the same.

Fig. 8a shows how the flow rate and driving pressure determinations constrain the average permeability of the uppermost basement in Hole 504B. The plots show two possibilities for the thickness of the layer accepting the flow, each based on the consistent trend in previous temperature logs to approach linear, apparently conductive profiles below \( 100 \) m into basement (Fig. 3). In the first case, an average permeability for the entire \( 100 \) m is calculated; in the other, most of the transmissivity is assigned to a 30-m zone at \( 330-360 \) mbsf underlying a 10-m-thick massive flow unit, based on initial interpretation of the earliest temperature logs in Hole 504B [13]. For the 100-m case, estimated average permeability is \( 10^{-14} \) m\(^2\); for the 30-m case, estimated permeability is about four times greater. These values are slightly less (by about half an order of magnitude) than estimates made by Becker et al. [13] in analyzing the initially strong downflow in 1979–1981, coupled with an estimate by Anderson and Zoback [12] of the effective pressure differential based on extrapolation of some short-term packer data. We discuss this comparison further in Section 5.2.

In Hole 896A, we could not determine the formation overpressure associated with the uphole flow because we were unable to seal the formation with the wireline CORK. We estimate a reasonable range of possible formation overpressures in Hole 896A based on previous determinations with long-term CORK observations at paired basement ridge-trough sites on the Juan de Fuca Ridge [28,40]. In those two pairs, the equilibrium formation overpressure at the basement ridge site was of similar magnitude or slightly less than the equilibrium underpressure at the nearby basement trough site, and the effective differential pressure at the time of sealing each ridge site (augmented by the thermal buoyancy of the warm fluids being produced) was a few kPa greater than the

![Fig. 7](https://example.com/fig7.png)

Fig. 7. Pressures measured with the wireline CORK observatory (a) during installation in 2001 and (b) for 8 months afterward, illustrating the differential between seafloor and formation pressure.
equilibrium formation overpressure. Allowing for further uncertainty, we use a range of 10–30 kPa for the likely effective positive driving pressures for the flow up Hole 896A. There is also considerable uncertainty as to the total thicknesses of the zones producing the uphole flow, so we again show two possibilities (Fig. 8b): a generic 100-m-thick layer comparable to that in Hole 504B, or the 40-m-thick zone at the top of basement that was shown to be the most permeable section on average in packer measurements [18]. The results for a 100-m layer indicate a permeability on the order of $10^{-13}$ m$^2$; if the transmissivity is concentrated in the upper 40 m, the average permeability of that section is about $4 \times 10^{-13}$ m$^2$. These values are consistent with the estimate of $2 \times 10^{-13}$ m$^2$ for the upper 40-m section determined from packer experiments at the time of drilling [18], and this consistency provides support for the inference of a natural overpressure on the order of 10–30 kPa.

4. Video results in Hole 896A and implications for permeability

In Hole 896A, video was recorded continuously from the time of re-entry, through the 191 m of casing, and then into uppermost basement to a pressure-determined depth of 253 mbsf. Fig. 9 includes selected, representative frame captures, and a compressed version of the ~2 min of video showing the exit from casing and the basement section to 226 mbsf is provided in the EPSL Online Background Dataset.

We focus here on an initial interpretation in terms of the hydrological architecture of the upper oceanic crust and the apparent presence of abundant microbiota in the borehole fluids in uppermost basement.

During ODP Leg 148, the section of upper basement imaged in the video logs was sampled in cores 1R–7R of Hole 896A, which spanned depths of 195.1–257.1 mbsf [11]. Only basaltic rocks were recovered from the entire section cored in Hole 896A, and recovery in the seven uppermost cores averaged 23%. Several lithologic types were identified in this section, including pillow lavas identified by evidence of chilled margins, breccias, and massive units that could be either intrusive flows or interiors of large pillows from which chilled margins were not sampled. The ODP reports [11] include a lithologic log constructed by expanding the average 23% recovery uniformly through the intervals cored; this includes a sequence of 11 identified units spanning the interval imaged in our video log. Fig. 9 presents a reinterpretation of depths of the unit boundaries in this lithostratigraphy, constrained within limits allowed by the uncertainties in placing incomplete core recovery.
within the known cored intervals and guided by patterns in geophysical logs such as the resistivity log also shown.

The combination of the video images, temperature and resistivity logs, and reinterpreted lithostratigraphy in Fig. 9 suggests the following interpretations. As noted in Section 3.2, the predominantly convex-upward temperature profile in Hole 896A displays two inflection points in the basement section, indicating that three zones independently produce fluids that contribute to the uphole flow. Correlating these inflection points with signatures in the resistivity log and the reinterpreted lithology suggests that the producing zones are permeable pillow and/or pillow/breccia units capped, at least locally, by more resistive, more massive, and presumably less permeable units above and below. Pillow unit 3 appears to be the shallowest of the three fluid sources, and pillow/breccia unit 10 the middle source. Pillow/breccia unit 13 may be the deepest of the three sources, but there are insufficient data deeper to indicate this definitively. If this interpretation is correct, it is consistent with the model of Pezard et al. [20], based largely on resistivity signatures in Hole 504B, for the construction and hydrological architecture of oceanic crust formed at intermediate spreading rates from sequences of permeable pillow lavas with occasional less permeable massive flows of greater thickness and lateral extent. It also supports the approach taken by Fisher and Becker [56] in numerical modeling of fluid circulation in the upper crust at this site with a permeability structure that incorporates discrete thin zones of high horizontal permeability.

Focusing on the middle producing zone, i.e., that between 220 and 230 mbsf, we note that the upper limit of this zone seems to be marked by a large wellbore collapse clearly visible at 220 mbsf and apparently corresponding to a low-resistivity spike.
Below this washout, the borehole fluid is noticeably cloudier and contains abundant particulate matter that appears like bacterial floc as observed in bottom waters near axial vents shortly after magmatic activity [57]. In fact, the inner surface of the entire length of casing is coated with a soft deposit that was not sampled but appears to be a combination of precipitate and bacterial growth. As the logging tool passed through the casing, the video indicates that some of this deposit was dislodged, but that the lowering speed of the logging tool outpaced the settling speed of the dislodged particles, with the possible exception of a few of the largest particles. Thus, the cloudy zone encountered from 223 to 230 mbsf, and a similar zone deeper than 234 mbsf, seem to contain particulate matter produced in situ. If it is bacterial floc, it is unclear whether it comprises in situ microbiota actually ejected from the formation or microbiota growing within the borehole in response to nutrients carried by the producing formation fluids. If the latter is true, then it also is unclear whether the apparent floc represents an in situ subsurface community or contaminant microbiota introduced during the original drilling process, or a combination thereof.

5. Discussion

5.1. Age variation and scale effects of upper ocean crustal permeability

Recent determinations of the permeability of uppermost oceanic basement using packer experiments [42] and borehole flow analyses [28] in a transect of young (0.9–3.6 Ma) sites on the Juan de Fuca Ridge flank have documented a clear age variation and spatial scale effects in the permeability of young upper ocean crust. These observations are consistent with a model of ocean crustal evolution by progressive sealing of fractures and voids [45,46], starting at the smallest scale and progressing through larger scale features that may be inadequately sampled in conventional borehole permeability testing. Figs. 10 and 11 update the permeability compilations reported in recent studies with the new flow-based determinations in somewhat older crust at Holes 504B and 896A reported here, as well as the permeability inferred from the thermal structure in the vicinity [5].

Our new permeability determinations remain consistent with the overall trend of decreasing upper crustal permeability with crustal age (Fig. 10). However, the new results from Holes 504B and 896A show greater consistency at older crustal age between short-term packer tests that investigate only a few meters into the formation and the permeability determination from longer-term borehole flows that penetrate to an intermediate scale (~ 100 m) much farther away from the holes. This suggests that the sealing process at Holes 504B and 896A has encompassed larger-scale void features with greater age, as predicted by the progressive-sealing model for crustal aging. This is illustrated more clearly in Fig. 11, which compares results from the Juan de Fuca and Costa Rica sites at the approximate scales of investigation of the various methods used to determine permeability. This shows greater flattening from the left side (smallest spatial scale) as site age increases, as would be expected if the progressive-sealing model for crustal evolution holds true. It suggests that the sealing process has proceeded to the 10–100-m scale in 5.9 Ma crust on the Costa Rica Rift, at least locally in the vicinity of Holes 504B and 896A.

At both the Juan de Fuca and Costa Rica sedimented ridge flanks, permeabilities at even larger spatial scales (>1 km) have been estimated from numerical simulations constrained by geothermal data. At both locations, vigorous hydrothermal circulation and much higher regional upper basement
permeabilities than values determined with either packer or flow data (Fig. 11) are required to achieve the nearly isothermal basement indicated by borehole data and by the inverse correlation between heat flux and sediment thickness [5,32]. For the Juan de Fuca sites, the very high permeabilities deduced from the thermal structure have been corroborated by other methods of assessing regional-scale permeability, namely from analyses of subseafloor pressure response to tidal loading signals and response following strain events associated with distant tectonic dislocations [43,44].

5.2. Temporal variability of borehole flow in Hole 504B: evidence for changes in formation pressures or permeability?

The temporal variability of downhole flow rates in Hole 504B has never been satisfactorily explained, particularly the apparently brief revitalization of downhole flow in 1991 (Fig. 3). Early speculation regarding the monotonic decay of the downhole flow rate observed from 1979 to 1986 centered on “quenching” of a radially finite underpressured reservoir penetrated by the hole [13], but this seems unrealistic in light of the revitalized flow sampled in 1991 and the very high regional permeabilities required for successful simulation of the nearly isothermal basement despite large variations in sediment thickness [5]. In this section, we explore whether temporal variability of formation pressure or formation permeability could provide a satisfactory explanation.

The formation underpressure at Hole 504B was initially estimated as 8–12 bars (0.8–1.2 MPa) using long-time extrapolations of short-term packer experiments over the intervals 199–214 and 211–214 m below the top of basement, conducted shortly after the first phase of DSDP drilling 214 m into the igneous crust [12]. This value is nearly two orders of magnitude greater than our 11–12-kPa measurement obtained on sealing the hole years after dissipation of any drilling-induced disturbance. Subsequent experience with packers in ODP has shown that short-term packer data collected soon after drilling can bear a strong imprint of the perturbation to borehole pressures due to circulation of cold seawater to flush cuttings during drilling. The effect is usually to temporarily produce a fluid pressure gradient from the borehole to the formation because of the density contrast between cold drilling fluids and warmer formation fluids. If the hole is suddenly sealed during this period, the recorded drop in sealed-hole pressure is not an accurate measure of true formation pressure relative to the hydrostatic gradient defined by the in-situ geothermal state. For example, data from a 3-h packer experiment collected shortly after drilling in Hole 896A indicated a drop in borehole pressure on activating the packer seal [18]; this could have been misinterpreted to indicate a formation underpressure, whereas our results indicate that a local overpressure was eventually reestablished in the hole. Thus, there must be large inaccuracies associated with the original estimate of a large underpressure in Hole 504B, owing to both the perturbation due to circulation of drilling fluids and the inherent inaccuracies in extrapolating any short-term data to a long-term value.

The maximum effect on borehole pressures in the upper part of Hole 504B from the introduction of cold drilling fluids can be calculated from the difference in densities of fluids at bottom water temperature (2 °C) and formation temperatures (~60 °C), and is on the order of 70 kPa. If the true formation underpressure we measured in 2001 held at the time of the original
pcker experiments in 1979, then the total apparent underpressure at that time would have been on the order of 80 kPa, fully an order of magnitude less than the original interpretation of 8–12 bars. It is unclear whether this difference can all be attributed to the likely inaccuracies noted above in the 1979 interpretation. Numerical analyses indicated that large underpressures can be maintained in impermeable crust deeper in the section, but not in the generally permeable uppermost section where the original interpretation was made [5].

If the original 8–12-bar estimate was inaccurate for the reasons noted above, then one likely possibility is that the actual underpressure has never been much more than the 11–12-kPa measured in 2001. In that case, the original flow-based calculation of permeability would have been biased too low, and the correct permeability would have been over an order of magnitude greater than that reported here from the 2001 results (Fig. 12). This would require that upper crustal permeability in Hole 504B permeability during the nearly 22 years the hole was left open to downhole flow. Slow sealing by precipitation because of the introduction of cold bottom water in the formation surrounding the hole is a reasonable mechanism to explain an overall reduction of permeability in this period. The brief revitalization in downhole flow in 2001 could be explained by a short-term tectonic enhancement of permeability superposed on the overall trend of decreasing permeability. The likelihood of occasional ongoing tectonic activity at the site is indicated by the seismic imaging of basement faults extending completely through the sediment cover near the sites [58].

If this interpretation is correct, then the apparent reduction of upper crustal permeability at small scales (<100 m) while Hole 504B was left open might serve as an analog for how sealing actually proceeds in nature over geological time scales. The artificial sealing “experiment” accelerated by the introduction of cold bottom water via the open hole might emulate the slower sealing of the crust induced by the much longer-term lateral flow of formation fluids in the undisturbed case of a permeable upper basement sealed by an impermeable sediment cover. If Fig. 11 accurately represents the spatial scales of the sealing process, with the permeability scale-dependence flattening from left to right as sealing proceeds from small scales to large scales, then the time scales probably slow as the sealing proceeds to larger and larger spatial scales. Constraining and quantifying the evolution of the spatial and temporal scale-dependence of upper crustal permeability is critical in integrating global fluxes. Doing so will require application of the full range of techniques to determine permeability in-situ, particularly those sensitive to the larger spatial scales, at representative sites older than our relatively young study sites on the flanks of the Juan de Fuca Ridge and Costa Rica Rift.

6. Summary

In 2001, we completed wireline re-entry logging and “wireline CORK” sealed hole observatory installations in two ODP crustal holes (504B and 896A) in thickly sedimented 5.9 Ma crust on the south flank of the Costa Rica Rift. The logging data and the long-term record from the wireline CORK in Hole 504B provide observations of temperatures and basement formation pressures, as well as video images within ~50 m of upper basement in Hole 896A. The results demonstrate the following:

Ocean bottom water was flowing down the 275-m cased section of Hole 504B and into uppermost ~100
m of basement at a very slow linear rate, 0.4 m/h. This is much slower than rates as high as 100 m/h that were estimated from temperature logs when the hole was first drilled in 1979, but consistent with the general decay of downhole flow indicated by additional temperature logs collected irregularly since then.

In contrast, Hole 896A, drilled into a sediment-buried basement high only 1 km away, was producing 57.8 °C formation fluids from uppermost basement up its casing, and apparently had been producing such warm fluids since it was first drilled in 1993. Inflection points in the temperature log indicate that at least three discrete zones in the upper section of Hole 896A are independently producing fluids of different temperatures, and the fluids flowing up the casing are a mixture from these independent sources.

This pattern—downflow of ocean bottom water in holes drilled into sediment-covered basement troughs and upflow of formation fluids in holes drilled into sediment-covered basement ridges—is consistent with similar observations made in other ridge flank holes, notably the comparable ridge—trough pair of Holes 1026B and 1027C in 3.5–3.6 Ma crust on the east flank of the Juan de Fuca Ridge [27,28,40,42]. This suggests a strategy of drilling sediment-covered basement highs when sampling basement formation fluids is a prime objective.

The data in both holes are consistent with moderately high average permeabilities in uppermost basement—order of 1–5×10⁻¹⁴ m² in the upper section of Hole 504B and 1–4×10⁻¹³ m² in the upper section of Hole 896A. These values are consistent with past determinations of average permeabilities in the vicinity of the hole using short-term packer experiments [12–15,18].

While the flow directions in the two holes were opposite in sense, formation fluid temperatures in uppermost basement are very similar, despite the difference in sediment cover and basement topography at the sites. This requires vigorous lateral hydrothermal circulation and associated heat transport within uppermost basement, and provides an important thermal constraint on numerical simulations of such circulation [5] that further require very high permeabilities on scales larger than those investigated by the borehole methods. The large-scale permeabilities required are orders of magnitude greater than those determined from the borehole flow observations, which provides further evidence for a significant spatial scale effect in the permeability of igneous upper oceanic crust. In combination with similar recent observations in younger sites on the flank of the Juan de Fuca Ridge, the new data also provide further evidence for an age-dependence of upper crustal permeability as well as an age-dependence on its spatial scale effect.

Finally, the video in Hole 896A images the discrete zones that produce formation fluids and in which much of the transmissivity of the basement is probably concentrated. Comparison to recovered core and geophysical logs suggests that much of this transmissivity is concentrated in thin pillow breccia zones capped above and below by more massive pillows or flows. The producing zones are notable for an increase in suspended particulate matter, which appears to be microbiota that is either produced directly from the formation or is blooming in the hole in response to nutrients advected from the formation.

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