THE DYNAMICS AND SIGNIFICANCE OF FLUIDS WITHIN THE SEAFLOOR

A.T. Fisher
Center for the Study of Imaging and Dynamics of the Earth, and Department of Earth Sciences
University of California, Santa Cruz

INTRODUCTION

Fluids are present throughout Earth’s crust and act as a primary medium of exchange between Earth’s interior, lithosphere and hydrosphere. Flowing fluids carry enormous fluxes of energy, magma, and solutes between these reservoirs. Fluids contribute to production of continental crust, generation of explosive volcanism, lubrication of plate boundary faults, formation of hydrates and mineral resources, and development and support of remarkable biological communities. Fluids affect the properties of sediments and basement rocks through which they move and are stored as a result of diagenesis, heat transfer, and stress-strain relations. These strong couplings present challenges to resolving the roles of fluids as agents of change, but have led to exciting scientific discoveries through ocean drilling.

Essentially all studies of fluid flow within the seafloor deal with at least one of these four topics: (1) driving forces, (2) hydrogeologic properties (transmissive and storage), (3) fluxes, and (4) fluid sources. In quantifying these properties and processes, researchers grapple with spatial and temporal scaling issues, and the common challenge of reconciling interpretations based on different approaches and assumptions. In many cases, laboratory and in situ measurements are used as input or constraints for sophisticated models. Results of such models often lead to ideas for new approaches or techniques. The following highlights selected from recent studies of seafloor fluids are based largely on results of Ocean Drilling Program (ODP) experiments.

TECHNICAL APPROACHES

Core material recovered from ODP boreholes provide valuable insights to conditions and processes occurring in the subsurface, particularly by allowing collection and analysis of pristine material. Core samples also present challenges for interpretation of crustal processes. Storage and transmissive properties are known to be scale dependent, and seafloor hydrogeologic systems are heterogeneous, often requiring measurement at the scale and crustal volume of interest.

One valuable legacy of ODP is the development of sophisticated tools for measuring fluid conditions and processes within the seafloor. These tools include logging instruments, packers, flowmeters, and long-term seafloor observatories (CORKs: Circulation Obviation Retrofit Kits). Logging tools create continuous records of formation properties. The addition of logging-while-drilling technology, where logging tools are incorporated into the bottom hole assembly, has let scientists access more hostile environments. Flow meters allow quantification of the rates at which fluids move into or out of the formation surrounding a borehole and provide important constraints on crustal hydrostratigraphy. Drillstring packers are used to isolate parts of boreholes, monitor and manipulate fluid pressures, and quantify formation responses to perturbations. CORK observatories allow boreholes to be sealed and monitored for years at a time, to recover from the disturbance due to drilling, to produce high-quality fluid samples, and to evaluate large-scale crustal properties. The case studies described below have benefited from a mixture of conventional and cutting-edge technical approaches and modeling.

CASE STUDIES

Basement Hydrogeology

Studies of core samples allow researchers to understand the distribution of rock types and alteration, but recovery in basement (particularly in young basalt) is often <20% and generally fails to represent the large-scale fracture patterns common in basement. Borehole studies have provided some of the most valuable, quantitative information on ocean basement rocks. Borehole packer and flowmeter measurements were conducted within basement boreholes during the Deep Sea Drilling Project (DSDP), and these tools have been modified and refined and have continued to provide valuable information during ODP.

A summary of basement permeability estimates from drillstring packer and flowmeter experiments (Fig. 1) illustrates several notable trends (Fisher, 1998; Becker and Fisher, 2000). Although tests in a wide variety of basement ages have indicated a wide range of permeabilities, the data are remarkably consistent within the measured depth intervals. The greatest permeabilities appear to be restricted to the upper few hundred m of the seafloor and tend to be concentrated within intervals having a thickness on the order of tens of m. Caution must be used in interpreting these data in terms of crustal-scale fluid flow because of assumptions in interpretation, scaling of hydrologic properties, and the limited view of crustal conditions based on testing of individual boreholes.

Case Study – Ridge Crest Hydrogeology: Drilling into “zero-age” crust has been a challenging goal for ODP. Considerable technical effort has yielded several promising approaches for bare-rock work; but the greatest
successes in ridge-crest drilling have been on sedimented ridges. Sedimented ridges are unique environments where the rate of magmatic emplacement is insufficient, relative to that of sedimentation, to allow basalt extrusion onto the seafloor. Instead, basaltic magma rises from depth and spreads laterally below the seafloor, forming an interlayered sediment-sill complex. The low-permeability sediments capping these systems limits the exchange of fluids, heat and solutes between the crust and overlying ocean, but allows unique opportunities to drill, core, sample and install observatories within some of the youngest seafloor.

Two ODP cruises visited Middle Valley, a sedimented rift at the northern end of the Juan de Fuca Ridge (Fig. 2A). Two holes were cased and sealed in Middle Valley during ODP Leg 139, establishing the first CORK observatories. Hole 858G was drilled in the Dead Dog vent field, within a few tens of meters of several clusters of active chimneys discharging hydrothermal fluids at temperatures up to 280°C. Dead Dog vent field is well-defined by side scan sonar surveys as an elongate area of high acoustic backscatter 400 m by 800 m on a side (Fig. 2B). The hole penetrated 260 m of sediment and 175 m of basal-tic basement interpreted as a buried volcanic edifice. Hole 857D was drilled 1.6 km south of the Dead Dog vent field through 470 m of sediments and 500 m of alternating sediments and sills; the deeper section here was thought to include a part of the hydrothermal reservoir. Geophysical and flow meter logs and packer experiments were completed, and both holes were sealed with CORK observatories (including thermistor chains, fluid samplers, and pressure gauges) and left to equilibrate. The observatories were visited by submersible and remotely-operated vehicle over several years, and reinstrumented during ODP Leg 169.

Pressure records downloaded from the observatories after fourteen months suggested that basement fluids in Hole 858G were overpressured relative to seafloor hydrostatic conditions by 180 kPa, while fluid pressures in Hole 857D were underpressured by 400 kPa. This pattern makes some sense, since basement fluids in an area of active venting should be overpressured, and the fluids within the reservoir need to be underpressured in order to draw recharge. But this distribution of under- and overpressures also seems to suggest that fluids within basement should flow away from the vent field at depth. In fact, the in situ gradient in the fluid impelling force is from the reservoir area (Hole 857D) towards the vent field (858G), as determined by correcting the seafloor pressures measured at the observatories for differences in fluid temperature and density with depth (Fig. 2C; Stein and Fisher, 2001). Based on the assumption that vigorously-convecting fluids at depth are isothermal at 280°C, the temperature-corrected difference in pressure head between the two sites is only 1.7 m. This remarkably small head difference between sites 1.6 km apart suggests that hydrothermal basement in this area must be extremely permeable.

A large-scale basement permeability estimate was made for this region using a technique commonly applied to pumping wells on land (Stein and Fisher, 2001). Holes 858G and 857D are considered to be observation wells located 50 m and 1600 m, respectively, from the center of the well field (the “pumping well”). Based on the temperature-corrected head difference between the observation points and an aquifer thickness of 10 to 1000 m, the basement bulk permeability necessary to supply fluid to the vents is $10^{-12}$ to $10^{-10}$ m$^2$, with the higher permeability value corresponding to the thinner aquifer (Fig. 2D). A value of $10^{-10}$ m$^2$ also was estimated for a 5 m-thick to 10 m-thick interval based on packer and flowmeter experiments and other observations (Becker et al., 1994).

Figure 1. Compilation of bulk permeabilities in oceanic basement from packer and thermal flow meter measurements (Fisher, 1998; Becker and Fisher, 2000). Data were collected in DSDP and ODP holes having a range of crustal ages and compositions, as noted. Range in depths into basement indicates either the full open interval of the tested borehole (for most tests), or a smaller interval (thought to contain the greatest permeability) identified on the basis of lithologic or well logs. Range in individual bulk permeability values indicates estimated uncertainty.
Case Study - Ridge Flank Hydrogeology: While high-temperature hydrothermal circulation at seafloor spreading centers results in spectacular vent fields, biological communities and ore deposits, basement below most of the seafloor hosts fluid flow at slower rates and lower temperatures. This “ridge-flank” circulation involves much larger global fluxes of fluid and heat and results in significant geochemical exchange for several elements. ODP Leg 168 explored aspects of ridge-flank hydrogeology through drilling and experiments along a transect of crust aged 0.9 to 3.6 million years (m.y.) (Fig. 3A).

Four sites instrumented with CORK observatories have been revisited several times to service instruments, collect fluid and biological samples, and download pressure and temperature data. The resulting data sets demonstrate the dynamics of distinct fluid processes within oceanic ridge flanks. Two CORKs were installed 2.2 km apart into a buried basement ridge-trough pair at the eastern end of the transect. The buried ridge CORK, at Site 1026, penetrated 250 m of sediment and 20 m of upper basement, while the buried trough CORK, at Site 1027, penetrated 600 m of sediment and 40 m of basement. Under purely conductive conditions, upper basement temperatures at Site 1027 would have been about 40°C warmer than those at Site 1026, but in situ temperature measurements indicated that uppermost basement at these sites was practically isothermal. This condition requires vigorous fluid convection in basement. The relatively small pressure gradients detected between the two CORKs suggest that effective basement permeability must be very high.

CORK experiments along the Leg 168 transect also have demonstrated that crustal fluid pressures at flank sites 10 s to >100 km from earthquake epicenters respond to seismic events (Davis et al., 2001). After filtering CORK pressure records to remove the influence of barometric pressure changes and tides, distinct signals remain that

Figure 2. A. Location of Middle Valley on the northern Juan de Fuca Ridge. B. Cartoon showing CORK observatories and the Dead Dog vent field. The green shaded region indicates the extent of the vent field, as mapped with side-scan sonar. Hole 858G is located within the vent field, and Hole 857D is located outside the vent field. Total fluid flux from the vent field is related to bulk basement permeability, based on the measured fluid pressure (corrected for local thermal gradients) and distances from the CORKed holes to the center of the vent field. C. Measured pressures (above hydrostatic in Hole 858G, less than hydrostatic in Hole 857D) are corrected for variations in fluid density, based on borehole temperatures, allowing calculation of the difference in effective pressure head between the two boreholes of about 1.7 m. This is the driving force available to move fluid at depth from outside the vent field to the base of the vent system. D. Given this head difference and possible aquifer thickness of 10 to 1000 m, bulk permeability on the order of $10^{-12}$ to $10^{-10}$ m$^2$ is required to supply observed vent discharge. A value at the upper end of this range was estimated from packer experiments in Hole 857D (see Figure 1). Modified from Stein and Fisher (2001).
correlate with independently-detected seismic events along plate boundary faults. An October 1996 event along the Nootka Fault led to an abrupt decrease in fluid pressure at Site 1027, followed by a gradual rise back to background values (Fig. 3B). A June 1999 event near the spreading axis of the Juan de Fuca Ridge lead to an abrupt rise in fluid pressure at Site 1024, followed by a slow decay of the pressure perturbation (Fig. 3C). The latter event is interpreted to have been associated with seafloor spreading along the ridge crest 20 km west of Site 1024. The strain is believed to be equivalent to that associated with a magnitude 6 seismic event, suggesting that a large fraction of the spreading was aseismic. The stresses associated with these events are thought to be transmitted through crustal rocks, and the gradual decay of pressure results from the hydrologic properties of the upper crust (Davis et al., 2001).

**Sediment Hydrogeology**

Seafloor hydrogeologic studies in sedimented settings present unique challenges. Sediments tend to be much more compliant than basement rocks, and are greatly modified by drilling and coring operations. Sediments contain pore fluids that yield geochemical information about diagenesis and hydrologic processes. Like many basement rocks, some sedimentary formations are fractured, requiring in situ hydrogeologic testing because laboratory analyses of small samples do not include critical flow pathways. In this section I highlight two examples that illustrate how our understanding of seafloor hydrogeology in sedimentary environments has been advanced by ODP experiments.

**Case Study - Active Margin Hydrogeology:** The Barba-dos accretionary complex has been visited for scientific ocean drilling during DSDP Leg 78A and ODP Legs 110, 156 and 171A. The primary focus of these expeditions was to understand the processes controlling deformation occurring at this active margin, with an emphasis on the décollement, the low-angle, plate boundary fault separating the accretionary wedge of the Caribbean Plate from the subducting sediments and basement of the North American Plate (Fig. 4A). The earliest drilling expeditions to this area concentrated on coring and sample analysis, in part because borehole measurements were extremely difficult within unstable formations. Leg 110 introduced packer technology to this environment, and Leg 156 included completion of the first successful packer experiments along a tectonic plate boundary.

Holes 948D and 949C were drilled into the toe of the accretionary complex during ODP Leg 156 (Fig. 4A). Both holes were cased through the decollement, and wire-wrapped, perforated casing was used to conduct drillstring packer experiments (Fisher and Zwart, 1997). These tests were complicated by unstable hole conditions and changes in background pressure during testing. After in situ testing was completed, the cased holes were fitted with CORK observatories. The CORKs were revisited by submersible eighteen months later, and Hole 949C was subjected to “artesian well” hydrologic tests by opening and closing the fluid sampling valve (Screaton et al., 1997). CORK records of fluid pressures in Hole 949C during Leg 171A provided an additional test of sediment properties between two boreholes based on excess pressures generated while drilling nearby Hole 1046A (Screaton et al., 2000).

**Figure 3.** Examples of the response of crustal fluid pressures to coseismic strain along the edges of the Juan de Fuca Plate, northeastern Pacific Ocean. Modified from Davis et al. (2001). **A.** Index map showing locations of ODP Sites 1024 and 1027, at western and eastern ends of the Leg 168 drilling transect (dashed line), where CORK observatories were installed. Stars indicate two seismic events, a magnitude 6.3 event along the Nootka transform fault in October 1996, and a magnitude 2.8 event near the spreading axis of the Juan de Fuca Ridge in June 1999. **B.** Pressure response of crustal fluids at Site 1027 to the 1996 event. **C.** Pressure response of crustal fluids at Site 1024 to the 1999 event.
Results of these tests yield a range in décollement permeabilities, from \(10^{-17}\) to \(10^{-19}\) m² (Fig. 4B). At the low end of this range, the borehole results are consistent with laboratory tests of fine-grained material recovered from the same locations, suggesting that these values may represent background, intergranular permeabilities. At the higher end of this range, the values are close to those suggested by steady-state numerical models of large-scale fluid flow and accretionary wedge dewatering. The highest-quality packer and single-hole CORK test results suggest a dependence of formation permeability on pore fluid pressure, with differences in permeability of five orders of magnitude as fluid pressure varies from hydrostatic to lithostatic (Fig. 4B). This result is intriguing because it may help to explain how excess fluid pressures and fluid flow may be coupled through non-linear changes in formation properties. The cross-hole test conducted during ODP Leg 171A resulted in greater apparent permeability at low pore fluid pressures than suggested by the trends deduced from the other tests (Screaton et al., 2000).

**Case Study - Passive Margin Hydrogeology:** Relatively little work has been done during ODP to elucidate hydrogeologic processes along passive continental margins, but drilling along the New Jersey margin on ODP Leg 174A provided new insights as to how fluid excess fluid pressures and fluid flow are coupled in this setting. Site 1073 was drilled through 650 m of Oligocene to Holocene sediments in 640 m of water (Fig. 5A). Sediment porosities were found to be anomalously high, leading to an interpretation that pore fluids were overpressured relative to hydrostatic (Dugan and Flemings, 2000). Fluid pressures below the Miocene-Pliocene boundary (Fig. 5B) were calculated to be within 95% of lithostatic values.

The creation of fluid overpressures requires the application of stress at sufficiently high rates that fluid cannot escape rapidly enough to maintain hydrostatic conditions. In passive margins, this can result from generation of hydrocarbons or other diagenetic processes, topographic forcing associated with an adjacent continental area, or through rapid sedimentation of fine-grained material. The latter process is thought to be primarily responsible for generation of excess pressures at ODP Site 1073 (Dugan and Flemings, 2000).

Results of two-dimensional modeling of coupled sedimentation, mechanics, and fluid flow in this setting suggest that excess fluid pressures are expected to develop within relatively permeable Miocene sediments below a cap of lower-permeability Pliocene sediments. Fluid specific discharge (volume flux/area) at the seafloor above the shallow section is relatively slow at \(<0.05\) mm/yr; considerably greater fluxes of \(>5\) mm/yr are predicted near the toe of the Miocene strata (Fig. 5C). Local velocities could be even greater, depending on the nature of permeability heterogeneity and subsurface pathways. These fluxes are geochronologically significant and could support seep communities without requiring a direct connection between continental (meteoric) waters and the continental slope. The models also suggest that the continental slope in this region may be broadly overpressured, and could lead to rapid (even catastrophic) slope failure and the creation of submarine canyons.

**MARINE HYDROGEOLOGY OPPORTUNITIES IN FUTURE SCIENTIFIC OCEAN DRILLING**

The ocean drilling work described here includes a variety of approaches used to understand and quantify

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**Figure 4. A.** Location of ODP Sites 948, 949 and 1046 at the toe of the Barbados accretionary complex (striped region). **B.** Bulk permeability versus fluid pressure, including packer and CORK results (Fisher and Zwart, 1997; Screaton et al., 1997; 2000). Fluid pressures are represented by the modified pore pressure ratio, \(\lambda^* = (P_m - P_h)/(P_l - P_h)\), where \(P_m\) = measured fluid pressure, \(P_h\) = hydrostatic pressure, \(P_l\) = lithostatic pressure. Lithostatic pressure will have \(\lambda^* = 1\), and hydrostatic pressure \(\lambda^* = 0\). Vertical bars indicate estimated uncertainties in test interpretations. Packer and single-hole CORK symbols are open for pressure at start of test, and filled for pressure at end of test. The dashed line indicates a least-squares best-fit (see equation) to the highest-quality packer and single-hole data.
the influences of subseafloor fluids on geological processes. These process-oriented studies focus on the dynamics of fluid-crust interaction, a strategy that has pushed the limits of available technology and required an interdisciplinary view of seafloor hydrogeology. Future studies will build on this foundation, and continue to benefit from technical development, long-term observation at a range of spatial and temporal scales, and active experiments. Advances in instrumentation, including miniaturization, new sensors, increased data storage capacity, and reduction in power requirements, will allow more information to be analyzed at higher data rates and with greater precision.

For example, new borehole observatory systems will monitor and allow sampling within multiple depth intervals. Although monitoring of natural processes will continue to provide useful and exciting results, future experiments also will include active perturbation of hydrogeologic systems, allowing interpretation of system dynamics with greater confidence, and "smart" monitoring technology that varies the rate of data and fluid sampling during events of interest. Future hydrogeologic studies also will link seafloor and subseafloor observations and sampling, and will include a combination of geological, biological, chemical and physical components.

REFERENCES


Figure 5. A. Index map showing location of ODP Site 1073 on the continental slope, New Jersey margin. Thin line perpendicular to slope indicates location of seismic line. Contour depths in meters. B. Seismic line showing regional stratigraphy and stratigraphic interpretation. C. Results of two-dimensional model of coupled sedimentation, compaction and fluid flow. Contours indicate effective stress, colors indicate overpressures (P*), and vectors indicate fluid flow after 1 million years of sedimentation. White line indicates Miocene-Pliocene boundary. Note generation of excess fluid pressure near the toe of the Miocene strata, as well as relatively rapid fluid discharge in this area. Modified from Dugan and Flemings (2000).