BOREHOLE OBSERVATORIES MONITOR ACTIVE HYDROLOGY BENEATH THE SEAFLOOR

Keir Becker, Division of Marine Geology & Geophysics, RSMAS, University of Miami
Earl E. Davis, Pacific Geoscience Centre, Geological Survey of Canada

A wide range of fundamental geological problems, such as the exchange of mass and heat between Earth's lithosphere and hydrosphere, the origin of valuable metal ore bodies, and even earthquake activity associated with deep-sea trenches, are linked to a common process — the widespread circulation of fluids beneath the seafloor, through oceanic sediments and underlying crust. Near mid-ocean spreading centers, such circulation is driven by thermal energy released by the formation of oceanic crust from magma, and is therefore termed "hydrothermal circulation." Near subduction zones, subsurface fluid flow is largely driven by compressional forces as plates converge, and the circulating fluids are generally lower in temperature than hydrothermal fluids.

Hydrothermal circulation at the crests and flanks of the mid-ocean ridges results in water-rock chemical exchanges that alter the original compositions of both the igneous oceanic crust and the circulating fluids and modulate the chemistry of the oceans. Hydrothermal vents, both at most ridge crests and at cooler seeps at subduction zones, support unique chemosynthetic biological communities on and beneath the seafloor, completely independent from photosynthesis. Therefore, it has been hypothesized that ancient hydrothermal systems may have been associated with the origins of life on Earth, and recent indications of hydrothermal sites elsewhere in the solar system are generating considerable excitement about the possible existence of primitive extraterrestrial life.

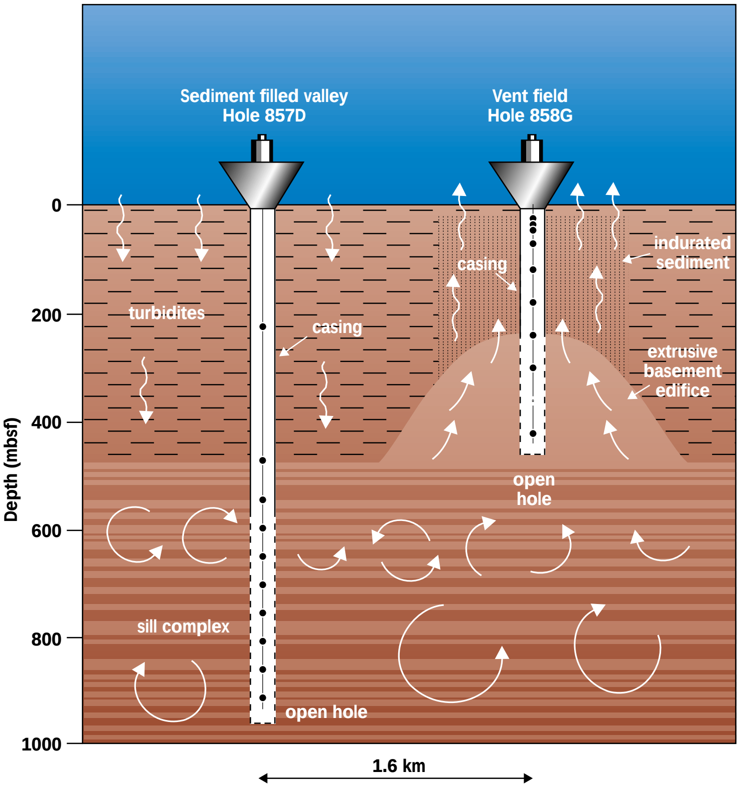

Figure 1: Configuration of the two Middle Valley CORKs, first deployed in 1991, as refurbished in 1996. Lines and dots down the centers of the holes represent thermistor cables and positions.

Present scientific understanding of hydrothermal circulation is largely inferred from the chemistry of fluids exiting the seafloor and from the patterns revealed by heat-flow measurements made just below the seafloor. ODP drilling now provides an innovative means of studying fluid circulation deep beneath the seafloor, by emplacing long-term sensors directly within the formation where circulation occurs. The ODP drilling process uses surface seawater to flush cuttings from the hole, and therefore often disturbs the very hydrothermal system we seek to study. These drilling disturbances make it difficult to conduct meaningful hydrological measurements or to sample pristine, *in situ* fluids from holes that are left open. To overcome this problem, ODP engineers and scientists have developed specialized borehole seals that prevent the flow of water into or out of selected ODP holes after they are drilled, and simultaneously allow emplacement of instruments for long-term use in the sealed holes [*Davis et al.*, 1992; *Davis and Becker,* 1993]. Once these holes are sealed, the hydrological conditions in the rock formation slowly return to the natural state that existed prior to drilling, and the instruments monitor the recovery to true *in situ* conditions as well as any natural hydrologic events that may also occur. Several sites on ridge crests and flanks and in subduction settings have now been instrumented using these so-called "CORK" (Circulation Obviation Retrofit Kit) experiments; ODP installs the instruments, and the data are recovered months to years later from manned or unmanned submersibles.

On the ridge flanks and crests, heat flow surveys dating back to the 1970's clearly demonstrated that hydrothermal systems can extend over large areas — 10's or even 100's of kms. However, we understand little about the subsurface workings of such systems, and this is one of the key objectives of the CORK experiments. A good example is provided by the first two CORKs, which were installed in a sediment-covered spreading center in the Pacific northwest (Figure 1) [*Davis and Becker,* 1994]. One of these CORKs is located in the midst of a hydrothermal-vent field

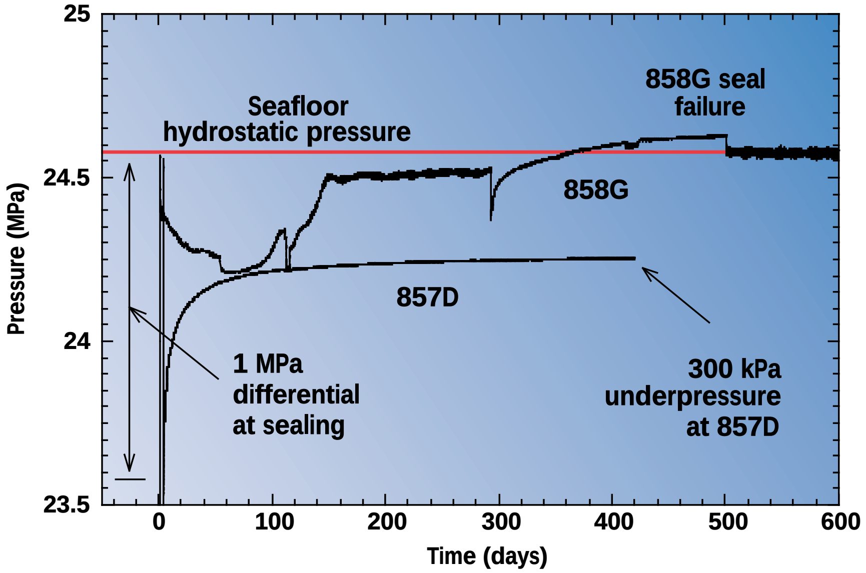

Figure 2: 1991-1993 long-term pressure records from the Middle Valley CORKs.

where fluids at temperatures of 260-270°C are expelled. Here, ODP Hole 858G was drilled through hardened sediments into an underlying volcanic edifice, which is thought to act like a permeable "chimney" in focusing the subsurface hydrothermal flow to produce the seafloor vents. Over a kilometer to the south, well away from the vent field, Hole 857D was drilled into highly permeable rocks that may serve as one of the sources of the fluids that vent near Hole 858G.

The data from these two CORKs show surprisingly different trends over time (Figure 2). In both holes, the earliest segments of the borehole pressure records show brief excursions toward extremely low values, caused by the invasion of cold and dense seawater during drilling. In the months that followed, the Hole 857D record shows a smooth recovery towards *in situ* pressures as the formation recovered from the cooling artifact of drilling. In contrast, the time series of pressure data from Hole 858G in the vent field shows several discrete events, including sudden offsets and distinct changes in trends. Some of these may be associated with natural activity in the vent field, while others were probably linked to hydrologic disturbances via a nearby exploratory drill hole that was inadequately backfilled with cement. A thermally induced failure of the CORK seals caused the event about 500 days after CORK deployment. When the seals failed, fluid pressures dropped suddenly to that of the column of seawater at the site ("seafloor hydrostatic pressure") and a full-amplitude tidal signal was observed.

The most surprising and fundamental result of these observations is the large difference in equilibrium pressures at the two sites. Before the seal failed, the pressure in Hole 858G had become greater than hydrostatic conditions, and was continuing to rise towards a value of about 0.1 MPa above a hydrostatic reference consistent with the local geothermal gradient. This is equivalent to about one bar and represents the excess fluid pressure available to drive water out of the formation at the vent field. In contrast, the long-term record at Hole 857D recovered to about 0.3 MPa below local hydrostatic conditions. This strong "underpressure" indicates that seawater must be slowly percolating down through the sedimentary column to replenish fluids circulating in the subsurface hydrothermal system, possibly linked directly to the vent field near the other hole.

Models using the constraints provided by the CORK data provide one way to quantitatively estimate the extent to which the formation is hydrologically connected. A more direct experiment was conducted when the two drill holes were re-instrumented in 1996 during ODP Leg 169. At that time, a unique cross-hole experiment was carried out to provide an independent estimate of the formation-scale permeability and hydrological connectivity between the holes. (Data from this experiment is scheduled to be recovered in September, 1997, using the remotely operated vehicle, *JASON*.) The high permeability inferred at this site, as well as at other sites instrumented during Leg 168 on the eastern Juan de Fuca ridge flank, suggest that fluids may move through the upper igneous crust at average rates of tens of meters per year, and carry heat and solutes laterally over distances of many tens of kilometers with great efficiency. If this is so, the oceanic crust may be one of the most hydrologically active formations on Earth.

References:

Davis, E.E., K. Becker, T. Pettigrew, B. Carson, and R. MacDonald, CORK: a hydrologic seal and downhole observatory for deep-ocean boreholes, *Proc. ODP, Init. Repts., 139,* 43-53, 1992.

Davis, E.E. and K. Becker, Studying crustal fluid flow with ODP borehole observatories, *Oceanus, 36(4),* 82-86, 1993.

Davis, E.E. and K. Becker, Formation temperatures and pressures in a sedimented rift hydrothermal system: ten months of CORK observations, Holes 857D and 858G, *Proc. ODP, Sci. Results, 139,* 649-666, 1994.

Subseafloor "Rivers" of Fluid and Heat

Andrew Fisher, Institute for Geophysics and Planetary Physics and Department of Earth Sciences, University of California, USA

Fluids are present throughout Earth's crust and move vast quantities of heat and chemicals between oceanic and lithospheric 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 biological communities. Some of the greatest challenges in marine hydrogeology are resolving the depths and distances over which flow occurs, and determining the nature of formation properties and driving forces that cause this flow. To meet this challenge, ODP scientists recognized the value of monitoring conditions within the seafloor, and developed technology to install observatories in a wide range of settings.

Several observatories have been installed at a seafloor spreading center in Middle Valley in the Pacific Ocean, off the western coast of North America (Figure 1). This is a place where new seafloor is created, so the observatories allow monitoring of "zero-age" crust. Two holes were drilled, cased and sealed in Middle Valley during ODP Leg 139, establishing the first long-term borehole observatories in the seafloor. Hole 858G was drilled in the Dead Dog vent field, within a few tens of meters of several clusters of active chimneys discharging fluids at temperatures up to 280 °C (Figure 2). Another hole (857D) was drilled 1.6 km south of the Dead Dog vent field through sediments and sills ("hydrothermal basement"). Geophysical and hydrogeological experiments were completed, and both holes were sealed with observatories (including temperature sensors, fluid samplers, and pressure gauges) and left to equilibrate. The observatories were visited by submersible and remotely-operated vehicles over several years, and reinstrumented during ODP Leg 169.

Pressure records downloaded from the observatories after 14 months suggested that, after correcting for differences in fluid density, the difference in fluid pressure between basement fluids in Hole 858G relative to fluids in Hole 857D was very small, equivalent to about 1-2 atmospheres of pressure. This small pressure difference is responsible for driving rapid flow of water to the vent field from the surrounding formation. This observation requires that hydrothermal basement below the vent field at this spreading center is extremely permeable (Figure 3).

Determining that basement permeability is very high is important because it means that small changes in pressure can travel long distances, and that fluids can move freely within the crust, greatly influencing the chemistry, biology and physical properties within the seafloor.

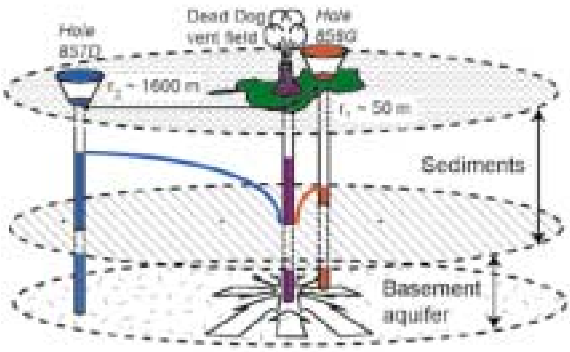

Figure 2

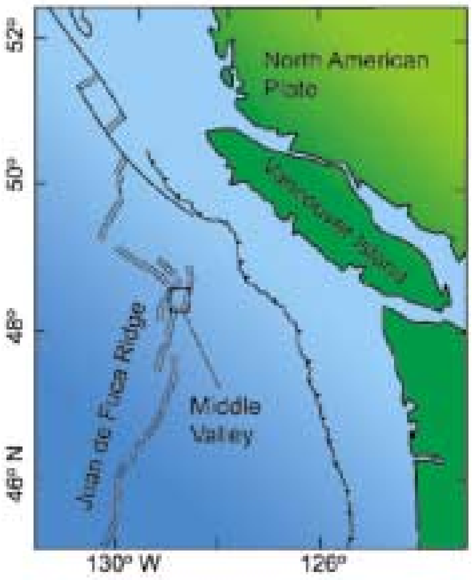

Figure 1

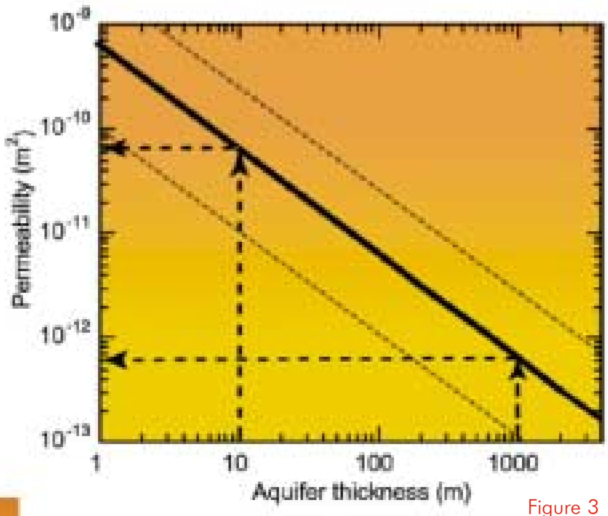

Figure 3

Watching Plates Move with CORK Observatories

Earl Davis, Pacific Geoscience Centre, Geological Survey of Canada; **Keir Becker,** Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA

Beneath much of the seafloor of the world's oceans, formation fluids circulate through the igneous crust and overlying sediments, transferring heat and chemicals between the interior and exterior of the Earth. CORK (Circulation Obviation Retrofit Kit) instrumentation was originally developed to document this flow through observations of temperatures, pressures, and compositions of formation fluids made well after drilling ends. Over the first decade of CORK monitoring experiments installed in a variety of ODP holes, a number of observations have been made that range well beyond the original objectives of understanding fluid circulation.

One particularly exciting aspect of CORK results is the unanticipated information provided about plate deformation (extension, compression, shearing, faulting, etc.) and associated earthquakes. CORK records show that fluid pressure and temperature respond to tectonic deformation, which often involves earthquakes but may also occur aseismically. Theory developed to account for how fluid pressure responds to seafloor tidal loading (another outgrowth of CORK observations) can be applied with little modification to explain the response to tectonic deformation. In fact, the observations of the former provide an excellent calibration for the latter. Data from CORKS have also shown that long-lasting changes in mechanical and hydrologic properties, inferred from changes in the formation-pressure response to seafloor tidal loading, result from plate strain, most notably at sites that are close to the location of earthquakes.

Changes in fluid pressure have been observed at sedimented ocean crustal sites as far as 120 km from relatively small earthquakes in the vicinity of the Juan de Fuca Ridge (Figure 1). They show that regional plate strain is observed to be greater than that which would be generated by seismic slip alone. During a series of small earthquakes on the ridge axis that began with a magnitude 4.6 earthquake, the strain observed at four CORK sites was equivalent to that which would have been produced by a much stronger, magnitude 6 event. Most of the displacement of the "spreading event" that was the cause of the plate strain and earthquakes must have taken place aseismically. Thus, research from CORKS is helping to explain the relationship between episodic plate motion and deformation and earthquake energy release.

CORK monitoring continues on the axis and flank of the Juan de Fuca Ridge (where a new swarm of seismic activity has taken place recently), the flank of the Costa Rica Rift, and the Nankai and Mariana subduction zones. New installations were just completed at the Costa Rica subduction zone. It is our hope that long-term hydrologic monitoring at all of these sites will provide new knowledge and understanding of earthquake rupture and plate strain processes, and the role of water in both.

Figure 1. Examples of pressure changes through time associated with seismic fault slip events in 1996 and 1999 (Stars). Pressures increase where the formation is compressed and decrease where it is extended, then return to unperturbed levels at rates that depend at each site on routes for hydrologic "drainage". Pressure and temperature changes associated with earthquakes have been observed in all of the instrumented holes shown.