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Article abstract

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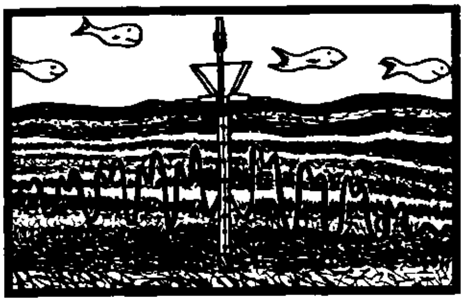

Using ODP Boreholes for Studying Sub-seafloor Hydrogeology: Results from the First Decade of CORK Observations

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SUMMARY

A system for sealing and instrumenting ODP boreholes was developed 10 years ago to allow interstitial fluids to be sampled, and natural fluid pressures and temperatures to be monitored over long periods of time. The capabilities of these CORK (Circulation Obviation Retrofit Kit) observatories have been expanded recently to allow monitoring and sampling in multiple isolated horizons, and to allow installations to be completed by wireline in previously drilled holes. To date, 16 hydrologic observatory sites have been established in ridge crest, ridge flank, and accretionary prism settings. Observations at these sites have provided precise constraints on the primary driving forces for, and thermal consequences of, sub-seafloor fluid flow caused by tectonic consolidation and thermal buoyancy. Deep in accretionary prisms, high formation pressures have been observed, confirming that plate boundary faults possess little strength. In young ocean crustal settings, surprisingly low lateral temperature and pressure gradients have been documented, implying that the extrusive rocks of the oceanic crust permit efficient fluid, heat, and chemical transport over distances of many kilometres. CORK observations have also revealed pressure variations and associated fluid flow resulting from co-seismic plate deformation, and from tidal, oceanographic, and barometric loading of the seafloor. The characteristics of the formation response to seafloor loading provide constraints on elastic and hydrologic properties, and allow quantitative estimates of crustal strain to be made from tectonic-strain-related pressure transients. Strain events have been observed up to 150 km away from several seismogenic dislocations along transform and seafloor spreading plate boundaries.

RÉSUMÉ

Un système d'instrumentation et de scellement des puits de forage du PSFM (Programme de sondage des fonds marins) a été mise au point il y a 10 ans pour permettre l'échantillonnage des fluides interstitiels ainsi que la mesure suivie de la température et de la pression des fluides sur de longues périodes. Les possibilités d'observation offertes par ces trousses d'obturation rétro-installées (TOR) ont été améliorées afin de permettre la mesure en continu et l'échantillonnage de multiples horizons isolés, et d'en permettre l'installation par filin dans les puits existants. À ce jour, 16 sites d'observation de ce genre ont été installés dans des environnements de dorsales, la crête et le flanc, et de prismes d'accrétion. Les observations réalisées sur ces sites ont fourni des balises précises quant à l'action des forces premières en jeu et les répercussions thermiques des mouvements de fluides sous les planchers océaniques causés par la consolidation tectonique et la poussée thermique. Dans les profondeurs des prismes d'accrétion, on a mesuré de forte pressions, ce qui confirme que les failles bordières des plaques n'ont que peu d'effet. Dans le contexte de croûtes marine jeunes, on a noté l'existence de gradients thermiques et de pressions étonnamment faibles, ce qui implique que les roches extrusives de la croûte océanique permettent un mouvement thermique, calorique et fluidique efficace sur des distances de bien des kilomètres. Les observations TOR ont également permis de découvrir que des variations de pression avec leurs mouvements de fluides associés étaient causés par la déformation tectonique co-séismique de la plaque, ainsi que de la charge océanographique, barométrique et tidal du plancher océanique. Les caractéristiques de la réaction de la formation à la charge sur le fond océanique permettent de circonscrire les propriétés élastiques et hydrologiques, et permettent des estimations quantitatives de la contrainte crustale à partir des transitoires de pression résultant de contraintes tectoniques. Des événements déformants ont été observés jusqu'à 150 km du lieu de plusieurs dislocations séismogéniques le long de frontières de transformation et d'expansion océanique.

INTRODUCTION

Background

Water is present throughout the Earth's crust and upper mantle, and it plays an important role in virtually every major geological process. Beneath the seafloor, more than 50% of the volume of unconsolidated and semiconsolidated sediment comprises free water, as does more than 10% of the volume of the extrusive igneous rocks of the oceanic crust. Large, but poorly constrained quantities of water are also bound in hydrous minerals, most of which are alteration products such as clays in the upper crust and serpentinites in the lower crust and upper mantle. Both free water occurring at high pressure and ductile hydrated minerals serve to facilitate rock deformation. Seismic rupture of faults, and the structural development of fold-and-thrust mountain belts also depend on the lubrication provided by water. Water and other volatiles serve as efficient fluxing agents to mobilize and lower the melting point of rocks to generate diapirism and volcanism at subduction zones. The large cooling capacity and high chemical reactivity of water speeds crustal solidification and facilitates formation of mineral deposits at seafloor spreading centres. Chemical exchange that takes place *via* exchange of water between the oceans and crust at ridge crests and flanks controls the composition of seawater. And many forms of life on Earth depend on water in the crust.

While sedimentary and igneous

interstitial water plays a central role in many geological processes, direct observations of hydrologic processes are rare. Much of what we know about the state and flux of formation fluids in marine settings has been inferred from physical and chemical observations made at the seafloor, or from the long-term integrated imprint of water-rock reactions observed in alteration products. Direct observations have been difficult, even with the capabilities provided by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). Boreholes drilled into hydrologically active systems serve as hydrologic "short circuits," commonly resulting in large quantities of water being exchanged between the ocean and rock formations, and precluding determinations of pressure, temperature, or natural fluid composition at the time of drilling.

CORK Instrumentation

To overcome these difficulties encountered in seafloor settings, a multi-institutional project was initiated to develop instrumentation capable of hydrologically sealing cased boreholes, and observing the formation state during and after recovery from drilling perturbations (Davis *et al.*, 1992; Fig. 1). The first CORK observatories were installed in two holes drilled in 1991 during ODP Leg 139 through the sediments and into igneous basement in the Middle Valley rift of the northernmost Juan de Fuca Ridge (Table 1). Other sites followed, including two in the Cascadia accretionary prism (Leg 146), two in the Barbados accretionary prism (Leg 156), one on the western Mid-Atlantic Ridge flank (Leg 174), four on the eastern Juan de Fuca Ridge flank (Leg 168), and most recently one in a Mariana forearc serpentinite diapir (Leg 195) (Table 1). While the specific objectives of these monitoring experiments have differed, all have been able to make use of the common capabilities of the instrumentation, which allowed seafloor and formation pressures and temperatures to be monitored over long periods of time (Fig. 2).

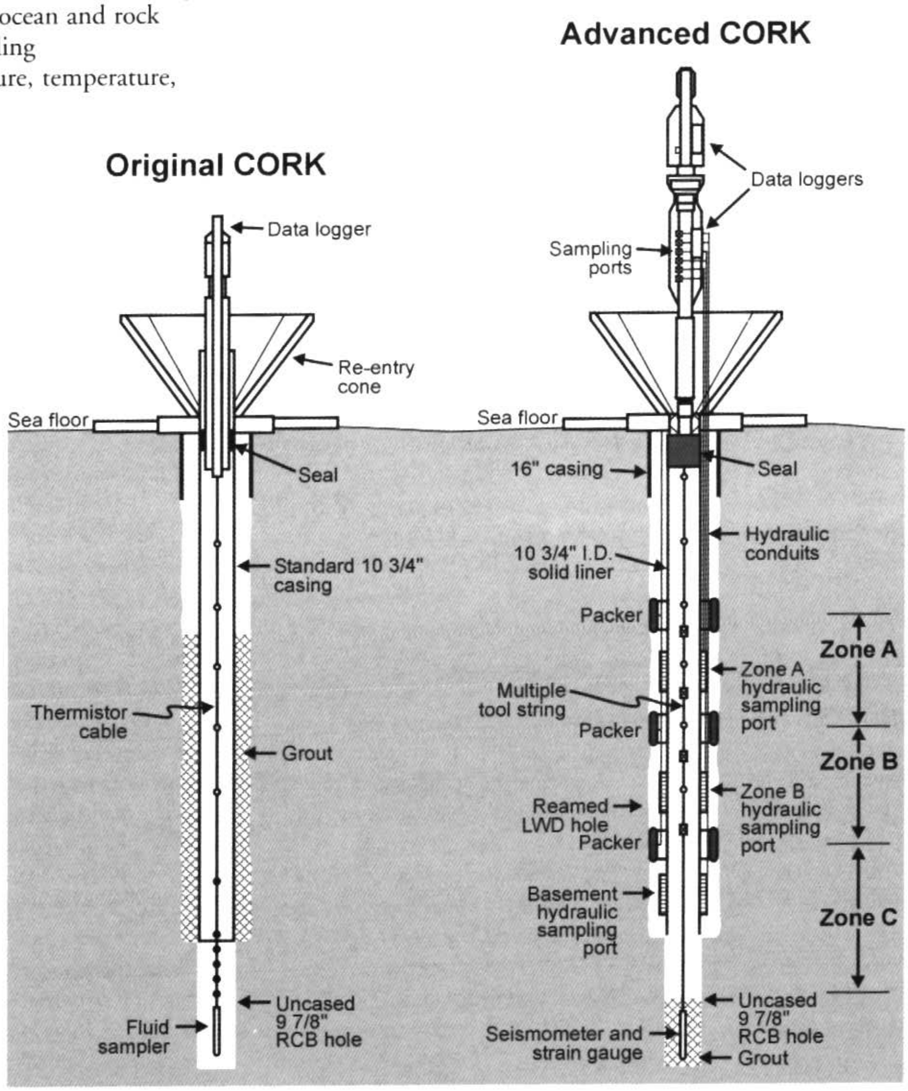

Figure 1 Schematic diagram of Original CORK and Advanced CORK borehole observatories. Exchange between permeable subseafloor formations and the ocean is prevented in the Original CORK by a seal within a solid liner (casing) that is grouted into impermeable sediment, and in the Advanced CORK by multiple inflatable packer seals assembled on the outside of a solid casing. Depths of casing strings and monitoring zones are usually based on a combination of seismic reflection, drill core, and logging constraints. Total penetration of systems installed to date has varied from roughly 100 m to 1000 m (Table 1).

Beginning with the Barbados installations, fluid samplers were added to the temperature sensor cables to allow continuous sampling of deep formation water. These "osmosamplers" make use of osmotically driven pumps that draw fluid continuously into long sections of small-diameter tubing (Jannasch *et al.*, 1997). At several of the CORKed sites, additional sampling and hydrologic testing have been completed using valved plumbing that bypasses the CORK seals.

OVERVIEW OF OBSERVATIONS

Long periods of time normally transpire between instrument installation (requiring the drill ship) and data recovery operations (requiring a manned or unmanned submersible), and long periods, commonly months and sometimes years, are often needed for the perturbations generated by drilling and open hole conditions to dissipate fully. Despite these inherent impediments, a significant body of new knowledge has accumulated in the decade since the first installation. We highlight some of the results in this section, and in the next section summarize the expanded capabilities expected to be available by the time this article is published.

Accretionary Prisms

High fluid pressures are believed to be the cause of the low stress coupling on subduction thrust faults inferred from forearc stresses, the lack of fault-related thermal anomalies, and the very low taper of accretionary prisms. The first CORK installation in an accretionary prism (Cascadia, Table 1) penetrated an out-of-sequence thrust fault at roughly 100 m depth (Davis *et al.*, 1995). Fluid pressure at that level was nearly hydrostatic (+13 kPa, compared to the +600 kPa pressure that would be present under lithostatic conditions), suggesting that the upper part of this accretionary prism is well drained, at least during the roughly one-year span of this monitoring experiment. However, evidence for transient hydrologic activity was found in the thermal structure, so present conditions may not correctly represent this dynamic system, in which fluid expulsion is probably dominated by episodic events.

Much deeper penetration was achieved in the Barbados prism (locations in Table 1). Two holes spanned the primary décollement, where a thick section of subducted sediments slide beneath those that are accreted. Pressures were found to be spatially variable but generally high, ranging from 0.3 to 0.9 times lithostatic at the two sites (Fig. 2; Becker *et al.*, 1997; Foucher *et al.*, 1997). Substantial temporal variations were also observed, and although their cause is not understood, they confirm that the hydrology of this décollement is dynamic.

More information about the hydrodynamics of accretionary prisms and faults was provided by a combination of drillstring packer and CORK pumping experiments (including a unique hole-to-hole experiment). These showed that the lateral permeability of the décollement can be much higher than the permeability of the surrounding sediment, and that the permeability is highly sensitive to the pore pressure (Fisher *et al.*, 1996; Screaton *et al.*, 2000). During the transient recovery from drained open-hole conditions at the time of drilling towards lithostatic conditions after sealing, the permeability of the décollement increased by four orders of magnitude. This behaviour probably provides strong feedback between hydrology and tectonics, and causes hydro-tectonic processes to be strongly non-linear. Even the small natural variations in pressure observed during the monitoring period (Fig. 2) must influence permeability to a certain degree.

In addition to providing information about the hydro-tectonics of subduction zones, CORK data have also helped to constrain the conditions under which

Table 1 ODP CORK site summary

Leg/Hole	Location (sediment/total)	Position	Water (m)	Penetration (m)	Operational
139/857D	Middle Valley	48°26'N 128°43'W	2432	470/936	1991- 2001+ (refit Leg 169)
139/858G	Middle Valley	48°27'N 128°43'W	2426	258/433	1991- 2001+ (refit Leg 169)
146/889C	Cascadia prism	48°42'N 126°52'W	1326	385/385	1992- 1993 (no seal)
146/892B	Cascadia prism	44°41'N 126°07'W	684	178/178	1992- 1993 (sampling - 2001)
156/948D	Barbados prism	15°32'N 58°44'W	4949	538/538	1994- 1996 (bad seal)
156/949C	Barbados prism	15°32'N 58°43'W	5016	468/468	1994- 1997
168/1024C	J. de F. E. flank	47°55'N 128°45'W	2612	152/176	1996- 2001+ (refit 2000)
168/1025C	J. de F. E. flank	47°53'N 128°39'W	2606	101/148	1996- 2001+ (refit 2000)
168/1026B	J. de F. E. flank	47°46'N 127°46'W	2658	247/295	1996- 1999 (bad seal)
168/1027C	J. de F. E. flank	47°45'N 127°44'W	2656	613/632	1996- 2001+ (refit 1999)
174/395A	MAR W. flank	22°45'N 46°05'W	4485	111/664	1997- 2001+
195/1200C	Mariana forearc	47°55'N 128°45'E	2932	203/203	2001- 2001+
196/1173	Nankai prism	32°15'N 135°02'E	4790	710/760	2001+
196/808	Nankai prism	32°21'N 134°57'E	4676	1289/1339	2001+
205/1039	Costa Rica prism	09°39'N 86°12'W	4352	400/450	Planned, Leg 205
205/1042	Costa Rica prism	09°40'N 86°11'W	4188	680/730	Planned, Leg 205
504B	CRR S. flank	01°14'N 83°44'W	3474	275/2111	2001+
896A	CRR S. flank	01°13'N 83°43'W	3459	172/469	2001+

gas hydrates form. CORK data from the Cascadia prism off Oregon define the P-T conditions at the base of the gas hydrate stability zone, and demonstrate that free gas is present in the section beneath the depth-limit of hydrate stability (Davis *et al.,* 1995; Wang and Davis, 1996; Wang *et al.,* 1998).

Ridge Flanks

Two components of fluid flow have been documented with CORK monitoring in young igneous crust of the Juan de Fuca and Mid-Atlantic Ridge flanks (Becker *et al.,* 1998; Davis and Becker, 1998; see Table 1 for details), and the observations allow rates of flow to be estimated and formation-scale permeability to be inferred. Most readily understood is the "d.c." component, *i.e.,* the hydrothermal circulation driven by buoyancy generated by contrasts in thermal and hence fluid-density structure. A clear example of this type of flow is documented at a sediment-buried igneous basement ridge on the eastern Juan de Fuca Ridge flank (Fig. 3), where two CORK sites were established at the crest of the ridge and in the adjacent valley to define the degree to which the thermal and pressure regime might differ from that which would exist under purely conductive conditions. The difference was profound, and a number of conclusions were reached about the circulation:

a) High rates of volumetric fluid flow in basement, on the order of 30 m per year, are required to explain a nearly isothermal basement surface. Temperatures in the uppermost igneous crust differed between the two sites by less than 2 K despite the large contrast in the thickness of sediment (less than 250 m *versus* more than 600 m) and substantial site separation (2.2 km). Under conductive conditions, the difference would exceed 40 K.

b) To support the high rate of flow inferred from the small temperature differential, upper basement must be characterized by very high permeability, of the order of 10^{-9} m^2. The pressure differential that is available to drive flow laterally through basement between the two sites (*i.e.,* the pressure difference relative to an isothermal basement hydrostat) is only about 1 kPa (equivalent to a 10-cm head of water).

c) The pressure differentials available to drive flow through the sediment sections that bury the crust at these sites are over an order of magnitude higher (*i.e.,* >10 kPa). However, attendant rates of flow are much lower (less than 1 mm per year), due to the very low sediment permeability.

d) Observations at this and other sites demonstrate that buried basement ridges are consistently overpressured. This provides predictable opportunities for crustal fluid sampling, either at boreholes drilled into buried edifices, or where permeable basement is exposed in outcrop at the seafloor. Natural flow through basement exposures provides an efficient means for heat and chemical exchange between the crust and the oceans.

Monitoring at all sites, but at ridge crest and ridge flank sites in particular, has revealed an additional component of flow that had previously gone unrecognized. This is an "a.c." component, driven by pressure differences established between volumes of rock having contrasting elastic properties that respond differently to variable atmospheric and oceanographic loads imposed at the seafloor (Davis and Becker, 1999; Davis *et al.,* 2000; Wang *et al.,* 1999). Seafloor pressure variations that can be observed in sub-seafloor formations occur over a broad range in frequency. The largest originates from ocean tides, and reaches more than 10 kPa amplitude at semi-diurnal periods (Fig. 3). The amplitudes of these a.c. signals in the formation relative to those at the seafloor constrain the bulk modulus of the rock matrix and the fluid it contains. The frequency-dependent phase of the formation signals relative to seafloor

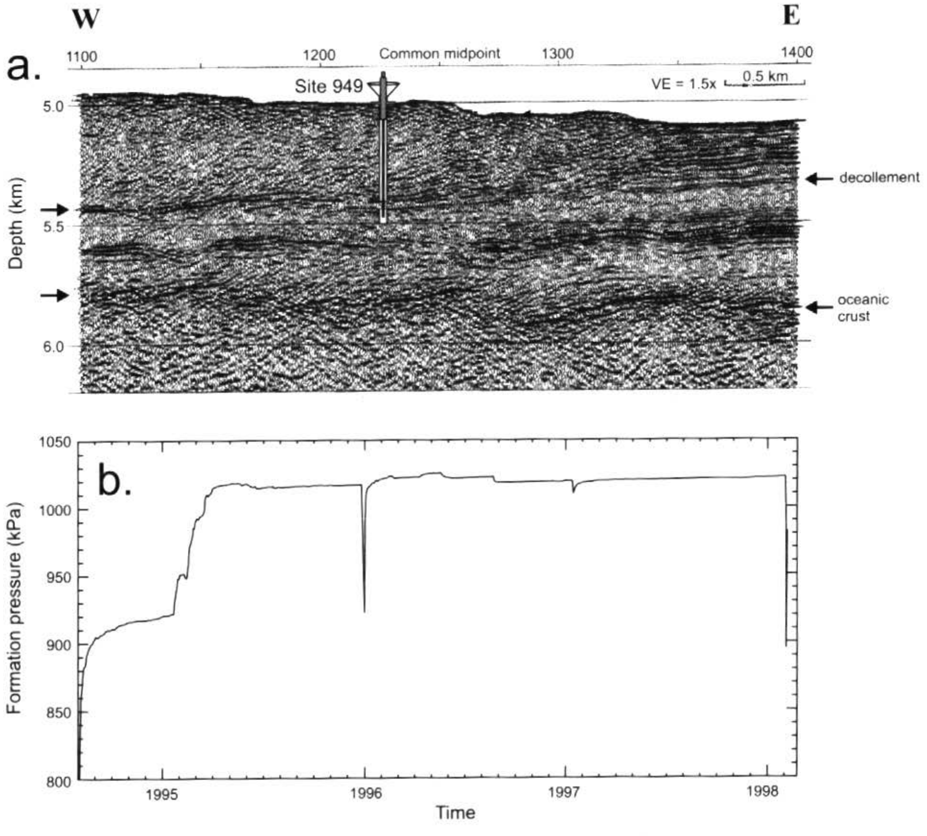

Figure 2 (**a**) Structural setting of Hole 949C drilled into the Barbados accretionary prism (Becker *et al.,* 1997). (**b**) Pressures (shown relative to hydrostatic) were monitored through a perforated and screened interval of casing spanning the décollement that separates the subducting North American plate and the overriding Caribbean plate. The large transient at the beginning of 1996 was generated during a submersible permeability testing program that used a valved seal bypass in the CORK. The small transient at the beginning of 1997 was the consequence of operations in a hole drilled for logging roughly 50 m from Hole 949C during ODP Leg 171A. Permeabilities were also derived from this transient (Screaton *et al.,* 2000). Other variations in pressure are natural, although their origin is not understood.

loading reveals the manner in which pressure variations diffuse from boundaries and between different rock units below the seafloor, and constrains the formation permeability over a scale commensurate with the diffusive wavelength. This reaches many kilometres in the upper igneous section at the ridge-flank CORK sites, implying a high permeability, of the same order as that inferred from the "d.c." observations.

Where thermal gradients are present, borehole temperature variations can serve as a quantitative indicator of a.c. fluid flow. Tidal-frequency thermal variations have been observed at several sites, and estimated rates of flow are found to be as large as the d.c., buoyancy-driven flow rates. Because the a.c. amplitude is large and the directions of the a.c. and d.c. flow differ, the a.c. component may play a significant role in dispersing fluids in the crust and promoting geochemical and microbiological activity.

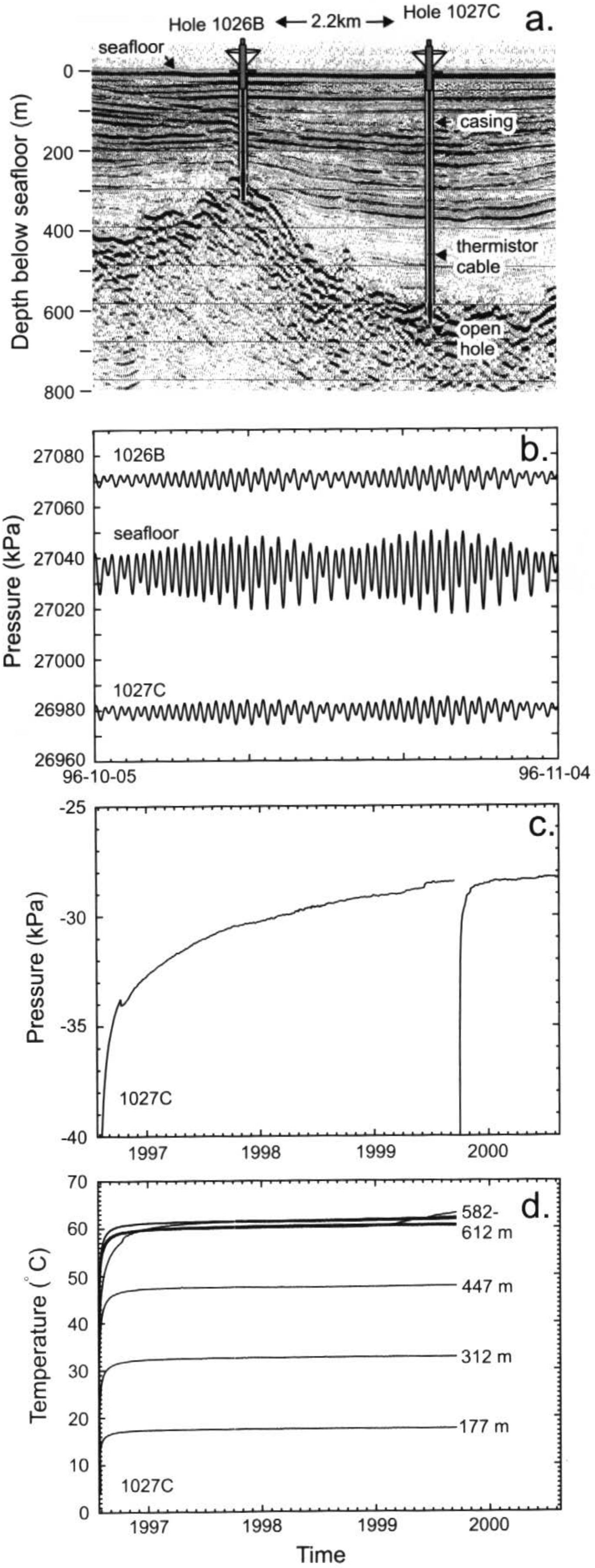

Figure 3 (at left) (**a**) Structural setting of Holes 1026B and 1027C drilled into 3.6-Ma crust of the sedimented eastern flank of the Juan de Fuca Ridge (Davis and Becker, 1998), where pressures and temperatures have been monitored continuously since CORK installations in 1996. Both holes were cased through the sediments and were deepened as open holes several tens of metres into igneous basement. (**b**) The influence of seafloor loading, imposed primarily by diurnal and semidiurnal tides, is evident in the one-month record of total seafloor and formation pressures, as are the average levels of non-hydrostatic pressure. (**c**) When seafloor loading effects are removed, a major and long-lived perturbation can be seen in the multi-year pressure record from Hole 1027C, along with small coseismic pressure transients in mid-1996 and mid-1999. The large transient in October 1999 was created when the CORK data logger, thermistor cable, and crustal fluid sampler were removed and replaced with a refreshed logger and pressure gauges. (**d**) Temperatures recover much more rapidly from the drilling perturbation than does pressure, suggesting that most of the long-term pressure transient is caused by the invasion of a large volume of cold water into the crust beneath the bottom of the thermistor cable at the time of drilling.

Mid-ocean Ridges

ODP Leg 139 was devoted to studying ridge-crest hydrothermal circulation and the formation of metallic ore deposits. Four sites were drilled during this leg in the Middle Valley sedimented rift of the northern Juan de Fuca Ridge, and two CORKs were installed (Table 1). The hydrologic structure at the Middle Valley CORK sites is in many ways similar to that penetrated by the Juan de Fuca ridge flank holes 1026B and 1027C as discussed above (Fig. 3), with one hole penetrating basement beneath a thick sediment section and the other penetrating a shallow basement edifice; although exaggerated, the hydrologic state is similar (Davis and Becker, 1994). Basement fluid temperatures at the two holes are similar (in this case roughly 280°C) despite the separation of the sites (1.6 km) and large contrast in sediment thickness (240 m *versus* 470 m). Pressure gradients within "hydrothermal basement" are small, and large pressure differentials are present across the sediment section (up to 400 kPa, or 40 m of equivalent head), with fluid within the buried volcanic edifice being positively pressured. This pressure drives flow through channels in the overlying altered sediment section to vent vigorously at the seafloor, produce large mineral deposits, and nourish unique chemosynthetic animal communities.

Co-seismic Strain

Potentially the most far-reaching result of CORK monitoring to date is that obtained when tidal and barometric signals are removed (a task that can be completed with great accuracy given the knowledge of both the seafloor loading and the formation response functions). The signal remaining is not without feature: co-seismic pressure transients are observed at sites up to 120 km distant from relatively small earthquakes (Fig. 4). The theory describing how fluid pressure responds to seafloor loading (Wang and Davis, 1996) can be applied with little modification to the response to tectonic strain. In fact, the observations of the former provide an excellent "calibration" for the latter, allowing volumetric strain to be determined quantitatively from pressure transients. Pressure transients associated with three earthquakes in the Juan de Fuca region have allowed several conclusions to be reached, including:

a) Regional plate strain is observed to be greater than that which would be generated by seismic slip alone. In the case of an earthquake swarm 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 magnitude 6 event. Most of the displacement of the "spreading event" that was the cause of the earthquakes must have taken place aseismically.

b) The decay of pressure following the plate strain events is observed to take place over times that vary from 6 hours to 100 days, according to the distance of the well-sedimented sites to basement outcrop. Permeability, estimated under the assumption of pure lateral drainage through the uppermost igneous crust, is of the same order as that described above, although this inference based on the very long-term drainage rate pushes the scale over which efficient hydrologic transmission takes place from several kilometres to 100 km.

c) As in the case of fluid flow induced by tidal loading, basement temperatures provide constraints on strain-induced flow. Drainage following the ridge axis event is seen by way of basement temperature transients that persist for several months. This is consistent with the time required for pressure at the distal sites to decay.

FUTURE EXPERIMENTS USING ADVANCED TECHNOLOGY

While monitoring and fluid sampling

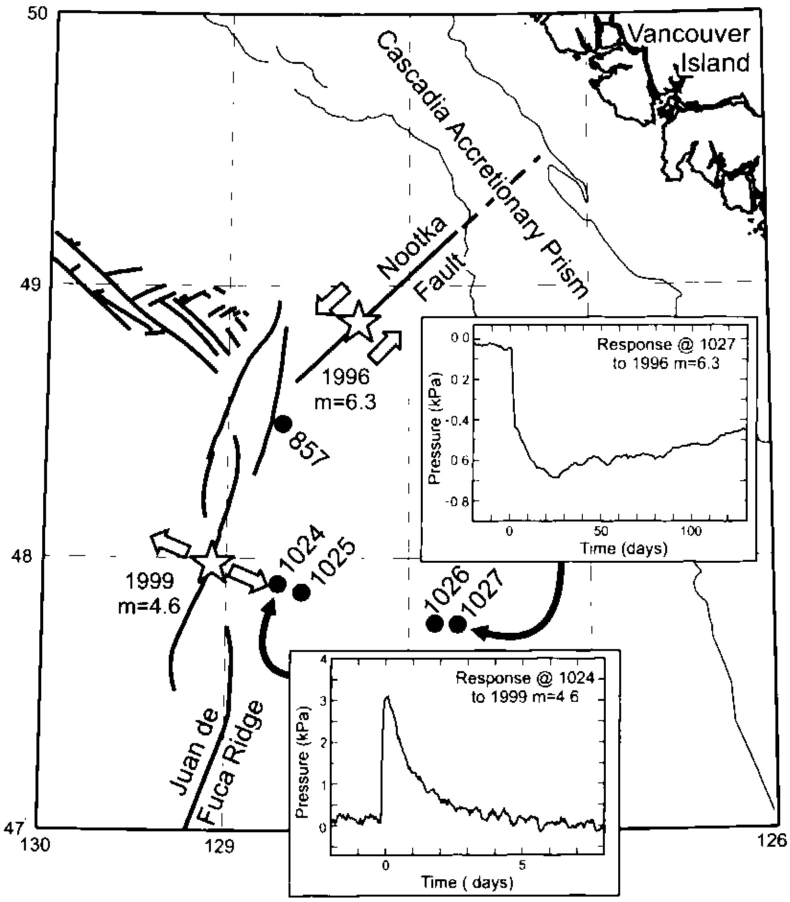

Figure 4 Examples of the response of crustal fluid pressure to coseismic strain of the Juan de Fuca plate caused by slip on the Nootka transform fault in October 1996 and by spreading on the Juan de Fuca Ridge axis in June 1999. Strain can be calculated from formation pressure with the "calibration" provided by the known response to seafloor loading. The estimated plate strain energy exceeds the earthquakes' seismic energy by a factor of 10 in the case of the Nootka strike-slip event, and a factor of nearly 100 in the case of the Juan de Fuca spreading event. Major amounts of aseismic slip are implied.

continues with original CORK instrumentation at sites on the Juan de Fuca and Mid-Atlantic Ridges and in the Mariana subduction zone forearc, plans are unfolding to expand the scope of borehole hydrologic monitoring. Technological improvements are proceeding on three fronts, and experiments are planned, scheduled, or underway at four locations.

Wireline CORKs

A new capability has been developed to make use of existing boreholes using seals and monitoring hardware that can be deployed from a standard oceanographic vessel. The first Wireline CORKs were deployed in Holes 504B and 896A on the sedimented Costa Rica Rift flank in August, 2001 (Table 1). A wireline control vehicle of the Marine Physics Laboratory of Scripps Institution of Oceanography (Spiess *et al.*, 1992) was used to steer the instrument strings into the holes, inflate the packers, and check proper functioning of all components. Observations in this pair of holes will be highly complementary to those made in the Juan de Fuca region, for while the crust is older, the structure is similar. The two holes penetrate basement of contrasting relief and sediment burial. Crustal fluid in the more thickly sedimented Hole 504B appears to be sub-hydrostatic, for seawater is known to have been flowing into the crust through the hole ever since it was first drilled more than 20 years ago. We expect that the associated perturbations will be very large and long-lived. This will make determining the equilibrium state of the crust challenging, but the perturbation amplitude and the recovery time constant will provide valuable new information about crustal hydrologic properties.

Advanced CORKs

A new generation of drillship-deployed CORKs was installed at two sites in the Nankai accretionary prism during ODP Leg 196 in June, 2001 (Table 1). Two more are scheduled for installation in the subduction complex off Costa Rica during Leg 205 in September 2002. These Advanced CORKs (ACORKs, Fig. 1) will have several advantages over the first-generation technology. 1) It will be possible to monitor pressures and sample fluids at multiple horizons, each isolated with inflated packers. Up to six zones were targeted at Nankai. 2) ACORKs can be drilled into the sub-seafloor using a mud-motor. This will allow installations in formations that are too unstable for standard cased holes to be established. 3) Packers, sampling/monitoring ports, and hydraulic lines are all situated on the outside of a water-tight casing string that is sealed off at the bottom with a removable "bridge plug." This will allow simultaneous independent experiments to be carried out within the casing that do not require hydrologic connection to the formation (*e.g.*, seismic, electrical, and thermal monitoring). It will also be possible to deepen the holes for additional open-hole experiments at any later time by temporarily removing the bridge-plug seal.

One of the primary objectives at the Nankai and Costa Rica margin sites is to use the permeable igneous crust as a hydrologic "artery" that may be continuously or episodically connected to the deeper part of the subduction system where intraplate thrust earthquakes are initiated. The ACORK pressure sensors will provide the equivalent of a stethoscope for sensing tectonic strain, and temperature sensors will be sensitive to fluid flow. Continuous formation-fluid sampling will also be carried out using small-volume osmosamplers that draw fluid from the multiple packer-isolated sections. In addition to the upper crust, monitoring and sampling intervals well be established above, across, and below the intra-sedimentary décollement.

NEPTUNE

The task of visiting sites to recover data (typically once every 2 years) or to service instrumentation is neither easy nor economical. The need for ships and manned or unmanned submersibles grows with every increase in the duration of monitoring and the number of operational sites. A new initiative, NEPTUNE (North East Pacific Time-series Undersea Networked Experiments), will facilitate borehole observatory science in the region of the northern Juan de Fuca plate by providing power and communications *via* seafloor fibre-optic cables (see www.neptune.ocean.washington.edu). An array of multi-disciplinary "nodes" will be distributed across the plate interior and along its spreading, transform, and subduction boundaries, and plans are being developed to establish borehole observatories at a number of these nodes. There are similar plans for sites off Japan. These cable connections will allow data to be gathered with much greater fidelity and over longer periods of time than is currently possible with the limits imposed by battery power and internal recording. Connections to shore will also greatly reduce the requirement for submersible site visits.

CONCLUSIONS

It is our hope that these technological advances will enable a growing group of investigators from various disciplines to explore a broad range of important hydrologic processes in ways that traditional approaches do not allow, *e.g.*, instantaneous snapshots made through remote geophysical imaging, and measurements of integrated signals recorded by alteration products. Advanced CORKs should permit the *in situ* measurements and sampling that are required for determining the instantaneous fluid composition, hydrologic state, formation properties, and state of stress, and provide the long-term observational capability that is required to characterize processes that are dynamic and that operate on a broad range of time scales.

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REFERENCES

Becker, K. and Davis, E.E., 1998, CORK reveals huge fluxes in off-axis hydrologic circulation: JOI/USSAC Newsletter, v. 11, p. 12-15.

Becker, K., Fisher, A.T. and Davis, E.E., 1997, The CORK experiment in Hole 949C: Long-term observations of pressure and temperature in the Barbados accretionary prism: Proceedings of the Ocean Drilling Program, Scientific Results, v.156, p. 247-252.

Becker, K., *et al.*, 1998, Site 395: Proceedings of the Ocean Drilling Program Initial Reports, v. 174B, p. 13-23.

Becker K., *et al.*, 2000, Logging while drilling and advanced CORKs in the Nankai Trough: Ocean Drilling Program, Leg 196 Scientific Prospectus 196, 61 p.

Davis, E.E. and Becker, K., 1999, Tidal pumping of fluids within and from the oceanic crust: New observations and opportunities for sampling the crustal hydrosphere: Earth and Planetary Science Letters, v. 172, p. 141-149.

Davis, E.E. and Becker, K., 1994, Formation temperatures and pressures in a sedimented rift hydrothermal system: Ten months of CORK observations, Holes 857D and 858G: Proecdings of the Ocean Drilling Program, Scientific Results, v.139, p. 649-666.

Davis, E.E. and Becker, K., 1998, Borehole observatories record driving forces for hydrothermal circulation in young oceanic crust: EOS, Transactions of the American Geophysical Union, v. 79, n. 31, p. 369-370.

Davis, E.E., Becker, K., Pettigrew, T., Carson, B. and Macdonald, R., 1992, CORK: A hydrologic seal and downhole observatory for deep-ocean boreholes: Proceedings of the. Ocean Drilling Program, Initial Reports, v. 139, p. 43-53.

Davis, E.E., Becker, K., Wang, K. and Carson, B., 1995, Long-term observations of pressure and temperature in Hole 992B, Cascadia accretionary prism: Proceedings of the Ocean Drilling Program, Scientific Results, v. 146, p. 299-311.

Davis, E.E., Wang, K., Becker, K. and Thomson, R.E., 2000, Formation-scale hydraulic and mechanical properties of oceanic crust inferred from pore pressure response to periodic seafloor loading: Journal of Geophysical Research, v. 105, p. 13,423-13,435.

Fisher, A.T., Zwart, G. and ODP scientific party, 1996, Relation between permeability and effective stress along a plate-boundary fault, Barbados accretionary complex: Geology, v. 24, p. 307-310.

Foucher, J.P., Henry, P. and Harmengnies, F., 1997, Long-term observations of pressure and temperature in ODP Hole 948D, Barbados accretionary prism: Proceedings of the Ocean Drilling Program, Scientific Results, v. 156, p. 229-238.

Jannasch, H.,W., Sakamoto, C., Wheat, C.G. and Johnson, K., 1997, Osmotically pumped chemical analyzers and samplers for long-term oceanographic monitoring: Extended Abstract; International Workshop in Marine Analytical Chemistry for Monitoring and Oceanographic Research (Brest, France, 17-19 November, 1997).

Screaton, E., Carson, B., Davis, E. and Becker, K., 2000, Permeability of a decollement zone: Results from a two-well experiment in the Barbados accretionary complex: Journal of Geophysical Research, v. 105, p. 21,403-21,410.

Spiess, F.N., Boegeman, D.E. and Lowenstein, C.E., 1992, First ocean-research-ship-supported fly-in re-entry to a deep ocean drill hole: Journal of the Marine Technology Society, v. 26, p. 3-10.

Wang, K. and Davis, E.E., 1996, Theory for the propagation of tidally induced pore pressure variations in layered subseafloor formations: Journal of Geophysical Research, v. 103, p. 11,483-11,495.

Wang, K., Davis, E.E. and van der Kamp, G., 1998, Theory for the effects of free gas in subsea formations on tidal pore pressure variations and seafloor displacements: Journal of Geophysical Research, v. 103, p. 12,339c-12,353.

Wang, K., van der Kamp, G. and Davis, E.E., 1999, Limits of tidal energy dissipation by fluid flow in subsea formations: Geophysical Journal International, v. 139, p. 763-768.

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