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Listening Down the Pipe

By Evan A. Solomon, Keir Becker, Achim J. Kopf, and Earl E. Davis

ABSTRACT. Since 1991, over 30 borehole observatories have been installed by the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program, and the International Ocean Discovery Program (IODP), mostly in young oceanic crust and in subduction zones. These installations have provided a sustained presence in the subseafloor environment, enabling collection of a new generation of long-term, time-series data sets of temperature, pressure, and deformation, as well as continuous fluid sampling and in situ active experimentation. These multidisciplinary observations have pushed the frontiers of knowledge about Earth's linked geodynamic, hydrological, geochemical, and biological processes.

ODP/IODP BOREHOLE OBSERVATORY DESIGNS AND INSTRUMENTATION

Nearly all of the designs for ODP/IODP subseafloor observatories[1] require some sort of reentry cone and casing to stabilize the upper part of the hole, and a plug to seal the inside of the borehole against hydraulic interference from the overlying ocean and to allow reestablishment of equilibrium in situ conditions post-drilling. The original observatory design (Figure 1a) was called the Circulation Obviation Retrofit Kit (CORK), and the term "CORK" is often loosely used to refer to all subsequent designs. Since 2001, CORK observatories have become more sophisticated, with multiple subseafloor seals that isolate intervals of interest, and they can now host a range of increasingly advanced instrumentation for geophysical, geochemical, and microbiological experiments (Figure 1b–e). For example, many of the CORKs deployed by IODP in the last two decades included OsmoSamplers that continuously collect formation fluid for several years and can be configured for fluid flow rate monitoring, microbiological sampling, and microbial colonization experiments (Figure 2; e.g., Wheat et al., 2003, 2011; Jannasch et al., 2004; Solomon et al., 2009; Orcutt et al., 2011; Cowen et al., 2012).

With the deployment of cabled ocean observatory systems in the United States, Japan, and Canada in the last decade, providing power to some of the installations is no longer a limitation, and a new generation of CORK observatories are transmitting subseafloor geophysical data to land-based laboratories in real time (e.g., Araki et al., 2017; Saffer et al., 2017; McGuire et al., 2018). "CORK-Lite" models that can be deployed by remotely operated vehicles allow installation of instrumentation in existing reentry boreholes without the aid of a drillship (e.g., Wheat et al., 2012), and some designs include the simple Smart and Genius plugs that permit temporary monitoring of a zone of interest (Kopf et al., 2011). With portable rock drills now used as mission-specific platforms in IODP, deployment of subseafloor observatories will also be possible from ships of opportunity (e.g., Kopf et al., 2015) and in regions where the drillships *JOIDES Resolution* and *Chikyu* cannot operate.

SELECTED SCIENTIFIC HIGHLIGHTS

Some of the most exciting achievements enabled by ODP/IODP observatories to date are listed below. They showcase the diversity of research endeavors and the breadth of the community involved in investigations of IODP's "Earth in Motion" theme, including the processes and natural hazards occurring on human timescales.

- Long-term sealed-hole pressure and temperature records have demonstrated that the uppermost young oceanic basement is highly hydraulically transmissive over regional (tens of kilometers or more) scales, supports extensive lateral fluid flow associated with small pressure differentials, and thus functions as an immense subseafloor aquifer (e.g., Becker and Davis, 2004; Davis and Becker, 2004; Fisher and Wheat, 2010).
- Cross-hole tracer experiments indicate significant structural control of ridge-parallel fluid flow and very low effective porosity in the upper oceanic crust (e.g., Neira et al., 2016).
- In situ monitoring of the radiocarbon content of dissolved inorganic carbon at the Mid-Atlantic Ridge flank revealed that seawater residence times in the oceanic crust can be 10 to 100 times longer than regional heat flow-based estimates, reflecting the heterogenous nature of fluid flow paths (Shah Walter et al., 2018).
- In situ monitoring of fluid composition and flow rates in young oceanic

[1] It is beyond the scope of this short article to describe the evolution of ODP/IODP observatory designs and subseafloor instrumentation in detail; for technical reviews, we refer the reader to Becker and Davis (2005) and Davis et al. (2018).

crust has enabled evaluation of the role of off-axis hydrothermal circulation in global geochemical cycles (e.g., Wheat et al., 2003; Fisher and Wheat, 2010).

- CORK fluid sampling has shown that dissolved organic carbon is removed from cool circulating fluids at the Mid-Atlantic Ridge flank, driven by microbially mediated oxidation, and that this removal mechanism may account for at least 5% of the global loss of dissolved organic carbon in the deep ocean (Shah Walter et al., 2018).
- In situ collection of microbial samples and cultivation experiments in CORKs installed in young oceanic crust show significant changes in microbial community structure between hydrothermal systems and through time (e.g., Cowen et al., 2003; Orcutt and Edwards, 2014; Jungbluth et al., 2016). Results from North Pond on the Mid-Atlantic Ridge show a diverse bacterial community engaged in both heterotrophy and autotrophy at potential rates that may exceed those in ocean bottom water (Meyer et al., 2016).
- Recent improvements in CORK design and CORK-compatible in situ fluid sampling equipment have enabled collection of large volumes of pristine basement fluid whose analysis shows that basalt-hosted ridge-flank fluids harbor a distinct assemblage of novel viruses, including many that infect archaea, pushing the known geographical limits of the virosphere into the oceanic basement (Nigro et al., 2017).
- Active and passive experiments at different spatial scales using CORKs have documented variation in fault permeability with fluid pressure in subduction zones (e.g., Screaton et al., 2000; Kinoshita and Saffer, 2018).
- Sealed-hole pressure records of the response of a surrounding rock formation to tidal loading yields information on the formation's in situ hydrologic and elastic properties, which inform hydromechanical models of a range of processes, such as pore pressure response to coseismic ground motion (e.g., Becker and Davis, 2004; Davis and Becker, 2004).
- Subseafloor pressure recorded in well-sealed borehole observatories provides an extraordinarily sensitive proxy for plate-scale strain on timescales ranging from years to coseismic slip, with the most sensitive strain monitoring done in hydrologically isolated low-porosity formations (e.g., Davis et al., 2004, 2013; Araki et al., 2017). These measurements have led to the discovery of a range of deformation events, from small earthquakes and dike intrusions, to shallow slow slip events that may accommodate a large fraction of the plate motions in subduction zones (see Wallace et al., 2019, in this issue).
- CORK pressure records show that fault slip in shallow portions of subduction zones can occur spontaneously, be triggered by dynamic stress changes (e.g., earthquakes), and can occur with little or no seismic expression (e.g., Davis et al., 2013; Araki et al., 2017; Wallace et al., 2019, in this issue).

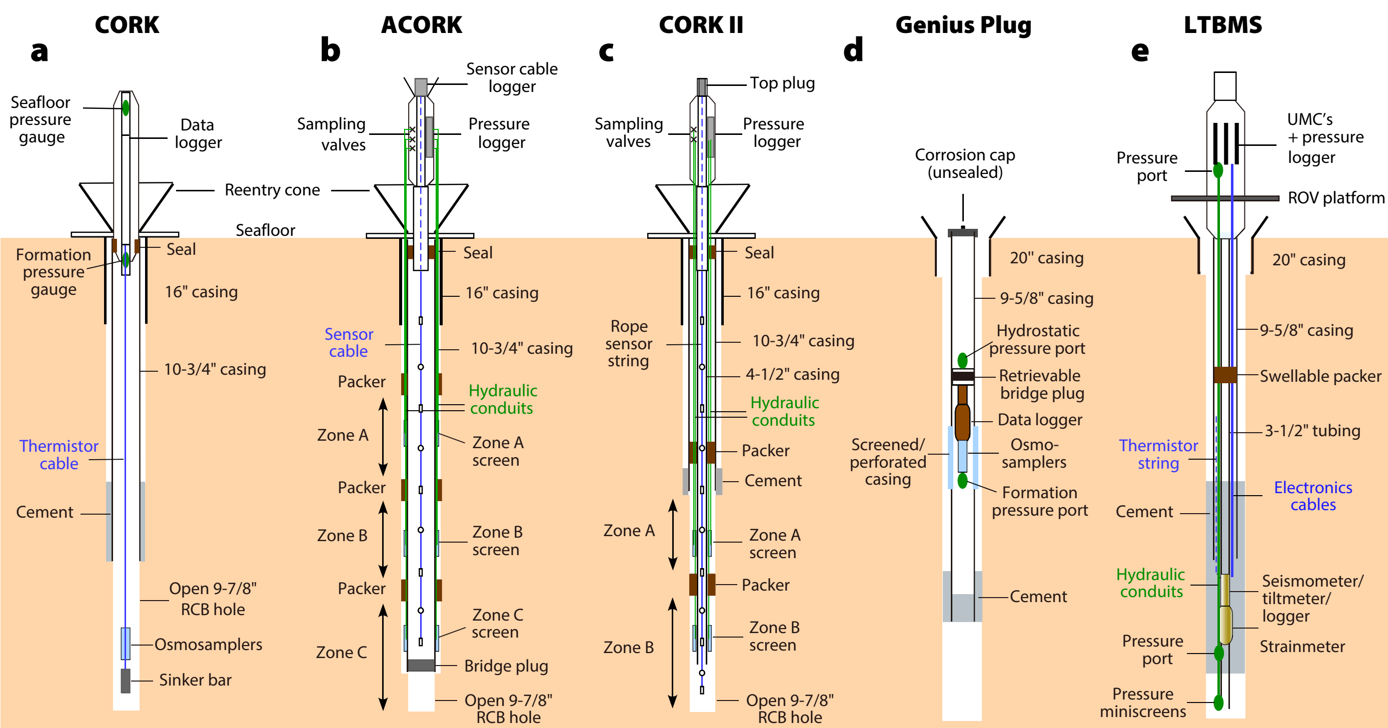

FIGURE 1. Schematic of the evolution of ODP/IODP borehole observatory designs. (a) The original CORK. (b) Advanced CORK (ACORK). (c) CORK II. (d) Genius Plug (Kopf et al., 2011). (e) Long-Term Borehole Monitoring System (LTBMS; Saffer et al., 2017). UMC = underwater mateable connector. See Davis et al. (2018) for a recent technical summary.

- High-resolution borehole temperature monitoring after the 2011 Tōhoku-oki earthquake at the Japan Trench enabled near-real-time estimation of the frictional shear stress and apparent friction coefficient, showing very low shear resistance to fault slip at shallow depth (Fulton et al., 2013, and 2019, in this issue)
- CORKs provided the first in situ measurements of fluid flow rates along a subduction zone megathrust at depth (Figure 2), documenting enhanced fluid flow in response to fault slip (e.g., Solomon et al., 2009; Fulton and Brodsky, 2016). Results also show that dewatering in the forearc of subduction zones occurs not only through the upper plate but also within the subducting igneous crust, with implications for pore pressure development and effective stress along the plate boundary (e.g., Solomon et al., 2009).
- Broadband seismic borehole observatories in the Western Pacific obtained direct and unexpected seismological evidence of the age-dependent lithosphere-asthenosphere boundary (Kawatsu et al., 2009).

CONCLUDING REMARKS

CORK borehole observatories track Earth's "pulse" at spatial and temporal scales that are not possible with traditional IODP coring techniques. Progressive improvements in CORK design and performance and in situ geochemical and microbiological sampling equipment have made probing the biogeochemistry of the crustal deep biosphere a more consistent and pristine research avenue in scientific ocean drilling (e.g., Jungbluth et al., 2016). Recent cross-hole experiments have provided direct measurements of formation properties at scales larger than can be obtained with conventional core-based analyses, and have illuminated how these properties may vary in time. Continuous monitoring with CORK observatories has improved the quantification of natural forces driving off-axis hydrothermal circulation and transformed our understanding of the role this circulation plays in marine biogeochemical cycles and in sustaining the deep biosphere. The ability to directly monitor the subseafloor environment removed from the influences of ocean phenomena at the seafloor has led to robust records of regional crustal strain associated with tectonic events both at mid-ocean ridges and in subduction zones. More recently, CORKs installed to document and understand the patterns of strain accumulation and release along subduction thrusts have the sensitivity and bandwidth to detect very small deformation at timescales from seconds to months. This has led to the detection of shallow slow slip events and illuminated their relationship to larger, more destructive subduction zone earthquakes.

The multidisciplinary progression in CORK design and instrumentation over the last few decades has given us a more holistic understanding of the subseafloor environment. Because CORKs can accommodate a wide range of experiments and instrumentation and respond to the rapid pace at which these technologies evolve, CORK-based monitoring and active experimentation should continue to play an important role in scientific ocean drilling over the next few decades. These multidisciplinary observations will continue to transform our understanding of Earth and how it evolves.

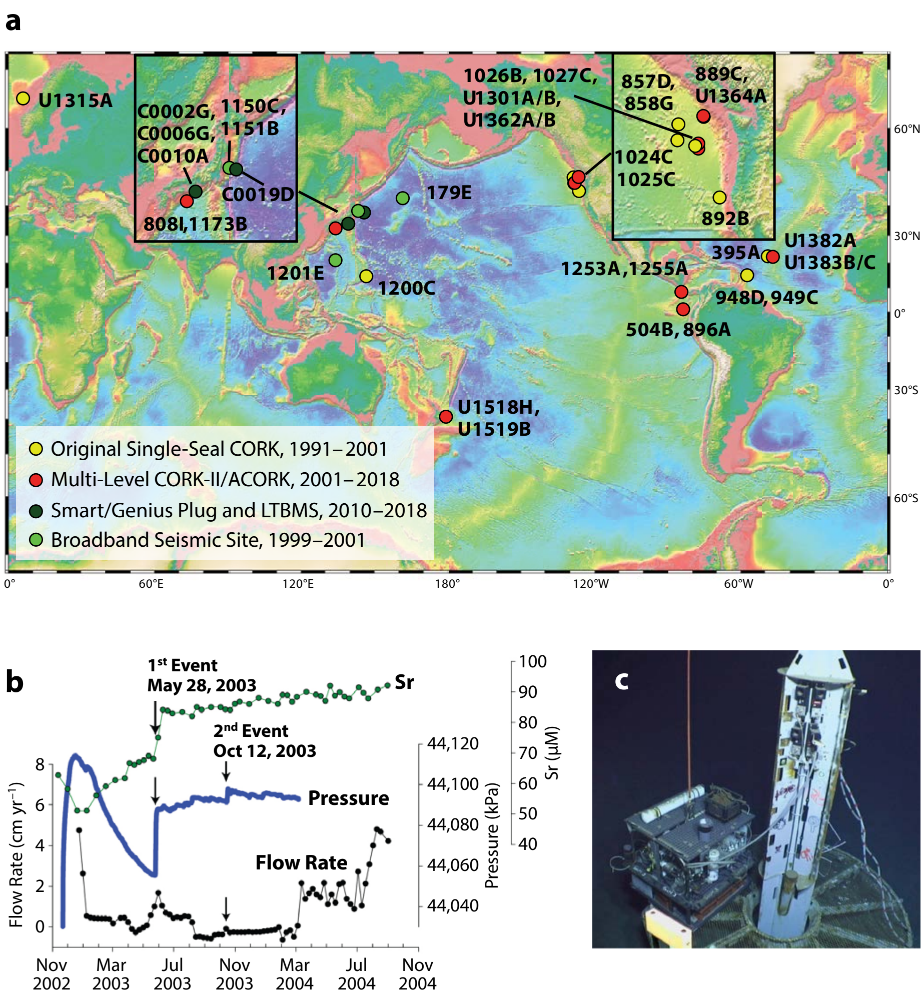

FIGURE 2. (a) Map of CORK locations. (b) CORK observatory record of pore pressure, fluid flow rate, and fluid composition changes along the shallow plate boundary during two slow slip events at the Costa Rica subduction zone (Reprinted from Solomon et al., 2009, with permission from Elsevier). (c) CORK-II wellhead deployed at the Mid-Atlantic Ridge during IODP Expedition 336. A Geomicrobe sampling system (Cowen et al., 2012) is sitting on the remotely operated vehicle platform and attached to the microbiology bay. Fluids are sampled from a screened interval within the igneous oceanic crust at depth.

REFERENCES

Araki, E., D.M. Saffer, A.J. Kopf, L.M. Wallace, T. Kimura, Y. Machida, S. Ide, E. Davis, and IODP Expedition 365 Shipboard Scientists. 2017. Recurring and triggered slow-slip events near the trench at the Nankai Trough subduction megathrust. *Science* 356:1,157–1,160, https://doi.org/10.1126/science.aan3120.

Becker, K., and E.E. Davis. 2004. In situ determinations of the permeability of the igneous oceanic crust. Pp. 189–224 in *Hydrogeology of the Oceanic Lithosphere*. E. Davis and H. Elderfield, eds, Cambridge University Press.

Becker, K., and E.E. Davis. 2005. A review of CORK designs and operations during the Ocean Drilling Program. In *Proceedings of the Integrated Ocean Drilling Program*, v. 301. A.T. Fisher, T. Urabe, A. Klaus, and the Expedition 301 Scientists, Integrated Ocean Drilling Program Management International, Inc., College Station, TX, https://doi.org/10.2204/iodp.proc.301.104.2005.

Cowen, J.P., S.G. Giovannoni, G. Kenig, H.P. Johnson, D. Butterfield, M.S. Rappe, M. Hutnak, and P. Lam. 2003. Fluids from aging ocean crust that support microbial life. *Science* 299:120–123, https://doi.org/10.1126/science.1075653.

Cowen, J.P., D. Copson, J. Jolly, C.C. Hsieh, B.T. Glazer, and C.G. Wheat. 2012. Advanced instrument system for real-time and time-series microbial geochemical sampling of the deep (basaltic) crustal biosphere. *Deep Sea Research Part I* 61:43–56, https://doi.org/10.1016/j.dsr.2011.11.004.

Davis, E.E., and K. Becker. 2004. Observations of temperature and pressure: Constraints on ocean crustal hydrologic state, properties, and flow. Pp. 225–271 in *Hydrogeology of the Oceanic Lithosphere*. E. Davis and H. Elderfield, eds, Cambridge University Press.

Davis, E.E., K. Becker, R. Dziak, J. Cassidy, K. Wang, and M. Lilley. 2004. Hydrologic response to a seafloor spreading episode on the Juan de Fuca Ridge. *Nature* 430:335–338, https://doi.org/10.1038/nature02755.

Davis, E., M. Kinoshita, K. Becker, K. Wang, Y. Asano, and Y. Ito. 2013. Episodic deformation and inferred slow slip at the Nankai subduction zone during the first decade of CORK borehole pressure and VLFE monitoring. *Earth and Planetary Science Letters* 368:110–118, https://doi.org/10.1016/j.epsl.2013.03.009.

Davis, E., K. Becker, M. Kyo, and T. Kimura. 2018. Foundational experiences and recent advances in long-term deep-ocean borehole observatories for hydrologic, geodetic, and seismic monitoring. *Marine Technology Society Journal* 52(5):74–86, https://doi.org/10.4031/MTSJ.52.5.4.

Fisher, A.T., and C.G. Wheat. 2010. Seamounts as conduits for massive fluid, heat, and solute fluxes on ridge flanks. *Oceanography* 23(1):74–87, https://doi.org/10.5670/oceanog.2010.63.

Fulton, P.M., E.E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R.N. Harris, W. Lin, S. Toczko, and Expedition 343, 343T, and KR13-08 Scientists. 2013. Low coseismic friction on the Tōhoku-oki fault determined from temperature measurements. *Science* 342:1,214–1,217, https://doi.org/10.1126/science.1243641.

Fulton, P.M., and E.E. Brodsky. 2016. In situ observations of earthquake-driven fluid pulses within the Japan Trench plate boundary fault zone. *Geology* 44:851–854, https://doi.org/10.1130/G38034.1.

Fulton, P.M., E. Brodsky, J.J. Mori, and F.M. Chester. 2019. Tōhoku-oki fault zone frictional heat measured during IODP Expeditions 343 and 343T. *Oceanography* 32(1):102–104, https://doi.org/10.5670/oceanog.2019.129.

Jannasch, H.W., C.G. Wheat, J.N. Plant, M. Kastner, and D.S. Stakes. 2004. Continuous chemical monitoring with osmotically pumped water samplers: OsmoSampler design and applications. *Limnology and Oceanography* 2(4):102–113, https://doi.org/10.4319/lom.2004.2.102.

Jungbluth, S.P., R.M. Bowers, H.-T. Lin, J.P. Cowen, and M.S. Rappe. 2016. Novel microbial assemblages inhabiting crustal fluids within mid-ocean ridge flank subsurface basalt. *The ISME Journal* 10:2,033–2,047, https://doi.org/10.1038/ismej.2015.248.

Kawatsu, H., P. Kumar, Y. Takei, M. Shinohara, T. Kanazawa, E. Araki, and K. Suyehiro. 2009. Seismic evidence for sharp lithosphere-asthenosphere boundaries for oceanic plates. *Science* 324:499–502, https://doi.org/10.1126/science.1169499.

Kinoshita, C., and D.M. Saffer. 2018. In situ permeability and scale dependence of an active accretionary prism determined from cross-borehole experiments. *Geophysical Research Letters* 45:6,935–6,943, https://doi.org/10.1029/2018GL078304.

Kopf, A., D.M. Saffer, E.E. Davis, S. Hammerschmidt, A. Labonte, R. Meldrum, S. Toczko, R. Lauer, M. Heesemann, R. Macdonald, and others. 2011. The Smartplug and Genius Plug: Simple retrievable observatory systems for NanTroSEIZE borehole monitoring. In *Proceedings of the Integrated Ocean Drilling Program*, vol. 332. A. Kopf, E. Araki, S. Tozcko, and the Expedition 332 Scientists, Integrated Ocean Drilling Program Management International, Inc., Tokyo, https://doi.org/10.2204/iodp.proc.332.105.2011.

Kopf, A., T. Freudenthal, V. Ratmeyer, M. Bergenthal, M. Lange, T. Fleischmann, S. Hammerschmidt, C. Seiter, and G. Wefer. 2015. Simple, affordable, and sustainable borehole observatories for complex monitoring objectives. *Geoscientific Instrumentation, Methods and Data Systems* 4:99–109, https://doi.org/10.5194/gi-4-99-2015.

McGuire, J.J., J.A. Collins, E. Davis, K. Becker, and M. Heesemann. 2018. A lack of dynamic triggering of slow slip and tremor indicates that the shallow Cascadia megathrust offshore Vancouver Island is likely locked. *Geophysical Research Letters* 45:11,095–11,103, https://doi.org/10.1029/2018GL079519.

Meyer, J.L., U. Jaekel, B.J. Tully, B.T. Glazer, C.G. Wheat, H.-T. Lin, C.-C. Hsieh, J.P. Cowen, S.M. Hulme, P.R. Girguis, and J.A. Huber. 2016. A distinct and active bacterial community in cold oxygenated fluids circulating beneath the western flank of the Mid-Atlantic Ridge. *Scientific Reports* 6, 22541, https://doi.org/10.1038/srep22541.

Neira, N.M., J.F. Clark, A.T. Fisher, C.G. Wheat, R.M. Haymon, and K. Becker. 2016. Cross-hole tracer experiment reveals rapid fluid flow in the upper ocean crust. *Earth and Planetary Science Letters* 450:355–365, https://doi.org/10.1016/j.epsl.2016.06.048.

Nigro, O.D., S.P. Jungbluth, H.-T. Lin, C.-C. Hsieh, J.A. Miranda, C.R. Schvarcz, M.S. Rappe, and G.F. Steward. 2017. Viruses in the oceanic basement. *mBio* 8(2):e02129-16, https://doi.org/10.1128/mBio.02129-16.

Orcutt, B.N., and K.J. Edwards. 2014. Life in the ocean crust: Lessons from subseafloor observatories. Pp. 175–195 in *Earth and Life Processes Discovered from Subseafloor Environments, Developments in Marine Geology*, vol. 7. R. Stein, D. Blackman, F. Inagaki, and H.C. Larsen, eds, Elsevier.

Saffer, D., A. Kopf, S. Toczko, E. Araki, S. Carr, T. Kimura, C. Kinoshita, R. Kobayashi, Y. Machida, A. Rösner, and L.M. Wallace. 2017. Expedition 365 methods. In *NanTroSEIZE Stage 3: Shallow Megasplay Long-Term Borehole Monitoring System*. D. Saffer, A. Kopf, S. Tocko, and the Expedition 365 Scientists, Proceedings of the International Ocean Discovery Program, vol. 365, College Station, TX, https://doi.org/10.14379/iodp.proc.365.2017.

Screaton, E.J., B. Carson, E. Davis, and K. Becker. 2000. Permeability of a decollement zone: Results from a two-well experiment in the Barbados accretionary complex. *Journal of Geophysical Research* 105:21,403–21,410, https://doi.org/10.1029/2000JB900220.

Shah Walter, S.R., U. Jaekel, H. Osterholz, A.T. Fisher, J.A. Huber, A. Pearson, T. Dittmar, and P.R. Girguis. 2018. Microbial decomposition of marine dissolved organic matter in cool oceanic crust. *Nature Geoscience* 11:334–339, https://doi.org/10.1038/s41561-018-0109-5.

Solomon, E.A., M. Kastner, G. Wheat, H.W. Jannasch, G. Robertson, E.E. Davis, and J.D. Morris. 2009. Long-term hydrogeochemical records in the oceanic basement and forearc prism at the Costa Rica subduction zone. *Earth and Planetary Science Letters* 282(1–4):240–251, https://doi.org/10.1016/j.epsl.2009.03.022.

Wallace, L.M., M.J. Ikari, D.M. Saffer, and H. Kitajima. 2019. Slow motion earthquakes: Taking the pulse of slow slip with scientific ocean drilling. *Oceanography* 32(1):106–118, https://doi.org/10.5670/oceanog.2019.131.

Wheat, C.G., H.W. Jannasch, M. Kastner, J.N. Plant, and E. DeCarlo. 2003. Seawater transport in the upper oceanic basement: Chemical data from continuous monitoring of sealed boreholes in a ridge flank environment. *Earth and Planetary Science Letters* 216:549–564, https://doi.org/10.1016/S0012-821X(03)00549-1.

Wheat, C.G., H.W. Jannasch, M. Kastner, S.M. Hulme, J.P. Cowen, K.J. Edwards, B.N. Orcutt, and B.T. Glazer. 2011. Fluid sampling from oceanic borehole observatories: Design and methods for CORK activities (1990–2010). In *Proceedings Integrated Ocean Drilling Program*, vol. 327. A.T. Fisher, T. Tsuji, K. Petronotis, and the Expedition 327 Scientists, Integrated Ocean Drilling Program Management International, Inc., Tokyo, https://doi.org/10.2204/iodp.proc.327.109.2011.

Wheat, C.G., K.J. Edwards, T. Pettigrew, H.W. Jannasch, K. Becker, E.E. Davis, H. Villinger, and W. Bach. 2012. CORK-Lite: Bringing legacy boreholes back to life. *Scientific Drilling* 14:39–43, https://doi.org/10.2204/iodp.sd.14.05.2012.

AUTHORS

Evan A. Solomon (esolomn@uw.edu) is Associate Professor, University of Washington, School of Oceanography, Seattle, WA, USA. **Keir Becker** is Professor, University of Miami, Rosenstiel School of Marine and Atmospheric Science, Coral Gables, FL, USA. **Achim J. Kopf** is Professor, MARUM, Center for Marine Environmental Science, Universität Bremen, Bremen, Germany. **Earl E. Davis** is Senior Research Scientist, Pacific Geoscience Center, Geological Survey of Canada, Sidney, BC, Canada.

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