# A review of CORK designs and operations during the Ocean Drilling Program[1]

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## Chapter contents




# Abstract

This paper provides a review of 1989–2003 designs and operations of the 20 Circulation Obviation Retrofit Kit (CORK) long-term subseafloor hydrogeological observatories installed in 18 holes during the Ocean Drilling Program (ODP). The basic configurations of the four models of CORKs developed during the ODP period are summarized: the original single-seal CORK (14 installations in 12 holes, 1991–2001) and three multilevel models, including the Advanced CORK or ACORK (2 installations, 2001), a wireline instrumented multipacker system or wireline CORK (2 installations, 2001), and the CORK-II (2 installations, 2002). The evolution of the scientific instrumentation installed in ODP CORKs and the history of postinstallation submersible operations are described. This instrumentation was provided by scientists with support of national ODP research funding, which also supported the extensive submersible time devoted to postinstallation data downloads and instrument servicing. Although the purpose of this paper does not include a review of CORK scientific results, we offer some comments on scientific lessons learned during the ODP CORK effort. We describe the funding and engineering support structure that held for the ODP CORK installations and close with some comments on the importance of engineering support for the Integrated Ocean Drilling Program goals involving long-term borehole observatories. We also provide a complete bibliography of CORK-related literature through 2004 and all of the data sets in digital form collected through 2003 from the six ODP CORK installations installed in either 1991 or 1996 near the Juan de Fuca Ridge, of which all but one are still in service.


# Introduction

This paper aims to provide a concise but comprehensive review of 1989–2003 designs and operations in support of long-term hydrogeological monitoring with 20 Circulation Obviation Retrofit Kit (CORK) subseafloor sealed-hole observatories installed in 18 holes (Fig. **F1**) during the Ocean Drilling Program (ODP). It aims partly to provide some technical and historical background for the deployment of three more CORKs of a refined design during the very first expedition of the Integrated Ocean Drilling Program (IODP) (**Fisher et al.,** this volume). More importantly, it attempts to collect sufficient detail about the designs and operations of ODP CORKs to provide a reference for deployment of CORKs of

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established design or further development of CORKs of new designs during IODP cruises. We also provide a complete history of submersible operations and a bibliography of publications to date related to ODP-era CORKs (see the "Appendix"), although we do not attempt to review the scientific contributions of the overall CORK effort. Finally, because of their relevance to IODP Expedition 301 CORK-II installations, we provide digital files (see "Supplementary Material") of most of the data files recovered to date from the four ODP Leg 168 CORK installations on the eastern flank of the Endeavour segment and the two nearby installations from ODP Legs 139 and 169 at Middle Valley.

The origins of the CORK experiment can be traced back to discussions during a 1987 workshop on wireline reentry of deep-sea boreholes (Langseth and Spiess, 1987). By that time, considerable experience had been gained in interpreting thermal observations of vertical flow in Deep Sea Drilling Project (DSDP) and ODP holes left open between permeable formation and ocean bottom water (e.g., Hyndman et al., 1976; Becker et al., 1983). However, we recognized that such borehole flow, which seemed to be fairly common in holes penetrating through sediments into oceanic basement, represented serious perturbations to the hydrological systems we were attempting to study via scientific ocean drilling; thus, some sort of sealed-hole experiment was necessary to allow reestablishment of equilibrium in in situ conditions to understand hydrogeologic state and processes. In 1989, we began to pursue the concept of an "instrumented borehole seal" (Fig. F2) with additional scientific collaborators, the science advisory structure, ODP engineers (principally T. Pettigrew), and funding agencies. The first two installations, planned for the Middle Valley sedimented spreading center, were added to the ODP schedule as of December 1989, based on a drilling proposal originally submitted in early 1986. They were successfully completed during Leg 139 in the summer of 1991 (Davis et al., 1992).

It was as we sailed for Middle Valley that the acronym "CORK," or "Circulation Obviation Retrofit Kit," was coined by ODP Operations Superintendent Glen Foss. The configuration of the original design bears an obvious resemblance to a cork in a bottle; "CO" referred to stopping the fluid exchange between formation and ocean bottom water that was to be expected if holes into hydrologically active formations were left unsealed; "RK" referred to the fact that the experiment could be installed in any reentry hole, whether drilled the day before or 20 y earlier. The CORK effort grew in prominence within ODP to a greater degree than we ever envisioned, and it became one of two primary threads (the other being the borehole broadband seismology effort, e.g., Purdy and Orcutt, 1995) that led to identification of "in-situ monitoring of geological processes" as one of three featured initiatives in the final ODP long-range plan (JOI, 1996).

Figure F3 illustrates a generic CORK configuration and summarizes the range of primary scientific objectives of these hydrogeological observatories. During the course of the ODP CORK effort, 14 installations were made during 1991–2001 with an original single-seal CORK design (Davis et al., 1992), and 6 more installations were made during 2001–2002 with three different models incorporating capabilities to isolate multiple zones in a single hole (Table T1).

The term "CORK" is sometimes used generically to represent any long-term sealed-hole experiment, but it is also used to refer specifically to the original single-seal CORK design. Following a two-part (December 1997/February 1998) CORK science and engineering workshop (Becker and Davis, 1998), the term "advanced CORK" was used generically to represent a sealed-hole experiment with a multizone isolation capability (Fig. F4). However, the proper noun "Advanced CORK" (acronym ACORK) is also used specifically as the name of the first of the three multizone models actually developed (Shipboard Scientific Party, 2002). The other two multizone models developed during the ODP period were (1) the "CORK-II" (Jannasch et al., 2003), based on a borehole instrument hanger design originally developed to support deployment of broadband seismometer/strainmeter packages in deep holes (Shipboard Scientific Party, 2000), and (2) a wireline instrumented multipacker system or "wireline CORK" (Becker et al., 2004), deployed from an oceanographic research ship using a wireline reentry "Control Vehicle" (Spiess et al., 1992). Design summaries for the original CORK and the three multizone models are provided below, as well as primary references for further details.

Obviously, the ODP CORK effort succeeded far beyond the vision we originally sketched out on a dinner napkin in 1989! Nevertheless, despite the welcome programmatic embrace of the concept and the substantial technological evolution that has taken place since then, some key proponent-driven aspects continued throughout ODP very much in the mode that led to the original deployments. These include

- The critical need for close collaboration among program engineers and scientific proponents to refine the measurement program incorporated in the installations;

- The sharing of costs between program funds for the seafloor and subseafloor infrastructure and additional funds for the "third-party" scientific instrumentation, raised by proponents' proposal submissions to national agencies; and
- The support of postinstallation submersible operations by national funding agencies outside of ODP programmatic oversight or commingled funds.

As IODP begins, these models appear to be continuing, so these aspects are explored in greater detail after the technical summaries of CORK designs and operations.

# CORK design summaries

All of the CORK designs described below require some sort of reentry cone and casing to stabilize the upper part of the hole. Designs of the reentry cones and casing systems evolved during DSDP and ODP, and the latest ODP standard is summarized in Graber et al. (2002). In brief, that standard includes the reentry cone, mud skirt, and casing hanger that provide for running up to four nested sizes of casing from the hanger ever deeper into the hole, at diameters of 20, 16, 13⅜, and 10¾ inches. For most of the descriptions below, except for the ACORK, a 10¾ inch diameter casing is assumed to be (1) deployed as the final casing string prior to the CORK installation and (2) in some way sealed into the formation through which it passes. Some installations have also included a smaller diameter liner; a liner is similar in concept to casing but is emplaced into open hole from deep within the inner casing (i.e., it is not hung at the casing hanger immediately below the reentry cone).

## Original CORK

The essential elements of the original single-seal CORK design (Davis et al., 1992) (Fig. F5) are (1) a CORK body that seals within the casing hanger system at the top of a reentry hole and (2) a long-term data logger and sensor string in the sealed hole. The CORK body provides an inner bore and landing shoulder that allows deployment (through the drill pipe) and internal sealing of the data logger and sensor string. This design requires prior establishment of a reentry hole, suitably cased; the standard is for the CORK body to seal inside the 10¾ inch casing hanger and extend up ~1.5 m above the rim of the reentry cone, although versions have been constructed for older holes with slightly different casing sizes and hanger systems (e.g., older DSDP reentry holes with 11¾ inch casing). Original CORKs have been deployed in two types of cased reentry holes: (1) those in oceanic crust that are cased through sediments and then cored with a 9⅞ inch bit to leave an open hole in underlying basement and (2) those in subduction settings, normally completely cased (and lined in some instances) with perforated sections through unstable zones of interest. After a suitable cased reentry hole is established (which may take several days to weeks), it has required an additional 24–36 h, on average, for deployment of the CORK body and sensor string, plus a landing platform to support subsequent experimental equipment and submersible operations at the CORK head.

Note that the instrumentation string is limited to a diameter less than ~3.75 inches that (1) allows deployment down the standard 4½ inch internal diameter drill pipe and (2) will pass through the CORK body inner bore until the data logger lands and seals. In theory, deployment of any kind of sensor string is possible if it meets this diameter restriction and it incorporates the necessary seals and landing shoulder. In practice, sensor strings (Fig. F3; Table T2) have typically comprised (1) thermistor cables below the data logger for temperature profiles within the sealed hole and (2) pressure gauges immediately above and below the data logger electronics housing for seafloor reference and sealed-hole pressure measurements, respectively. Where the hole is left filled with seawater, as is normal practice, the single pressure gauge below the data logger averages the fluid pressure signal from any open hole section below the casing or perforated section within casing. Where the hole is left filled with fluid of different density than seawater (e.g., heavy mud, as in the case of Hole 948D), a vertical array of pressure gauges may provide additional information (Foucher et al., 1997). The data logger incorporates an underwater-mateable connector (UMC) accessible at the top of the CORK for submersible-based data transfer and reprogramming, which has usually been attempted at average intervals of ~2 y (see **"Submersible operations,"** below).

The CORK body assembly includes ½ inch stainless steel or titanium tubing that allows fluid pressure or fluid samples from the sealed section of the hole to be brought to a valve on the wellhead that is accessible by submersible. This also permits the hydrologic properties of the isolated zone of the formation to be actively tested using submersible-borne pumps linked to the wellhead valve. The first CORK sensor strings included thin-walled ½ inch diameter Teflon tubing run from the open hole section to the tubing in the CORK body, but this proved unsatisfactory as a fluid sampling method, largely because of damage to the tubing during deployment. Starting in 1994, a majority of sensor strings in CORKs of the original design have instead included self-contained long-term fluid "OsmoSamplers" driven by osmotic pumps (Shipboard Scientific Party, 1995, 1997; Jannasch et al., 2003) and hung on the thermistor cables deep in the hole. These have required recovery of the data logger and sensor string using submersibles some years after original deployment from the drillship (see **"Submersible operations,"** below, for details).

## Advanced CORK

As noted above, the original CORK averages pressure signals from the open hole or perforated interval, so it is not suitable for resolving processes in hydrogeologically layered systems via a single hole. The Advanced CORK, or ACORK (Shipboard Scientific Party, 2002) (Fig. **F6**), was the first concept developed to achieve the goal of separately isolating multiple zones in a single hole. It achieves the objective by incorporating large-diameter casing-mounted packers at desired depths as integral parts of the final casing string (10¾ inch diameter for the two installations to date, but smaller sizes are feasible). The packers incorporate pressure-tight, lengthwise hydraulic pass-throughs, allowing fluid pressures and/or samples to be transmitted from sampling screens on the outside of the casing to gauges, loggers, and/or samplers mounted on the wellhead via tough, industry-standard hydraulic umbilicals strapped on the outside of the casing. In the two ACORKs deployed to date (deep strings seaward of and at the toe of the Nankai accretionary prism), the ACORK casing itself was entirely solid, although it would be possible to modify the design to provide hydraulic access between the formation and the inside of the casing. After assembly beneath the rig floor, the ACORK casing string was deployed into a predrilled pilot hole with reentry cone (that had been established during earlier logging-while-drilling operations) and run into the hole without rotation using a mud-motor-driven underreamer system, much like any simple (noninstrumented) casing string might be deployed. Once an ACORK casing string is landed into the reentry cone and the packers are inflated using the rig floor pumps, the casing can be reentered with a coring assembly for deeper drilling, as was done in one of the two Nankai installations to penetrate into underlying oceanic basement. After any hole deepening, the bottom of the casing is intended to be sealed with a drillship- and/or wireline-removable bridge plug, which completes the seal of the deepest monitoring interval and leaves the inner bore free for an instrument string, albeit one without direct hydraulic access to the formation. The ambitious Nankai deployments were flawed because of an inadequate underreamer and premature setting of a bridge plug, but they achieved most of their objectives in a difficult setting and demonstrated the utility of the ACORK concept.

## CORK-II or sealed borehole instrument hanger with OsmoSamplers

The next planned deployments were to be at the Costa Rica margin, where experience had indicated that any pilot holes for ACORKs could not be expected to remain open to the planned depth of monitoring. Motivated partly by the difficulties with the Nankai ACORK installations, a new approach, dubbed "CORK-II," was taken that would permit multilevel monitoring deep within an otherwise normally prepared, cased reentry hole. It represented an adaptation of the "borehole instrument hanger" system that had been developed for the broadband seismometer/strainmeter installations in deep reentry holes in the western Pacific (Shipboard Scientific Party, 2000). In those installations, the instrument package was attached to the end of a small-diameter (4½ inch) casing that was suspended from a hanger that landed in the reentry cone; the small-diameter casing conveyed the instruments deep into the hole, provided a structural member for the cabling from the instruments to be run to the seafloor, and also provided the conduit by which the instruments were cemented in place once deployed. For the CORK-II (Jannasch et al., 2003) (Fig. **F7**), the 4½ inch casing string incorporated packers that could be inflated deep in the hole (either in open hole or within 10¾ inch casing) and perforated sampling screens that would allow formation fluids to be sampled by OsmoSamplers deployed down the inside of the drillstring and 4½ inch casing. Like the ACORK, the CORK-II packers incorporate length-wise hydraulic pass-throughs that allow fluid pressures and samples from the isolated zones to be conveyed to the wellhead by umbilicals mounted on the outside of the 4½ inch casing. In the Costa Rica margin CORK-II design (Jannasch et al., 2003) (Fig. **F7**), the OsmoSamplers also carried long-term self-contained temperature recorders. The OsmoSampler/temperature-recorder packages were deployed on Spectra rope attached to retrievable plugs that landed deep within and sealed the inner bore of the 4½ inch casing. Great difficulties were experienced during later submersible-based attempts to recover these plugs and samplers from deep within the holes, so for subsequent CORK-II designs (**Fisher et al.,** this volume), the sampling devices were run on Spectra rope extending to sealing plugs accessible directly at the wellhead.

## Wireline CORK or wireline instrumented multipacker system

The wireline CORK (Fig. F8) followed, in many ways, an independent approach that utilized the capabilities of the Control Vehicle of the Marine Physical Laboratory (MPL), Scripps Institution of Oceanography (La Jolla, California, USA), for wireline reentry of existing cased holes from an oceanographic research vessel. The Control Vehicle had been developed partly with U.S. Science Support Program support as a facility for wireline reentry, logging, and emplacement of instruments within stable reentry holes without requiring a drillship (Spiess et al., 1992). The concept for the "wireline CORK" included an in-cone platform from which was suspended a bundled sensor string that included electrical leads, a mechanical strength member, hydraulic tubing, and inflatable packers to seal the hole at the desired depths. As with the ACORK and CORK-II, the packers incorporated hydraulic pass-throughs to allow fluid pressure signals and samples to be transmitted to gauges and valves on the in-cone platform via tubing from the zones isolated by the packers. In this case, the packers also incorporated electrical feed-throughs to bring thermistor signals from the isolated zones up to a data logger on the in-cone package. The sensors and data loggers were quite similar to those used for contemporary drillship CORKs. Two such installations were deployed in 2001 from the *Roger Revelle* in a pair of deep crustal reentry holes on the Costa Rica Rift (Becker et al., 2004). One of these worked well with only one packer to seal at the base of the casing and isolate the open hole section below. The other incorporated two packers, one intended to seal in casing and the other to seal in open hole, thus isolating two zones in the formation; that installation failed when the deeper packer became stuck in open hole ~20 m above its intended inflation position, so that the upper packer was not pulled the final ~20 m to its intended seat within the upper casing.

## CORK instrumentation packages

Table T2 provides a summary of the specific instrumentation originally installed in each ODP CORK. The scientific measurement objectives for the original CORK design were actually modest: long-term records of temperature profiles and pressure in the sealed hole, sampled hourly. The geometry of the original CORK and down-the-pipe deployment method for the instrumentation defined a small-diameter form factor and the basic geometry of the instrumentation package. This included an elongated, small-diameter data logger housing, above which was mounted a seafloor reference pressure gauge and UMC for communication with the data logger, and below which was suspended in the sealed hole a thermistor cable and single absolute pressure gauge (multiple gauges not being useful in the normal case of the hole left filled with seawater). As is described below, various other options were ruled out early because of the basic form factor. The instrumentation for the majority of single- and multiseal CORKs were provided by our collaborative group supported by the U.S. National Science Foundation (NSF) and the Geological Survey of Canada, so we focus on the evolution of that instrumentation in this review. However, we note that the Institut Francais de Researche pour l'Exploration de la Mer (IFREMER) provided a quite successful sensor string of independent design for one of the single-seal CORKs installed in 1994 (Table T2) and refer the reader to Foucher et al. (1997) for details.

### Pressure gauges

With the exception of the IFREMER string noted above, all the ODP-era CORKs utilized Paroscientific Digiquartz depth sensors (4000 or 7000 m models, as appropriate) to provide absolute pressure measurements. The associated "Paroscientific Intelligent Module" analog-to-digital converters (ADCs) have been incorporated within the data loggers for all installations except the IFREMER string. The narrow form factor required by the original CORK design essentially precluded consideration of a differential pressure gauge to assess formation pressure relative to hydrostatic because passage of one or more fluid line(s) through or into the electronics housing would have been required. The Paroscientific gauges have proven to be sufficiently accurate and very reliable over the long term, so they have also been used in the multilevel ACORK and CORK-II, even though the newer configurations would allow use of differential gauges. Recorded pressures have been accurate to ~0.01% of the full-scale range, and pressure variations have been resolved to 1 ppm of full scale (~40 cm and ~4 mm, respectively, for the Juan de Fuca deployments). Precise differential pressure determinations are facilitated by hydrostatic reference checks before installation and at the time of service or recovery operations.

### Thermistor cables

The initial CORK deployments provided the greatest temperature-measuring challenge of all the installations because of high formation temperatures in excess of 270°C. (The use of thermocouples on the sensor string for such high temperature settings was ruled out because of the complication in providing reference junctions at the tops of long cables.) We standardized on a Thermometrics "SP100" thermistor of high nominal resistance so that line resistances could be ignored and specially aged at high temperature for >4 months to achieve acceptable long-term stability. For the initial installations, two cable manufacturers were contracted to mold the thermistors into cables specified to be able to withstand the expected temperatures; unfortunately, one (Vector Schlumberger) could not deliver in time and the readings from the cables from the other (Cortland Cable Co.) displayed problems indicative of pervasive seawater leakage at the high temperatures within days of deployment. For subsequent installations, we took attachment of the thermistors to the multiconductor cables into our own hands, with significantly better results (in formations at lower temperatures), using three different methods:

1. Bringing each conductor pair and thermistor into a grease-filled Teflon capsule of our design;
2. A proprietary epoxy encapsulation of the thermistors by Ocean Design Inc., with leads brought out for crimp pins and slip-on rubber boots sealing over the crimps to conductors; and
3. Molding by Branter/SeaCon of the thermistors into MAW-2 connectors, with the mating MAW-2 then molded onto each conductor pair at the appropriate depth.

Early conductor cable designs by Cortland Cable Co. incorporated 10 twisted pairs around a ¼ inch Kevlar center strength member; insulation of the 20 gauge wires was Teflon of the grade appropriate for the expected temperatures. There were quality control problems with the insulation on these cables, and for 1996–1997 deployments at moderate temperatures (20°–65°C), we changed to a design by Neptune Technologies (now unfortunately out of business). These included outer Kevlar and polyester braiding as strength member and abrasion cover, respectively, a conductor core made by South Bay Cable of 12 twisted pairs of conductors with extra-thick insulation of polypropylene, and MAW-2 conductors molded onto the conductor pairs with a proprietary Neptune Technologies technique. These worked very well in multiyear deployments on the Juan de Fuca and Mid-Atlantic Ridge flanks, although the two units at highest temperatures (60°–65°C) displayed some degradation after 2 years that seemed to originate where the MAW-2 conductor pairs were molded to the cable conductor pairs.

Our experience with thermistor strings seems to be consistent with industry experience in long-term reservoir monitoring using more sophisticated cable assemblies. In those efforts, the most significant long-term failure rates are with conductors and connectors, not with sensors or electronics (M. Kamata, presentation at IODP interim Technical Advisory Panel, pers. comm., 2003). Similarly, our worst problems have been with the conductors and thermistor-conductor connection. These problems were wholesale with the first cables at very high temperatures; even with the subsequent, better quality designs, problems in general increase with both long time and in situ temperature, as insulation degrades and/or seawater penetrates insulating materials.

Finally, an important aspect of our experience is that about half of the thermistor cables deployed to date have had to be field-shortened, often under tight time constraints, when the realized open hole depths fell short of planned depths. We anticipated this likelihood and over the years have employed two methods when shortening was necessary: folding the cable or reterminating the top of the cable assembly. The former was necessary for the original cable designs with a central Kevlar strength member that could not be easily reterminated, and it worked reasonably well as long as proper thimbles were used at the folds to avoid crimping the conductors. The latter was made possible when we changed to the Neptune Technologies cable design, in which the strength termination was a Kevlar cable grip applied to the outer braid cable strength member. It was also made possible by the success of our original design for bringing the thermistor and borehole pressure signals into the electronics pressure case, given the restriction to a single bulkhead connector feasible with the narrow-diameter form factor. We made these connections by bringing the thermistor conductors into an oil-filled boot, where they were mated individually, using standard single-pin connectors with slip-on rubber boots, to leads on a custom-molded multilead "pigtail" that brought all the signals to the connector that mated to the bulkhead connector on the electronics package. For all the single-seal CORK deployments except the IFREMER string in Hole 948D, the custom pigtail included 20 thermistor leads plus the standard four-pin connector to the sealed-hole pressure gauge, which was also made up within the compliant oil-filled boot. The boot and its conductor feed-through bulkhead were made by our group; the connector system was made by Branter/SeaCon, based on the MINM-25 bulkhead and mating cable connector models. The design proved to be reliable for all the installations.

## Data loggers

Functionality of the data loggers for the original CORK design (ODP Legs 139 through 195) was constrained largely by the form factor dictated by the deployment scheme and pressure case diameter. All components in the reentry cone assemblies (pressure sensors, cable terminations, and electrical connectors including the UMCs, batteries, and electronics) were required to fit within the 64 mm (2.5 inch) inside diameter of the pressure-case and strength-member sections of the assembly, which totaled ~13 feet in length.

As noted above, the data loggers for all but one of the original CORKs were provided by our collaborative group, and these were manufactured by Richard Brancker Research, Ltd. Power in all of these units was supplied by four 3.6 V lithium thionyl chloride "D" cells, which provided a nominal capacity of 26 A·hr at 7.2 V. This limit, the power consumption dictated by the particular processor and memory used, the number and type of sensors, and the logging rate, defined the monitoring lifetime, which ranged from ~2 y in early units with all channels operational, to several years in some instances (e.g., in Hole 857D, pressures and internal temperature were logged hourly with on-board power from 1996 until 2003, when an auxiliary battery pack was connected). Memory capacity grew as low-power technology advanced, from 0.5 MB in early deployments to 2 MB in later ones, allowing 2 to several years of operation between data downloads (again, depending on the number of sensors employed). Typical CORK instruments provided analog-to-digital conversion for up to 15 analog devices. Typically, these comprised 10 formation thermistors, an on-board thermistor, and two precision resistors that provided a check on logger drift (although none was ever detected). Twelve-bit and, later, thirteen-bit conversion was applied to a temperature range of 0°–100°C and, in some cases, 0°–300°C, to provide a resolution ranging from 0.01 to 0.07 K. Two installations included tilt sensors. Data were typically recorded once per hour, although during certain periods (e.g., hydrostatic sensor checks) sampling intervals were sometimes reduced to the minimum of 10 s allowed by the logger. All data lines have been date/time-tagged with output from quartz oscillators. Drift, determined with periodic checks at the time of submersible visits, has been found to be linear, although often several minutes per year. Clock checks and resets, data downloads, and logger reprogramming were accomplished via a 9600 baud RS-232 serial link utilizing the UMC system described in **"Submersible operations."**

Despite the highly robust and reliable characteristics of the original CORK data loggers, the relaxation of the diameter constraints permitted by the externally mounted pressure cases of the ACORK configuration stimulated a redesign of the data loggers. Incremental steps were taken on all fronts. The new instruments accommodated greater numbers of pressure and temperature sensors (e.g., 7 pressure sensors were included in the Hole 808I deployment, and 16 thermistor sensors were included in the wireline ACORK in Hole 504B). Much greater temperature sensitivity was achieved with a 24 bit ADC. The limiting factor became the inherent noise of the electronics; resolution realized was significantly better than 1 mK. Space was available for larger battery packs (24 "DD" lithium chloride cells providing 420 A·h at 7.2 V). This, with increases in memory capacity to 8 MB and in serial data transfer rate to 38.4 Kbps, allowed practical logging rates and monitoring lifetimes to be increased substantially. Most of the multilevel CORK installations operating at 10 min sampling rates are limited by battery shelf life and should run for 10 y or more.

Further advances in low-power, high-speed components have prompted improvements in CORK logger technology during the transition from ODP to IODP. These have been applied to the Expedition 301 installations (see **Fisher et al.,** this volume, for further details) and are available for future installations. The new instruments employ flash memory cards for greatly expanded memory capacity, which, along with improvements in power dissipation, allow for significantly better capability for long-term logging at higher rates. The greatest technological advance comes with a new ADC for the Paroscientific pressure sensors designed by Bennest Enterprises, Ltd. A frequency resolution of roughly 2 ppb has been achieved with a 800 ms measurement; applied to the full dynamic range of the pressure-sensitive transducers, this equates to a pressure resolution of 20 ppb, a factor of 50 better than previously attained. This new sensitivity (~2 Pa, or 0.2 mm of water) will permit new studies of oceanographic (infragravity waves, tsunami, and turbulence), seismic (surface waves), and hydrologic phenomena. Another advance involves the portability of the sensor and logging system. Hydraulic connections are provided by lightweight submersible-mateable connectors, and with the reductions in power consumption (and therefore in battery volume), the sensor and logger housings are smaller and more portable. This allows the instruments to be carried to and mated with the wellhead plumbing easily by submersible if they are not mounted on the ACORK instrument frame at the time of drilling, and replaced later if necessary.

# Submersible operations

Table **T3** summarizes operations with manned and unmanned submersibles at ODP-era CORKs after their initial installation. The level of submersible activity at the CORKs has been extensive, involving many of the international deepwater research vehicles. The costs for this activity have been supported primarily by national ODP funding agencies outside of commingled ODP funding. From the first dive with *Alvin* in 1991 at the first CORKs, the submersible pilots and support engineers for all the vehicles we have used have met nearly all of the needs and challenges associated with operations at the ODP CORKs. Submersible operations at CORKs have typically included routine data downloads at periodic intervals, sampling or pumping operations at the wellhead valve, and occasional complex instrument recoveries and reinstrumentation attempts; further details on these three aspects are provided in this section.

Data downloads and logger reprogramming have been accomplished by incorporating a single UMC in each CORK, with the mating connector linked for serial communication to a personal computer via through-hull wiring into the submersible, to the surface ship via remotely operated vehicles (ROVs), or, in two instances, to the surface ship via two-way acoustic modem (Meldrum et al., 1998). For the original CORK, the UMC was the economical "OD Blue" connector made by Ocean Design, Inc. The male connector incorporated four bands for contacts along a single pin that required no azimuthal orientation for mating, and it was assembled into a "top hat" unit that fit over the top of the CORK wellhead and assured proper alignment for mating with the female connector centered on the top of the data logger (fig. 2 of Davis et al., 1992). This system worked well aside from some quality control problems with the spacing among the banded contacts, such that full contact was not made with certain male units in certain female units. Careful selection of the connectors actually used prevented any malfunctions in the field. Manufacture of the OD Blue model was discontinued at about the same time that the multizone CORK models were being designed; these later installations utilized more expensive, better quality, but more difficult to mate multipin CM-2008 series ROV connectors made by Branter/SeaCon.

Hydraulic coupling to the wellhead valves has been required for access to sealed hole intervals, whether for sampling fluids, pumping into zones for active hydrological tests, or calibrating the pressure records. Most CORK installations have utilized a standard Aeroquip (model FD76-1002-08-10) hydraulic quick-connect/quick-disconnect system that is commonly used on farm tractors. The coupler is generally incorporated into a mating device with a T-handle so that the submersible pilot can push it into place; occasionally, there have been problems making the connection when the valve position was awkward and/or the submersible had difficulties overcoming the reactive forces during the coupling process. Tubing of the desired material is run off the coupler to the sampling device or pump on the wellhead or in the submersible basket. This system has proven satisfactory where sealed-hole pressures are superhydrostatic but unsatisfactory where the formation is underpressured. Efforts are being made to improve the submersible coupler to guarantee a tight seal under conditions of negative or low positive formation pressure.

For active pump-testing of zones isolated in CORKs, the pumps (supplied by scientists to date) must be carefully designed to interface with submersible electrical and hydraulic systems. The designs may vary depending on whether the objective is high pump rates in relatively permeable formations, yielding low pressure signals, or low pump rates, yielding high pressure signals in tight formations. In one unfortunate example of the latter (Hole 949C), local pump-generated transients working against the low formation permeability exceeded the working range of the pressure gauge, which then failed completely. Thus, design refinements are probably in order for the submersible-based pump systems for any active formation testing done at CORKs during IODP. In new installations, such as the ODP ACORK and CORK-II designs, such problems can be avoided by using three-way valves that have been incorporated. These allow the gauges to be switched to ambient seawater and isolated from any excessive transients during pumping, and they also provide a simple way to perform hydrostatic checks for intergauge calibration and drift tests.

At eight single-seal CORK installations, attempts have been made to recover original data loggers and sensor strings some years after initial deployment, either to retrieve downhole OsmoSamplers or because the instrumentation had been damaged, and most of these holes have also been resealed with a dummy plug or reinstrumented with a data logger with pressure sensors but no sensor string. No attempt has been made yet to deploy a long replacement sensor string using submersibles. Various methods have been used to recover the sensor strings, all first requiring the submersible to install a tool at the wellhead that latches onto the data logger and retracts the mechanical "dogs" that had originally latched the logger into the CORK body. In some cases, the latching tool has been attached to a rope run to flotation on the sea surface; after recovery of the submersible, the rope was pulled onto the ship and the packages were winched out. In one case (Hole 948D), the latching device was attached to flotation that had been predeployed to the seafloor with counterweights; the instrument string was floated up when the counterweights were released. In other cases, a bail was attached to the latching tool so that the MPL control vehicle could engage it and pull the instrumentation using the main ship's winch. In another case, an ROV was used to install the latching device, which was attached by strong line to the ROV "garage": once the ROV was retracted into the garage, the ship's winch was used to recover both the ROV system and the sensor string. Finally, the OsmoSampler packages for the Costa Rica margin CORK-II installations were run on landing plugs that seated deep in the hole. A submersible-mounted winch system was used in the attempts to recover those strings, but without success. Recovery and replacement of those strings required the drillship early in IODP operations.

It should be noted that in two attempts to recover sensor strings with OsmoSamplers (Holes 1025C and 1026B), the basaltic formation had closed in on the portion of the sensor string in open hole; during the unsuccessful recovery attempts, significant pull (up to ~5000 lb) had to be generated to break the thermistor strings, leaving the OsmoSamplers in the holes. In an earlier installation without OsmoSamplers (Hole 892B), hydrates had apparently frozen in around the sensor string, even within casing, and again significant pull (~7000 lb) had to be applied to break that string, in an attempt to clear the top of the hole for other experiments.

Reinstrumentation has generally involved predeploying the data logger with a running tool attached to a system of weights and floats that allows the submersible first to release predeployment weights to maneuver the package into the hole under near-neutral buoyancy and then to release the floats and attached running tool for the return to the surface. The recovery and reinstrumentation operations have utilized unlatching and running tools designed by ODP engineers. Many of these tools are currently warehoused at Texas A&M University (College Station, Texas, USA) and presumably could be made available for similar operations in the future.

# A few scientific lessons learned and challenges for the future

Each of the series of original and multilevel CORK installations completed to date has benefited from the experience gained from the preceding deployments. Technical examples are discussed above, and in this section, we focus on more basic issues critical to the scientific return from sealed-hole observatories. In some cases, the time between programs was insufficient to allow proper scientific and engineering evaluation and response (e.g., between Legs 196 and 205), but in most instances, modifications could be made to account for previously unanticipated problems, to study processes in ways previously unrecognized, and to incorporate new technology. For example, it became evident from the first deployments (ODP Legs 139 and 146) that a local record of seafloor pressure was necessary to account for and properly understand the formation pressure response to seafloor loading. Astronomically derived tidal constituents calibrated with satellite data and tide-gauge records could not be relied upon at the precision required, and no information could be had about other loading constituents across the broad frequency range of interest. Hence, subsequent installations included seafloor pressure sensors identical to those used for monitoring formation pressure. The paired data have allowed seafloor loading (as a source of noise) to be removed from the formation records and have provided novel constraints for estimating elastic and hydraulic properties of the formation (with seafloor loading as a formation signal source). We include here a brief list of other lessons and challenges that we believe are important for planning future CORK installations. These should be considered in the context of common first-order goals for CORK instrumentation, namely

- To obtain a high-fidelity record of pressure that has minimum phase or amplitude distortion over as broad a frequency range as possible,
- To record as accurately as possible formation temperatures as a function of depth and time, and
- To permit collection of representative formation-fluid samples that are as free from the effects of drilling and postdrilling contamination as possible.

The list is by no means comprehensive, but it should serve to help guide future designs.

- Correct observations of both transient and average pressure state depend critically on the quality of the seal created by the CORK system. Leakage through the CORK seals or plumbing, between the casing and formation, around packers, or through nearby unsealed pilot boreholes can cause pressure losses. Pressures in formations with high permeabilities and storativities seem to be relatively insensitive to minor amounts of leakage, although high rates of associated flow can cause thermal perturbations and associated pressure offsets. If the thermal perturbations are well constrained, the latter can be accounted for, but they undermine the confidence with which interpretations can be made. Pressures measured in low-permeability formations are sensitive to leaks in a more direct manner; large pressure offsets can be created with little flow, and thermal perturbations may not provide a good test for leakage. In all settings, great effort must be made to create leak-free installations and thermal observations should be made to test for flow and to constrain the buoyancy perturbation if flow is thermally significant.

- Another source of pressure signal distortion is system compliance. This can arise from compressibility of the fluid filling the cased boreholes in original CORKs or the umbilical tubing in ACORK or CORK-II installations and from compliance of the tubing or of the packers or seals that isolate monitored levels. The compliance of the thick-walled steel hydraulic tubing used to date is negligible, but at high frequencies, the compressibility of the water filling the umbilicals can couple with the high resistance of low-permeability material to filter high-frequency signals. Care must be given to minimizing the diameter of hydraulic tubing and to purging lines of any air or free gas. Little is known about the role of packers, but they may cause problems with high-frequency signal distortion in low-permeability formations.
- Combined fluid sampling with temperature and pressure monitoring must be approached with care for the reason that the means of sampling can constitute a leak. In most instances to date, fluid sampling has been done with samplers sealed into the formation, so this has not been a problem. In the multilevel CORKs installed during ODP Legs 196 and 205 and Expedition 301, provision was made for sampling at the seafloor via small-diameter umbilical lines. With this configuration, a proper balance must be achieved that allows a rate of flow that is great enough to make the transit time from the sampled level to the seafloor acceptably short but not so great as to cause a loss in pressure or a distortion of the thermal structure. As in the case of real leaks, this poses the greatest challenge in low-permeability formations.
- Great value has been realized in very long, continuous records. Of particular interest have been transients related to seismogenic strain. These signals are relatively rare and often small and can be characterized only in the absence of installation transients and with the careful removal of seafloor loading effects. Their frequency content is very broadband, ranging from short-lived (seismic surface waves, instantaneous elastic strain) to quasi-permanent deformation. Changes in the character of the response to loading have also been observed at the time of such events. Studies of such phenomena require uninterrupted records that are influenced minimally by such things as changes in sensors (resulting in calibration offsets and changes in drift) and by perturbations associated with hole opening.
- Perturbations caused by the invasion of cold, high-density seawater into the formation during drilling and any time after when holes are unsealed can be very large, particularly in high-permeability formations. The effect is exaggerated in subhydrostatic holes. Such unnatural flow affects temperatures and pressures and displaces formation water, precluding the collection of pristine formation fluid samples. Choosing sites that are naturally superhydrostatic helps to overcome this problem, as does minimizing the time between when permeable formations are first penetrated and when they are sealed. An additional problem with original CORKs arose with the large volume of water contained in the cased sections below the seafloor seal. This amounts to an unwanted reservoir of seawater trapped after installation that slowly mixes into the formation. This problem created challenges for the sampling efforts in the Leg 168 holes (Wheat et al., 2003). The multilevel CORKs designed for Legs 196 and 205 and Expedition 301 dealt with this problem by including bridge plugs or packer seals near the bottom of the main casing strings.
- With each new level of resolution provided by technological improvements to sensor design, memory capacity, and power efficiency, new signals have been observed. The earliest instruments provided only 12 bit digital temperature resolution. Applying this to the large dynamic range necessary at their ridge axis sites was adequate for the primary task of characterizing the crustal thermal structure, but many questions remained unexplored. Subsequent advances to a 24 bit thermistor ADC have overcome this problem and have allowed things like tidally modulated formation-fluid flow and bottom water thermal stability to be observed and quantified. Advances in the resolution of pressure have also been realized, in the way of higher resolution, greater absolute accuracy, and greater sampling rates. Increases in pressure resolution (2 orders of magnitude), memory capacity (3 orders of magnitude), and data transfer rates (1.5 orders of magnitude) now permit observations of seismic surface waves, oceanographic infragravity waves, tsunamis, and other subtle signals, both at the seafloor and within the formation. This capability points clearly to the future need for hydrologic observations provided by CORKs to be integrated with other collocated

and simultaneous observations such as crustal deformation, seismic ground motion, and seafloor compliance.

# Third-party funding and scientific instrumentation support models during ODP

Throughout the term of ODP, many national ODP funding agencies, such as NSF, identified research funds that could be granted for downhole tools and experiments independent of the commingled membership contributions that supported basic ODP coring, drilling, and logging operations. It was this kind of funding that supported the acquisition of the scientific instrumentation deployed in the first CORKs, as well as any submersible operations required after installation from the drillship. This model held for all the CORK installations during ODP and appears to be continuing at the beginning of IODP. It has some advantages, as well as disadvantages that are essentially complexities that can be handled by good communication and close cooperation among the investigators, the drilling program managers and engineers, funding agencies, and the scientific advisory structure.

The greatest advantage of this support model was leveraging additional funding and scientific and technical expertise toward scientific objectives of both ODP programmatic priority and national scientific importance. The instrumentation installed in the ODP CORKs was not inexpensive, nor was it readily available off the shelf. The program could have afforded from commingled funds neither the instrumentation nor the associated technical expertise to develop the instrumentation; nor could it have provided the even more costly postinstallation submersible time. The division of funding and responsibilities has required a close level of coordination among those involved, particularly in two aspects.

First, obtaining the third-party support for the scientific instrumentation and submersible support has entailed a dual proposal process, with the proposal for national funding for the instrumentation being submitted as the associated proposal for the drilling operation neared or reached a scheduling decision in the science advisory structure. This obviously has required extra work on the part of proponents in preparing proposals. That this approach has been made to work reasonably well is due in large part to the cooperation and interest of the national funding program managers (e.g., the NSF ODP office in the majority of cases).

Second, for the dual-funding model to work, the division of cost, engineering, and acquisition responsibilities must be defined very clearly and as early as possible in the process. In the past, this has been made to work by frequent communication and close cooperation among the scientific proponents and program engineers. The division of responsibilities for the original CORK (Fig. F5) was fairly straightforward, as follows: Drawing on commingled ODP program funds, the drilling operator provided the reentry cone, casing, and CORK body; this could be defined as the seafloor and subseafloor "infrastructure" in which was hung the scientific instrument string that was provided by scientific proponents with added support from national sources of ODP research funding. As noted above, the national ODP research funding also provided the submersible time and funding for associated activities after initial deployment from the drillship. This model set a precedent that could be applied to the multilevel ACORK and CORK-II models, with some careful attention required so that nothing "fell between the cracks" in defining the difference between program-provided "seafloor and subseafloor infrastructure" and scientist-provided "instrumentation" in those more complicated designs. For the ACORK (Fig. F6), the program provided the reentry cone, ACORK casing, packers, umbilicals, and bridge plug; the proponents provided the pressure logging instrumentation on the wellhead and instrument string for the central bore from national ODP funding, which also supported the necessary submersible time after the drilling operations. For the CORK-II (Fig. F7), the program provided the reentry cone, cased hole, instrument hanger and 4½ inch casing, umbilical tubing, and seal plug on which the downhole OsmoSamplers were run; the scientific proponents applied for national ODP funding to provide the downhole samplers and temperature loggers, pressure logging instrumentation on the wellhead, and necessary submersible time. The wireline CORK (Fig. F8) was funded entirely by the NSF, although DSDP and ODP had invested years earlier in establishing the reentry holes.

The greatest disadvantage of the dual-funding/responsibility model is that the expertise and documentation for the instrumentation installed in the CORKs resides with scientists/proponents and their engineers and is therefore neither maintained centrally within the program nor easily made available by the program to other proponents. In addition, this means that the program does not maintain a central record of updated instrumental status in the various installations. In practice, proponents other than our group have provided successful CORK instrumentation. For example, scientists and engineers from IFREMER provided a sophisticated instrument string that worked very well in one of the 1994 CORK installations (but unfortunately that CORK body did not seal the hole). Another example is the thermistor string provided by scientists and engineers from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) for the Nankai ACORKs (but that string could not be installed because of operational problems with both ACORKs).

Generally, the support model described above, although somewhat complicated, has been made to work well with careful coordination among scientists, program engineers, and program managers. There have been a few exceptions, which have occurred mostly when program engineering support has been requested or expected for postinstallation submersible operations but was not specifically identified in relevant operator budgets from commingled funds; this reinforces the need in current and future installations for early and frequent communication among proponents, program engineers and managers, submersible support engineers, and funding program managers. Whether this kind of model should hold throughout IODP is currently under debate; with sufficient resources, improvements can certainly be made.

# Some concluding comments and opinions

## Importance of engineering support

We cannot overemphasize the critical importance to the overall ODP CORK effort of the support provided by three groups of engineers: those at the drilling operator, those associated with third-party instrumentation, and those associated with the submersible operators. The contributions of these engineers have been central to the scientific success of the CORK effort and are too important to merely list in a traditional acknowledgments section (as is done below). As has been alluded to earlier, the overall funding structure and support models for ODP allowed for the drilling operator to provide the engineering support for the original installations from commingled program funds, but only for limited postinstallation submersible activities and not for the scientific instrumentation. As IODP began, a similar support model was applied for the Expedition 301 installations (**Fisher et al.,** this volume), but if IODP is to embrace observatory science and serve a wider scientific community, as described in the Initial Science Plan, better support models are probably needed (e.g., see Fisher and Brown, 2004). It is not yet fully clear how support for IODP borehole observatory efforts is going to be supplied via a more complex IODP management structure involving a central management organization (IODP Management International) and three implementing organizations as drilling operators. In an ideal world, the IODP program (via IODP Management International and the implementing organizations) would have sufficient program resources to support all the necessary engineering for borehole observatories, the associated instrumentation, and all postinstallation submersible operations. But this may be unrealistic to expect immediately given programmatic fiscal constraints, so some elements of the support model developed for ODP CORKs will probably remain important in the short term.

## "Standard" CORK models for IODP?

At the beginning of IODP, there have been calls for the program to "standardize" on a few CORK models for IODP use in something akin to off-the-shelf mode and/or to provide a "primer" with a straightforward decision tree for selecting the model appropriate for given objectives. This has been motivated both from a program planning and budgeting perspective (partly to minimize the needs for new engineering support discussed above) and to assist a new generation of investigators in proposing sealed-hole hydrogeological monitoring experiments. Although these are laudable objectives, we are not sure it is useful to "standardize" beyond the basic configurations described in **"CORK design summaries"** for several reasons. These include

- The inherent flexibility in most of those basic configurations to tailor the instrumentation capabilities to the objectives (e.g., the modified CORK-II described by **Fisher et al.,** this volume),
- The fact that IODP does not currently provide commingled program funding for the instrumentation or submersible time,
- The perspective developed in **"A few scientific lessons learned and challenges for the future"** that each design and instrumental advance has brought important new observations, and
- That "standardizing" could stifle initiatives to develop even more capable configurations of sealed-hole observatories.

At least two current examples of the last include an effort to marry long-term seismic monitoring capabilities with the formation-pressure monitoring CORK capabilities and an effort to design a simpler single-zone pressure-only monitoring installation that can be deployed in spatial arrays in both a time- and cost-effective manner. Thus, it is not clear to us whether scientific creativity would be served by standardizing on a few fixed models.

Nevertheless, the basic configurations described in "CORK design summaries" will probably serve as a basis for a majority of applications. Where monitoring a single zone is the objective, if the necessary instrumentation can be made at diameters of <3.75 inches, then minor modifications of the original single-seal CORK design would provide a well-proven and both time- and cost-effective technology, and the programmatic responsibilities could be assessed and budgeted in straightforward fashion. Where monitoring from multiple depth zones is the objective, options include the ACORK, CORK-II, or even closely spaced arrays of original CORKs, each extending to different depths. Where monitoring in a preexisting reentry hole is the objective, the wireline CORK is an option that does not require use of a drillship, and options from a drillship would include a single-seal original CORK or multilevel CORK-II. Choosing among these options depends on a variety of operational factors and on balancing programmatic cost considerations against scientific objectives. With respect to programmatic costs, we note here only that the ACORK may be perceived as much more expensive than other options, but that is partly because the ACORK itself comprises the main casing string; when true casing costs are added to the other designs, the cost differential is reduced considerably. Even if cost considerations are not the limiting factor, only a few easy rules can be developed. For example, if the prime objective is sampling formation fluids, especially in basement, then the CORK-II concept may be more suitable than the ACORK. On the other hand, if the prime objective is monitoring profiles of physical parameters like pressure, especially through a long sedimentary section, then the ACORK concept may be more appropriate. However, these are intended only as examples, not as fixed rules appropriate for every setting. The only easy conclusion is that the choice of a configuration must rely on careful consideration of specific scientific objectives and site-specific geological and operational constraints.

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# Appendix

## CORK publications—November 2004

### I. Primary hardware descriptions

Davis, E.E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., 1992. CORK: a hydrologic seal and downhole observatory for deep-ocean boreholes. *In* Davis, E.E., Mottl, M.J., Fisher, A.T., et al., *Proc. ODP, Init. Repts.,* 139: College Station, TX (Ocean Drilling Program), 43–53.

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### II. Primary CORK results

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**Figure F1.** Location map of all ODP-era original and multilevel CORK installations. Topography by W.H.F. Smith and D.T. Sandwell.

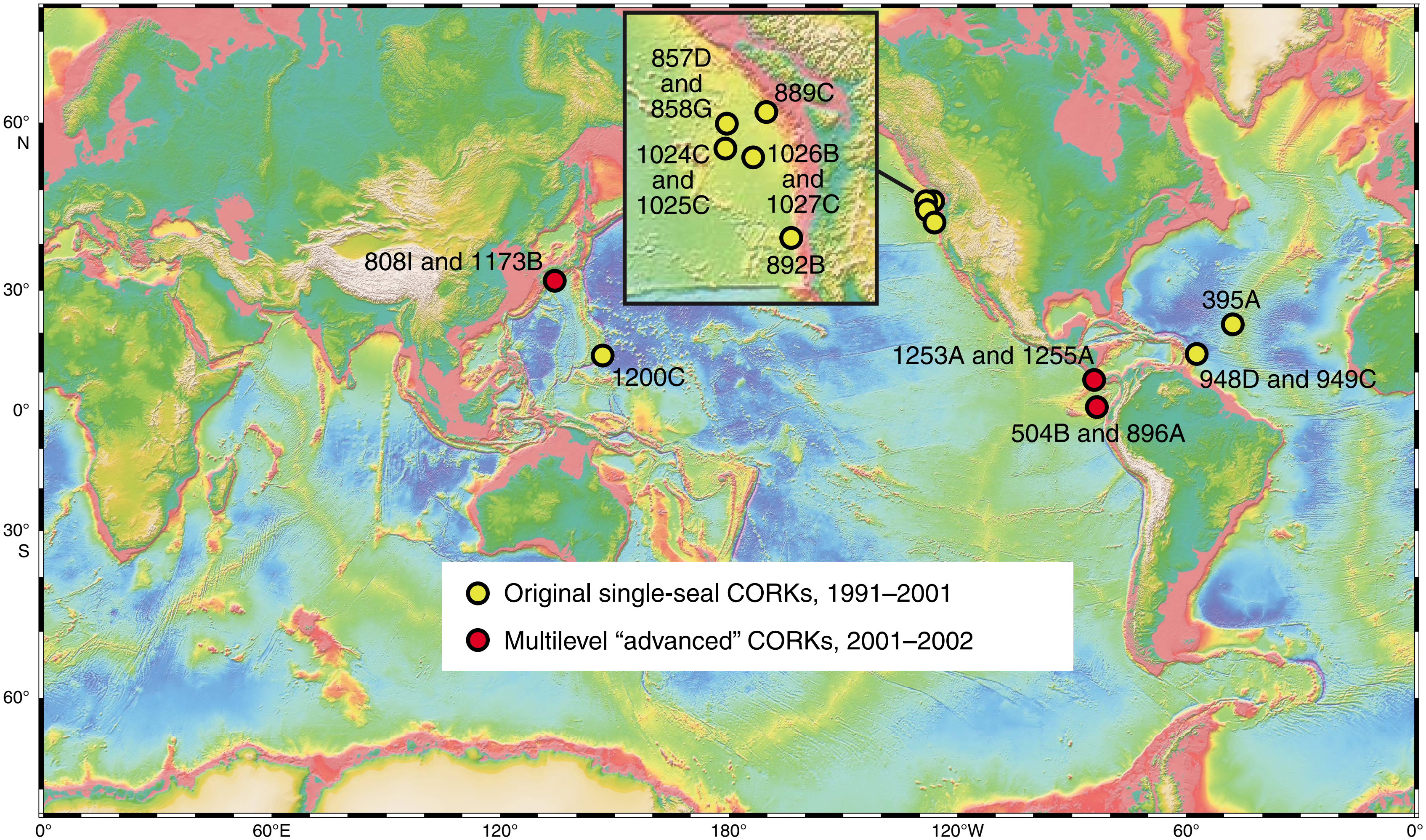

**Figure F2.** Early conceptual sketch of the instrumented borehole seal, drawn 2 months after an October 1989 meeting of ODP engineers, B. Carson, and the authors. This sketch was then used as the primary illustration in a winter proposal to the Geological Survey of Canada and a February 1990 proposal to the National Science Foundation for the associated instrumentation costs for the first CORK installations during the summer of 1991.

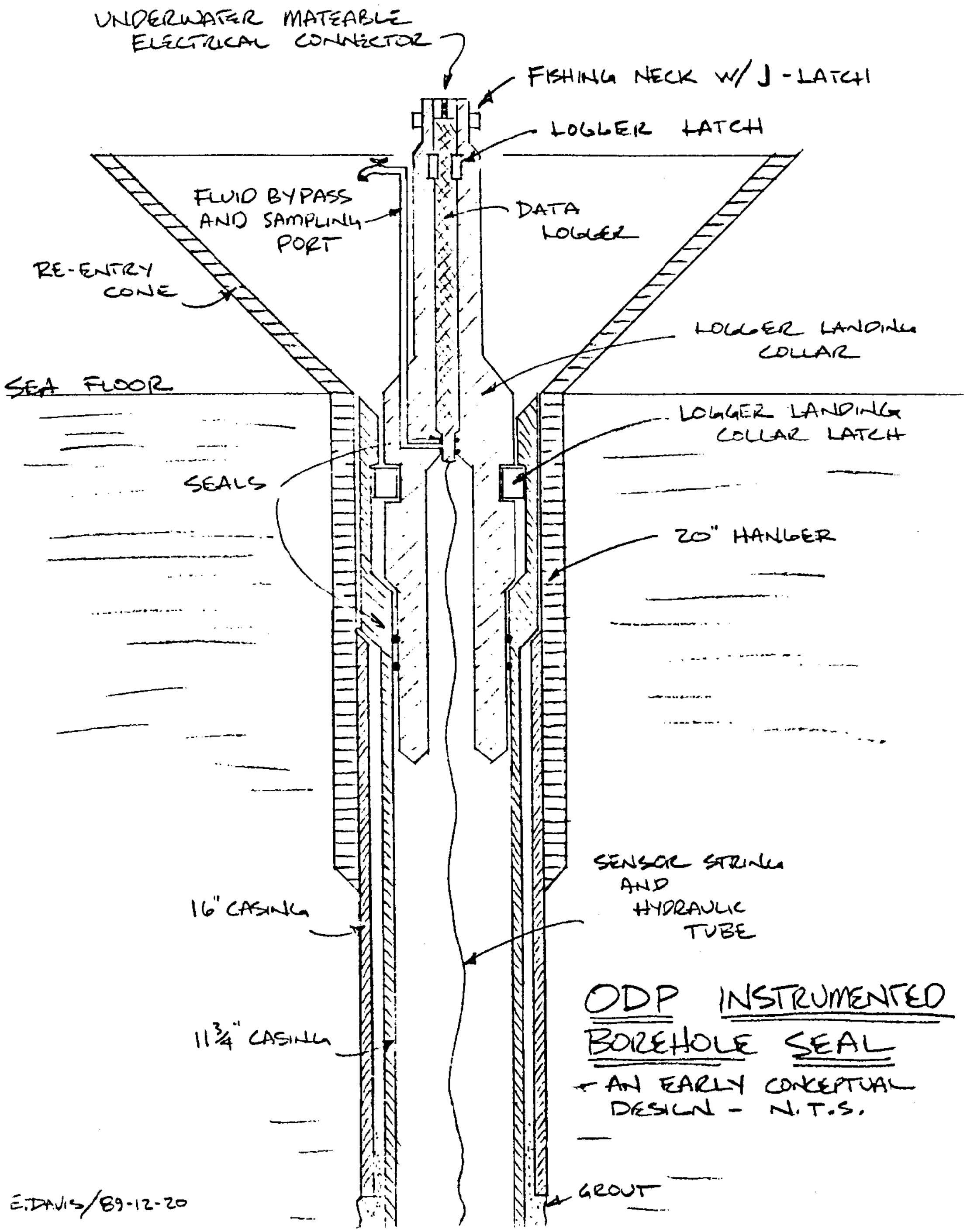

**Figure F3.** Schematic CORK hydrogeological observatory and summary of scientific objectives.

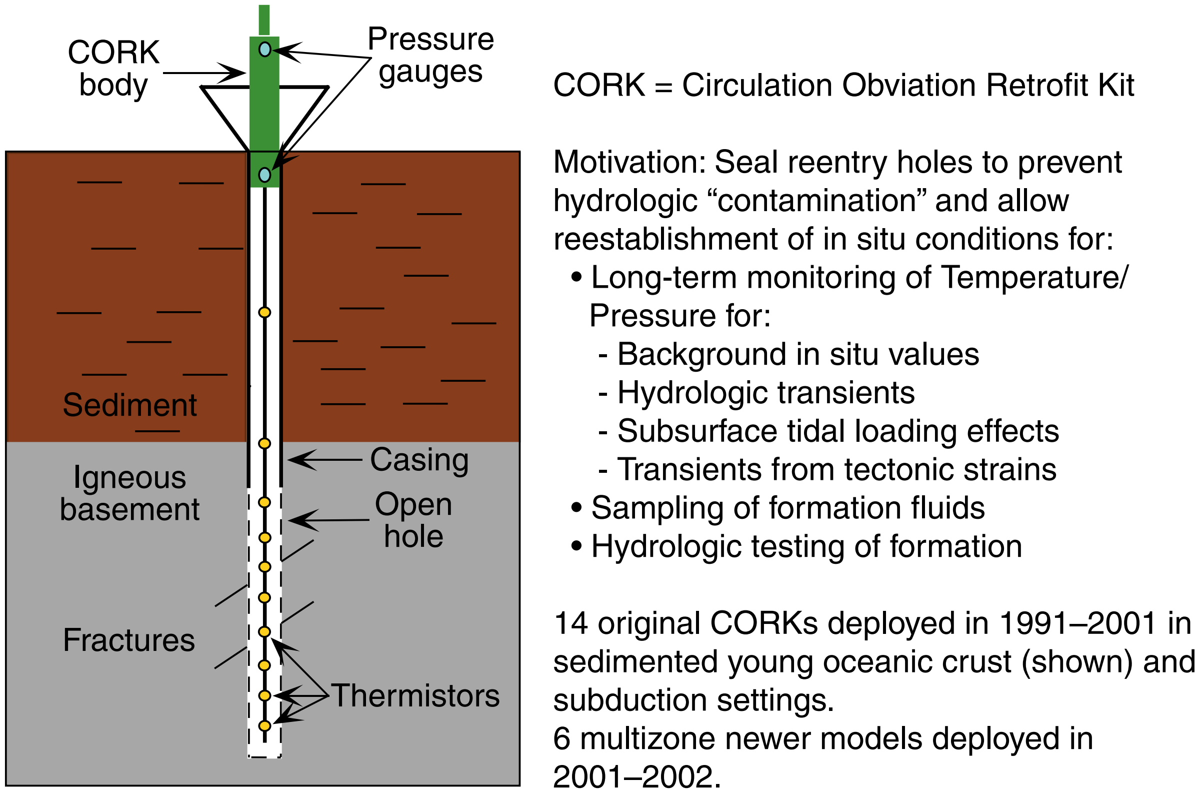

**Figure F4.** Generic multilevel monitoring objectives in an accretionary prism and ocean crust (from Becker and Davis, 1998).

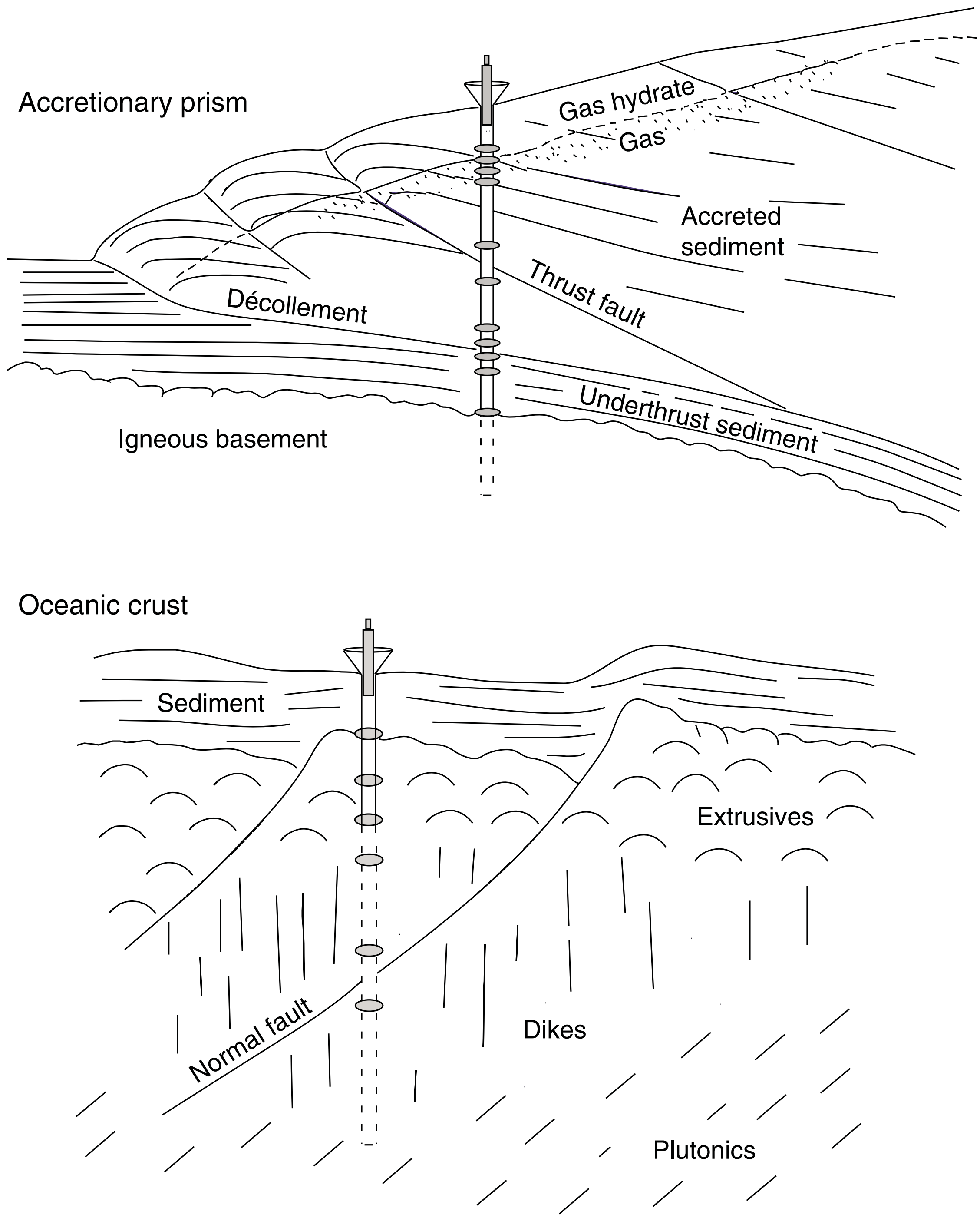

**Figure F5.** Engineering schematic of the single-seal CORK design (from Graber et al., 2002). Red = CORK body, blue = scientific instrument string. ROV = remotely operated vehicle.

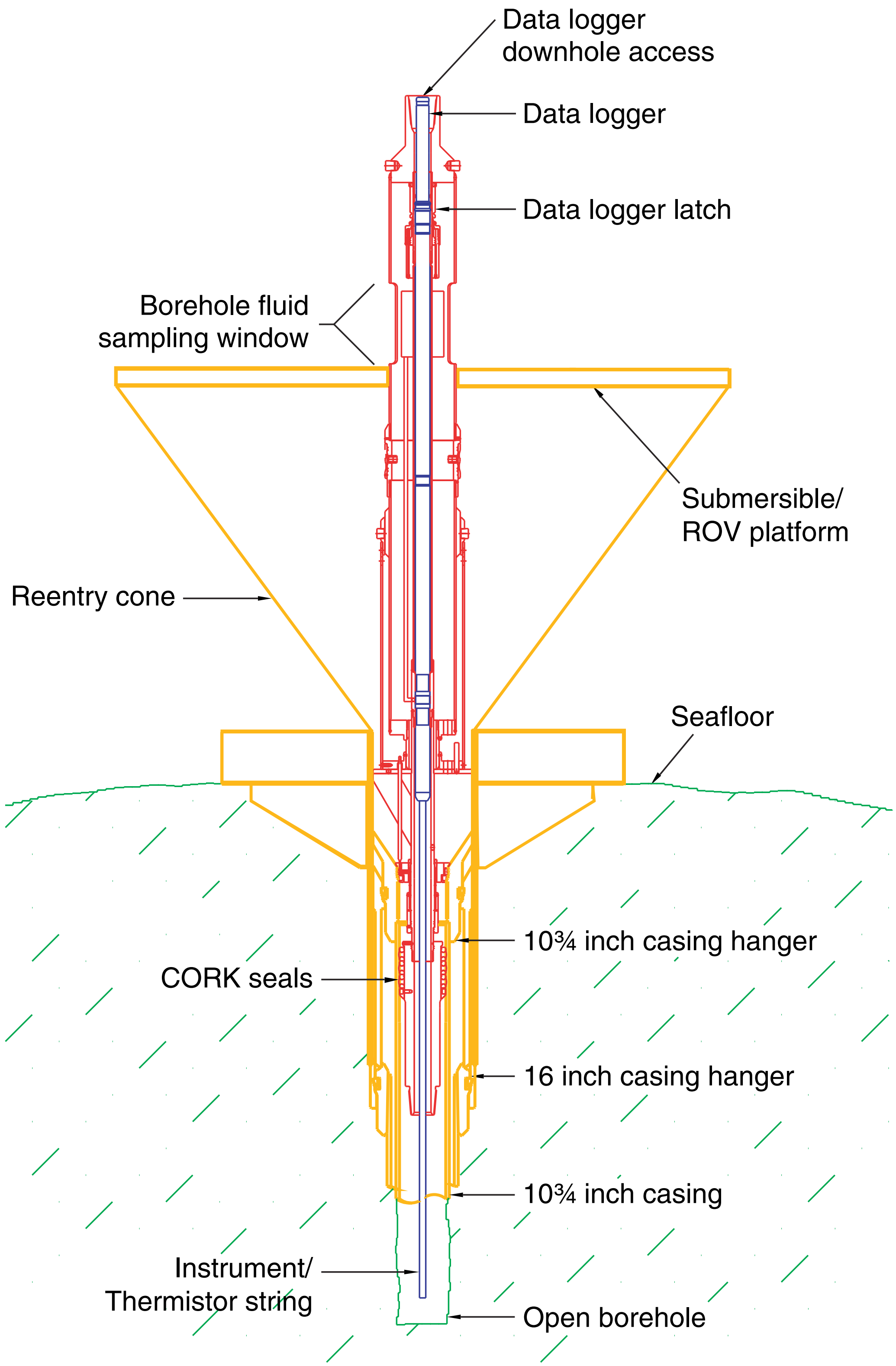

**Figure F6.** Engineering schematic of the Advanced CORK (ACORK) design (from Graber et al., 2002). ROV = remotely operated vehicle.

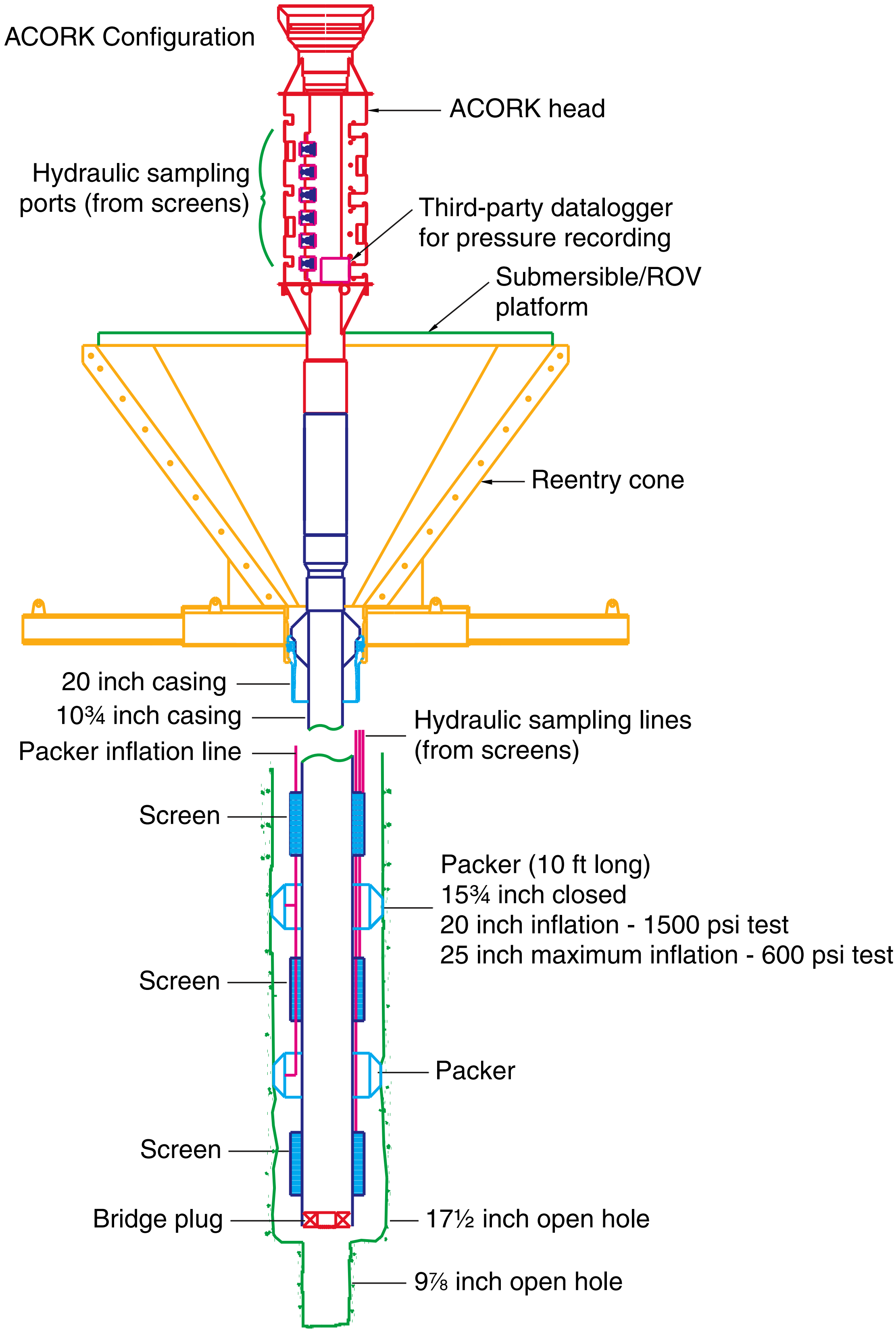

**Figure F7.** Schematic of the CORK-II as installed at the Costa Rica Margin (from Shipboard Scientific Party, 2003). ROV = remotely operated vehicle. TD = total depth.

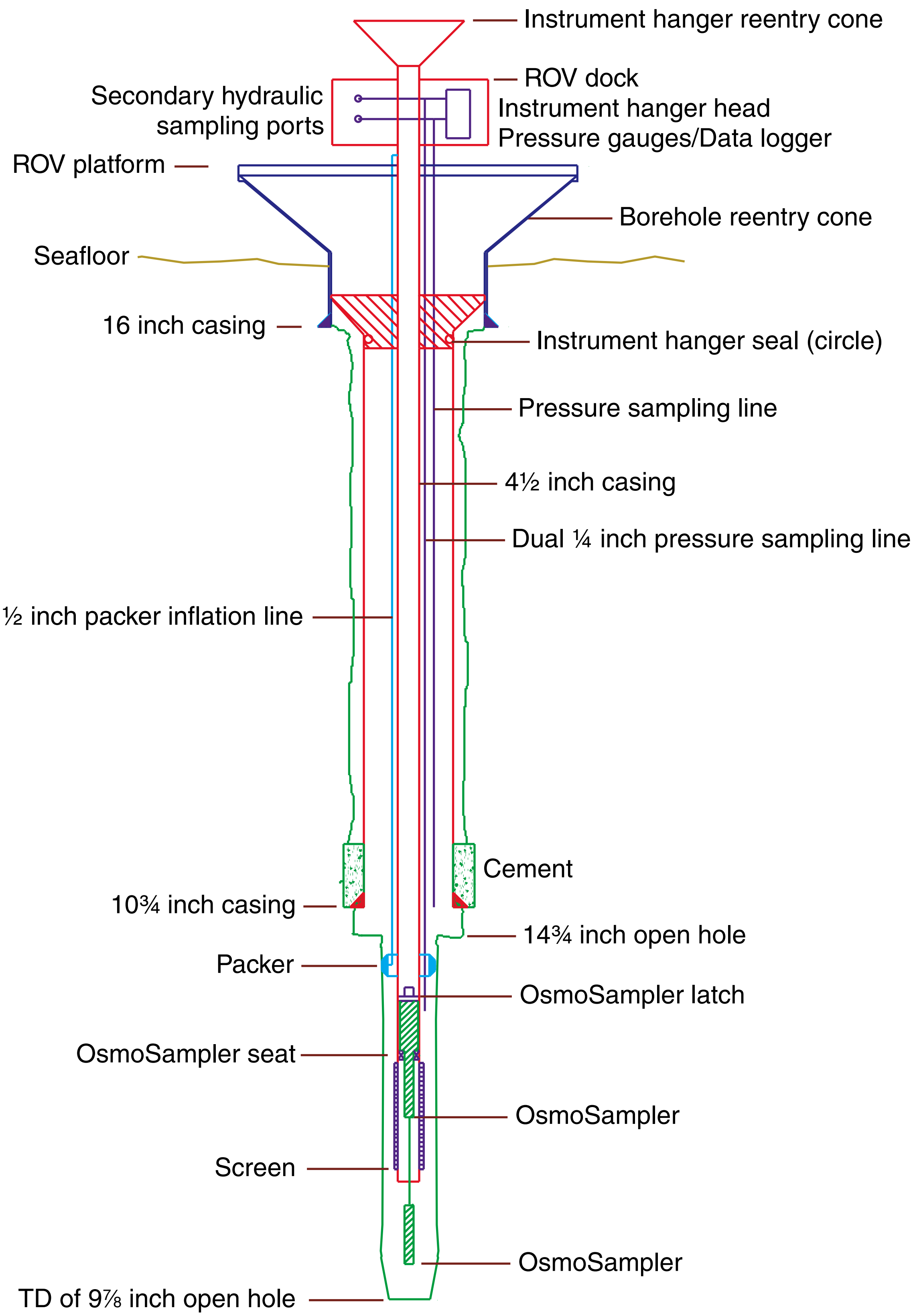

**Figure F8.** Schematic of the wireline instrumented multipacker system or wireline CORK.

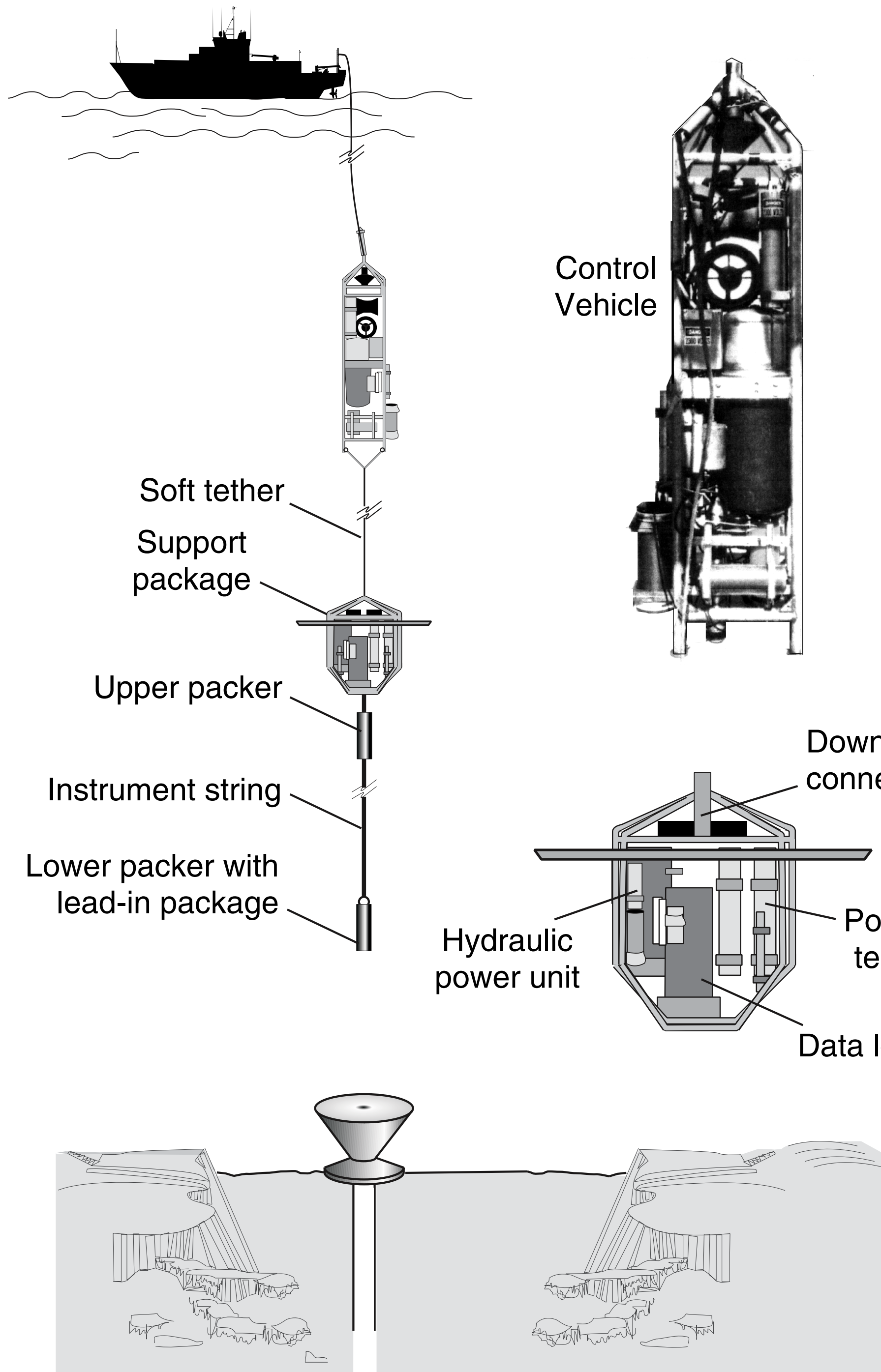

**Table T1.** Summary of site characteristics, ODP CORK installations.

| Leg/Hole | Setting | Position | Water depth (m) | Penetration (m) (sediment/casing/total) | Type | Operational period |
|---|---|---|---|---|---|---|
| 139/857D<br>169/857D | Middle Valley sedimented spreading center | 8°26′N, 128°43′W | 2432 | 470/574/936 | CORK | 1991–1992;<br>1996–present |
| 139/858G<br>169/858G | Middle Valley | 48°27′N, 128°43′W | 2426 | 258/274/433 | CORK | 1991–1993;<br>1996-2000? |
| 146/889C | Cascadia prism (Vancouver Island) | 48°42′N, 126°52′W | 1326 | 385/259 (liner to 323)/385 | CORK | 1992–1993 |
| 146/892B | Cascadia prism (Oregon) | 44°41′N, 126°07′W | 684 | 178/94 (liner to 146)/178 | CORK | 1992–1994 |
| 156/948D | Barbados prism | 15°32′N, 58°44′W | 4949 | 538/535/538 | CORK | 1994–1995 |
| 156/949C | Barbados prism | 15°32′N, 58°43′W | 5016 | 468/466/468 | CORK | 1994–1998 |
| 168/1024C | JFR east flank (1.0 Ma) | 47°55′N, 128°45′W | 2612 | 152/166/176 | CORK | 1996–1999;<br>2000–present |
| 168/1025C | JFR east flank (1.2 Ma) | 47°53′N, 128°39′W | 2606 | 101/102/148 | CORK | 1996–1999;<br>2000–present? |
| 168/1026B | JFR east flank (3.6 Ma) | 47°46′N, 127°46′W | 2658 | 247/248/295 | CORK | 1996–1999<br>2004–present |
| 168/1027C | JFR east flank (3.6 Ma) | 47°45′N, 127°44′W | 2656 | 613/578/632 | CORK | 1996–present |
| 174B/395A | MAR west flank (7.3 Ma) | 22°45′N, 46°05′W | 4485 | 92/111/664 | CORK | 1997–present |
| 195/1200C | Mariana forearc | 13°47′N, 146°00′E | 2932 | —/202/266 | CORK | 2001–2003 |
| 196/1173B | Nankai Trough | 32°15′N, 135°02′E | 4790 | 1058/927/1058 | ACORK | 2001–present |
| 196/808I | Nankai Trough | 32°21′N, 134°57′E | 4676 | 731/728/756 | ACORK | 2001–present |
| —/504B | CRR south flank (5.9 Ma) | 01°14′N, 83°44′W | 3474 | 275/276/2111 | Wireline | 2001–2002 |
| —/896A | CRR south flank (5.9 Ma) | 01°13′N, 83°43′W | 3459 | 179/191/469 | Wireline | — |
| 205/1253A | Costa Rica Trench | 09°39′N, 86°11′W | 4376 | 400/506/600 | CORK-II | 2002–present |
| 205/1255A | Costa Rica Trench | 09°39′N, 86°11′W | 4309 | 153/144/153 | CORK-II | 2002–present |

Note: JFR = Juan de Fuca Ridge, MAR = Mid-Atlantic Ridge, CRR = Costa Rica Rift.

**Table T2.** Summary of instrumentation originally installed in ODP CORKs.

| Leg/Hole | Type/Year | Pressure | Temperature | Fluid sampling | Data logger | Comments |
|---|---|---|---|---|---|---|
| 139/857D<br>139/858G | CORK/1991 | P1 | 20-conductor cables by CCC, with thermistors assembled by CCC | 1/2 inch FEP tubing on temperature string<br>1/2 inch PFA tubing on temperature string | RBR 12 bit temperature, 24 bit pressure, 1 h sampling | Thermistor cables and sample tubing failed early at high temps |
| 146/889C<br>146/892B | CORK/1992 | P1 | 20-conductor CCC cable with specified breakouts, thermistors assembled by PIs in grease-filled Teflon capsule (5 × 5/8 inch diameter) | None | RBR 12 bit temperature, 24 bit pressure, 12 bit tilt, 1 h sampling | Most sensors failed on deployment in bad weather<br>Cable folded 4 times for short hole; worked well until failure at 1.5 y when hydrates froze in hole |
| 156/948D | CORK/1994 | Integrated string with 3 PaineR gauges + 20 Pt RTD sensors, all with serial transmission of digital signals | | None | Institut Francais de Recherche pour l'Exploration de la Mer, 1 h sampling | String worked well but CORK body did not seal |
| 156/949C | CORK/1994 | P2 | 20-conductor CCC cable; 10 thermistors in OD "GEO-01-01" epoxy casting attached by PIs | 1 downhole OS | RBR 12 bit temperature, 24 bit pressure, 1 h sampling | Long cable folded twice to fit shorter hole; sensors failed below second fold; OS unit never recovered |
| 168/1024C<br>168/1025C<br>168/1026B<br>168/1027C | CORK/1996 | P2 | 10-thermistor NT cable with MAW-2 connectors molded at breakouts; thermistors molded by SC in MAW-2 connectors assembled by PIs | 1 downhole OS near bottom of each cable | RBR 13 bit temperature, 24 bit pressure, 1 h sampling except for brief periods at higher rates | 3 cables field-shortened by reterminating at top; cables worked well; 2 OS units recovered in 1999 but hole collapsed around other 2 OS units |
| 169/857D<br>169/858G | CORK/1996 | P2 | Cables as for 1992 CORKs in Holes 889C/892B | None | RBR 13 bit temperature, 24 bit pressure, 1 h sampling except for brief periods at higher rates | Cables failed within months due to high temps |
| 174B/395A | CORK/1997 | P2 | Cables as for 1996 CORKs in Holes 1024C/1025C/1026B/1027C | None | RBR 13 bit temperature, 24 bit pressure, 1 h sampling except for brief periods at higher rates | Borehole pressure readings flawed in least significant bits for undetermined reasons |
| 195/1200C | CORK/2001 | P2 | Recycled cable recovered from Hole 1024C in 1999 | 2 downhole OS | RBR 13 bit temperature, 24 bit pressure, 1 h sampling except for brief periods at higher rates | Cable folded multiple times; most conductors failed; OS units recovered 2003 |
| 196/1173B<br>196/808I | ACORK/2001 | P6<br>P7 | None | 1 special 1/8 inch stainless steel tube to manifold | RBR no temperature, 24 bit pressure, 10 min sampling | Instrumentation working well despite other installation flaws |
| —/504B<br>—/896A | Wireline CORK/2001<br>*Roger Revelle* | P2<br>P3 | 36-conductor cabling by South Bay Cable; OD encapsulated thermistors installed by PIs | Special hydraulic tubing to manifold | RBR 24 bit temperature at 1 h sampling, 24 bit pressure at 10 min sampling | 504B installation worked well; logging at both sites terminated at ~1 y for unclear reasons (seawater leakage?) |
| 205/1253A<br>205/1255A | CORK-II/2002 | P3 | Memory temperature loggers by Antares | 2 downhole OS<br>1 downhole OS | RBR 24 bit seafloor temperature at 1 h sampling, 24 global bit pressure at 10 min sampling | OS and Antares units recovered and replaced 2004; worked well |

Notes: For pressure monitoring in single-seal CORKs: P1 = single Paroscientific Digiquartz gauge in sealed interval, P2 = P1 plus second Paroscientific Digiquartz gauge for seafloor reference. For later multizone models: P# = seafloor reference gauge plus n = # – 1 Paroscientific Digiquartz gauges on seafloor manifold registering pressures of n zones. CCC = Cortland Cable Co., RBR = Richard Brancker Research, Ltd., NT = Neptune Technologies, OD = Ocean Design Inc., SC = Brantner/SeaCon. FEP and PFA are grades of Teflon. OS = OsmoSampler.

**Table T3.** Chronology of submersible operations at CORKs installed during the ODP period.

| Year/Month | Holes | Cruise | Submersible dives | Funding | Operations/Comments |
|---|---|---|---|---|---|
| 1991/Sep | 857D, 858G | AII-125-32 | *Alvin* 2457, 2458 | NSF | Successful data downloads shortly after installation of first CORKs; pressures recording well but thermistor cables already degrading at very high temperatures (>260°C) |
| 1991/Oct | 858G, 858F | AII-125-33 | *Alvin* 2468 | NSF | Attempt to seal pilot Hole 858F ~5 m from Hole 858G |
| 1992/Sep | 858G | Tully/Vents 2 | *ROPOS* (1 dive) | GSC | Data download in Hole 858G |
| 1993/Sep | 892B | AII-131-3 | *Alvin* 2651, 2653, 2654 | NSF | Fluid sampling, pump tests, data downloads |
| 1993/Sep–Oct | 857D, 858G, 889C, 892B | AII-131-4 | *Alvin* 2664–2669 | NSF | Data download in Hole 858G showed CORK seal failed, hole producing hot fluids. Attempt failed to recover Hole 857D logger damaged during Leg 146 refurbishment attempt in poor weather. Data download in Hole 889C showed severe damage due to Leg 146 installation in poor weather. Attempted acoustic modem installation and pump test in Hole 892B |
| 1994/Aug | 892B | AII-131-18 | *Alvin* 2813 | NSF | Final download in Hole 892B |
| 1995/Jul | 892B | AII-132-10 | *Alvin* 2964–2965 | NSF | Recovered data logger from site, breaking off cable assembly frozen in the hole by hydrates |
| 1995/Dec | 948D/949C | Nadir/ODPNaut I | *Nautile* (6 dives) | IFREMER + NSF | Data downloads and pump tests at both sites; recovered instrument string from Hole 948D with flotation when data showed CORK body not sealed |
| 1997/Oct | 857D, 858G, 1024C–1027C | AT-03-8 | *Alvin* 3144, 3146, 3148–3151 | NSF | Data downloads at six CORKs; installation of microbiological sampling devices on seafloor valve in Hole 1026B |
| 1998/Jan | 949C, 395A | Nadir/ODPNaut II | *Nautile* (3 dives) | NSF | Completion of pump tests in Hole 949C (seal compromised); data download in Hole 395A |
| 1998/Jun | 892B | AT-03-21 | *Alvin* 3231–3233 | NSF | Use of Hole 892B wellhead (no data logger) for hydrates/geochemistry experiments |
| 1998/Jul | 1026B | AT-03-23 | *Alvin* 3240, 3241 | NSF | Recovery and deployment of microbiological sampling devices |
| 1999/Jun | 892B | AT-03-35 | *Alvin* 3416, 3417 | NSF | Use of Hole 892B wellhead for hydrates/geochemistry experiments |
| 1999/Sep | 857D, 858G, 1024C–1027C | AT-03-39 | *Alvin* 3465–3467, 3469, 3471–3473, 3475–3477, 3479, plus MPL control vehicle | NSF | Data downloads at six sites, recovery of sensor strings and OsmoSamplers in Holes 1024C–1027C, reinstrumentation with pressure-logging systems, fluid sampling in Hole 1025C and 1026B wellheads; cut short by weather and operational difficulties |
| 2000/Aug | 857D, 1024C–1027C | AT-03-55 | *Alvin* 3600, 3603–3609 | NSF | Recovery of hydrates/geochemistry apparatus in Hole 892B; completion of AT-03-39 objectives in Holes 1024C–1027C; data download in Hole 857D but Hole 858G not responding |
| 2001/Jul | 395A | AT-05-03 | *Alvin* 3671 | NSF | Data download |
| 2002/Aug | 808I, 1173B | KR02-10 | *Kaiko* 261, 262, 264, 266 | JAMSTEC | Data download, close valves apparently opened by vibrations on Leg 196 deployment |
| 2002/Sep | 1026B | AT-7-20 | *Jason* 2 | NSF | Fluid and microbiological sampling in Hole 1026B |
| 2002/Nov | 504B, 896A, 1253A, 1255A | AT-07-25 | *Alvin* 3840, 3841 | NSF | Download data, verify that packers had inflated in Holes 1253A and 1255A |
| 2003/Mar | 1200C | Thompson | *Jason* 2 | NSF | Download data, recover OsmoSamplers and sensor string |
| 2003/May | 808I | KR03-05 | *Kaiko* 296 | JAMSTEC | Deploy submersible-operated bridge plug to seafloor in Hole 808I and download data; *Kaiko* lost on recovery from dive and cruise aborted |
| 2003/Jun | 857D, 1024C, 1025C, 1027C | Thompson | *Jason* 2 | NSF | Download data (Hole 1025C did not respond); install supplemental battery packs in Holes 857D and 1024C |
| 2003/Jul | 1026B | Thompson | *Jason* 2 | NSF | Fluid and microbiological sampling in Hole 1026B |
| 2004/Feb–Mar | 1253A, 1255A | AT-11-08 | *Alvin* 3977–3984 | NSF | Download pressure data, attempt to recover OsmoSamplers (later done from *JOIDES Resolution*, summer 2004) |
| 2004/May | 808I, 1173B | YK04-05 | *Shinkai* 6500 812, 813 | JAMSTEC | Download pressure data, insufficient dive time to install bridge plug in Hole 808I, so it was recovered |
| 2004/Sep | 1026B, 1027C, 1301A, 1301B | Thompson | *ROPOS* | NSF + GSC | Download pressure data in Hole 1027C; install pressure data logging systems in Holes 1026B, 1301A, and 1301B (see Fisher et al., this volume) |

Notes: NSF = U.S. National Science Foundation, GSC = Geological Survey of Canada, IFREMER = Institut Francais de Researche pour l'Exploration de la Mer, JAMSTEC = Japan Agency for Marine-Earth Science and Technology.