Wireline Coring and Analysis under Pressure: Recent Use and Future Developments of the HYACINTH System

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Introduction

The pressure of the deep sea and of deep earth formations has subtle effects on all aspects of physics, chemistry, and biology. Core material recovered under pressure, using pressure cores, can be subjected to sophisticated laboratory analyses that are not feasible *in situ*. Though many fields of study might benefit from pressurized cores, most obviously, any investigation on gas- or gas-hydrate-rich formations on land or under the sea certainly requires pressure coring.

Downhole Pressure Coring and HYACINTH

Scientific investigations of marine gas hydrate formations have provided the impetus for all wireline pressure core development apart from proprietary oilfield technology, including the HYACINTH (HYACe In New Tests on Hydrate, 2001) system. The first scientific wireline pressure corer, the Pressure Coring Barrel, was developed by the Deep Sea Drilling Project to capture gas hydrate. It was used by Kvenvolden et al. (1983) in depressurization and gas collection experiments to quantify gas hydrate within cores. The Ocean Drilling Program (ODP) later developed the Pressure Core Sampler (PCS; Pettigrew, 1992; Graber et al., 2002), and the Pressure-Temperature Coring System (PTCS) was developed for Japan Oil, Gas and Metals National Corporation (JOGMEC, formerly Japanese National Oil Company, JNOC; Takahashi and Tsuji, 2005). Both of these systems were used almost exclusively for gas hydrate research. The HYACE (HYdrate Autoclave Coring Equipment, 1997) and the subsequent HYACINTH programs (Schultheiss et al., 2006; Schultheiss et al., 2008a), funded by the European Union, were also driven by the need for gas hydrate research.

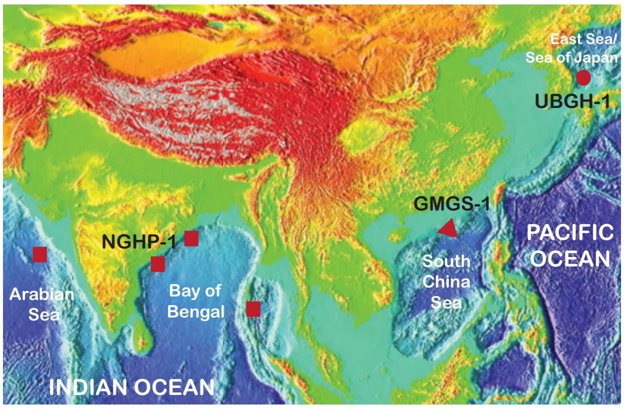

Figure 1. Map of South and Southeast Asia (based on http://www.ngdc.noaa.gov/mgg/image/2minrelief.html) showing the location of recent gas hydrate expeditions NGHP-1 (red squares), GMGS-1 (red triangle), and UBGH-1 (red circle).

The HYACINTH vision of scientific pressure coring encompassed not only coring tools but also an array of downstream core processing equipment and capabilities. The two coring tools, the Fugro Pressure Corer (FPC) and the Fugro Rotary Pressure Corer (FRPC; previously HYACE Rotary Corer, HRC), were designed to recover high-quality cores in a complete range of sedimentary formations. The combined suite of equipment (the HYACINTH system) enables these cores to be acquired and transferred in their core liners from the pressure corers into chambers for non-destructive testing, sub-sampling, and storage as required.

The HYACINTH system has continually improved over the ten years since its inception. ODP and the Integrated Ocean Drilling Program (IODP) have played major roles in this development, allowing the tools to be initially tested (ODP Legs 194 and 201) and then used on both recent gas hydrate expeditions (ODP Leg 204, Hydrate Ridge, offshore Oregon; Tréhu et al., 2003; IODP Expedition 311, Cascadia Margin, offshore Vancouver Island, Canada; Riedel et al., 2006). Since that time, further improvements to the performance and capabilities of the coring and analysis assemblies have been made, and the system has allowed new scientific insights into the structure of natural marine gas hydrate deposits.

Recent HYACINTH Expeditions

Since the completion of IODP Expedition 311 in 2005, the HYACINTH system has been used on four major gas hydrate expeditions for quantification of gas hydrate and detailed measurements on gas-hydrate-bearing sediments. The need to assess the nature, distribution, and concentration of gas hydrate in the marine environment has multiple driving forces. Scientific interest in gas hydrate centers on carbon cycling and climate impact, but to the oil and gas industry hydrate is an irritating geohazard, and to national governments it is a potential resource ripe for exploitation. Political climate change has made national energy independence a high priority for governments, and in the last few years, the biggest financial input into marine gas-hydrate-related drilling expeditions has come from national governments and their associated national energy and geological organizations. Of the four recent expeditions since IODP Leg 311 on which the HYACINTH coring and analysis system has been used, one was to define geohazards related to oil and gas production, and three were to quantify resources for the governments of India, China, and Korea.

India, 2006

The first Indian National Gas Hydrate Program drilling expedition (NGHP-1; Fig. 1) took place on the drillship *JOIDES Resolution* in the summer of 2006, led by the Indian Directorate General of Hydrocarbons (DGH) and the United States Geological Survey (USGS). It was designed to investigate the gas hydrate resource potential of sites around the Arabian Sea, the Bay of Bengal, and the Andaman Sea (Collett et al., 2006). This was an ambitious program, lasting 113 days, involving over a hundred scientists and technical staff from India, Europe, and the United States, and drilling thirty-nine locations at twenty-one distinct sites. It was a hugely successful program, collecting more gas-hydrate-bearing cores than any previous expedition and describing in detail at multiple scales one of the richest gas hydrate accumulations ever discovered (Collett et al., 2008).

As part of the coring program, forty-nine pressure cores were recovered under pressure and analyzed at sea and postcruise. These included IODP PCS cores as well as HYACINTH FPC and HRC/FRPC cores. The onboard pressure core analysis included routine core measurement of all pressure cores in the HYACINTH Pressure Core Analysis and Transfer System (PCATS). All nondestructive data was collected at *in situ* pressure. The analytical portion of the PCATS is designed to measure continuous profiles of P-wave velocity and gamma density at *in situ* pressure and temperature conditions on HYACINTH pressure cores, as well as collect high-resolution 2D X-ray images (Fig. 2). To perform these analyses, the PCATS extracts the lined cores from the HYACINTH corer autoclaves under pressure and moves them past the sensors. The PCATS was modified to accept PCS corer autoclaves. As the PCS core could not be extracted under pressure, only gamma density and X-ray images could be collected on these cores and at a reduced resolution.

The X-ray images collected from pressure cores taken in the Krishna-Godavari Basin showed hydrate structures with remarkable complexity and in unprecedented detail (Fig. 2A). Cores were rotated in the PCATS to understand their three-dimensional nature. Less dense (lighter) patches in the original X-ray (Figs. 2A, 2C) are dipping veins of gas hydrate when seen from a perpendicular view (Fig. 2D). The P-wave velocity and gamma density profiles also reflect this anisotropy. In the first data set (Fig. 2C), the profiles were taken perpendicular to (through) the major gas hydrate veins, and a slight lowering of density and a smooth increase in P-wave velocity is seen in the area of greatest gas hydrate concentration (Fig. 2C). In the second data set (Fig. 2D), the

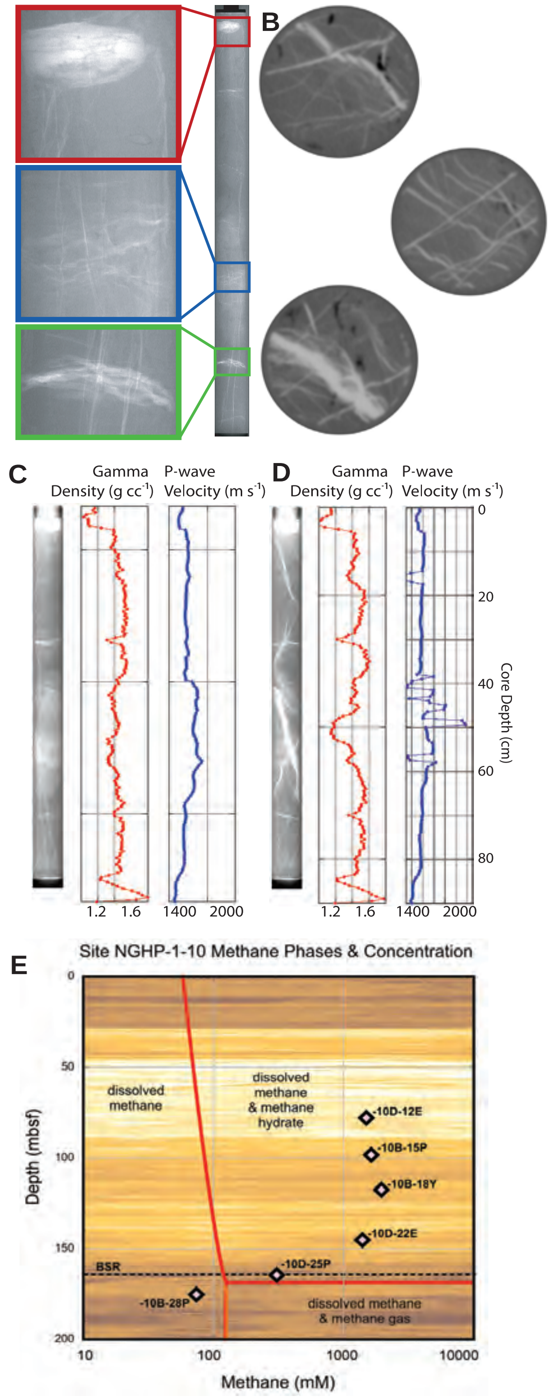

Figure 2. Data from a HYACINTH FPC core obtained on NGHP Exp. 1 using the PCATS and a medical CT scanner, and methane concentration data from the same site obtained from pressure cores. All data and images from Collett et al., 2008. In the X-ray images, denser features (carbonate nodules) are dark; less dense features (gas hydrate veins) are light. [A] X-ray image with enlargements showing different gas hydrate morphologies (nodules, lenses, veins) in fine-grained sediment. [B] Horizontal X-ray computed tomographic slices of the same pressure core showing the complexity of cross-cutting gas hydrate vein features present in this clay core. [C] and [D] Two sets of PCATS data (X-ray images, P-wave, and gamma density profiles) collected at right angles to each other on the same pressure core. [E] Logarithm of methane concentration vs. depth, plotted over phase boundaries for Structure I methane hydrate (calculated after Xu, 2002, 2004). Background image is resistivity-at-bit data (lighter=more resistive) collected in a nearby hole. Dashed line is extrapolated depth of seismic Bottom-Simulating Reflector (BSR) which agrees closely with the calculated thermodynamic Base of Gas Hydrate Stability (BGHS) as indicated by the solid horizontal line of the phase diagram.

profiles are taken parallel to (along) the major gas hydrate veins, showing low-density zones and a complex P-wave velocity profile. Some extreme values are artifacts caused by pulse interference effects from hydrate structures.

A decision was made to hold five of these cores for additional, more detailed shore-based investigations. The morphology of the gas hydrate within this clay-hosted deposit is worth extended study, not only to explain the mechanisms of gas hydrate growth in fine-grained sediments but also to predict the sediment behavior during gas hydrate dissociation. Models predicting the behavior of such gas-hydrate-bearing sediments during dissociation, whether for well-bore stability, geohazard assessment, or potential methane gas production, are certainly dependent on the small-scale spatial relationship in the sediment. X-ray computed tomography (CT) scans showed that the fine-grained sediments hosted a complex gas hydrate vein network (Fig. 2B). The pressure cores were individually transferred into the Instrumented Pressure Testing Chamber (IPTC; Yun et al., 2006) using the PCATS. Measurements of P-wave velocity, S-wave velocity, electrical resistance, and strength of the sediment were made at regular intervals along the three pressure cores. Cores were then sub-sampled under pressure with the HYACINTH PRESS system (Parkes et al., in press) or rapidly depressurized and placed in liquid nitrogen for further analyses at varous laboratories.

The rest of the pressure cores had been depressurized onboard the ship directly after PCATS analyses to determine the exact methane content and hence the gas hydrate saturation (Fig. 2E). Pressure cores are the "gold standard" for gas hydrate quantification and are used to calibrate other methods of gas hydrate detection. The slow, isothermal release of pressure from a pressure core allows gases to exsolve from pore fluids and allows gas hydrate to dissociate. Measuring the quantity of gas, its composition, and its evolution relative to time and pressure provides information on the quantity, composition, and surface area of gas hydrate (Kvenvolden et al., 1983; Dickens et al., 2000; Milkov et al., 2004). The fundamental number obtained through these experiments is the nominal concentration of methane in the pore fluids, assuming all methane is in solution. If this nominal concentration is greater than the calculated methane saturation, gas hydrate (or free gas, depending on the thermodynamic conditions) is assumed to be present, and the amount can be quantitatively calculated. Data that shows the sediment is under-saturated in methane is equally important, as careful pressure core analysis is the only technique that can confirm the absence of gas hydrate. Figure 2E shows pressure core methane data from the same site as the core shown in Figs. 2A–D. All pressure cores taken above the base of gas hydrate stability were oversaturated in methane, allowing calculation of the exact quantity of gas hydrate contained in the cores.

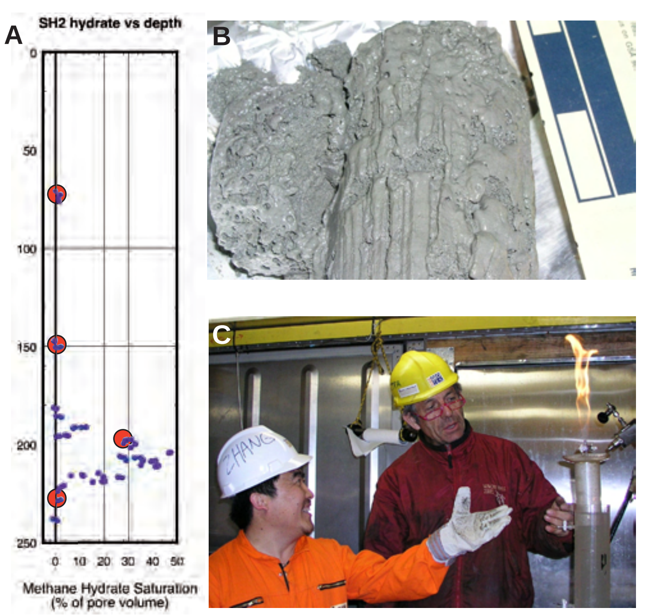

Figure 3. [A] Gas hydrate saturation from porewater freshening (blue circles) and from depressurization experiments and methane mass balance from pressure cores (red circles) at Site SH2 in the Shenhu area, South China Sea (Wu et al., in press). [B] Example of gas-hydrate-bearing sediment from 204 mbsf at Site SH2. Though the core has a gas hydrate saturation of approximately 30% by pore volume, no gas hydrate was visible to the naked eye. [C] A gas-hydrate-bearing pressure core is slowly depressurized to release methane. A rough compositional test is sometimes performed before gas chromatographic analysis.

China, 2007

China's first gas hydrate drilling expedition, GMGS-1 (Fig. 1), was carried out by Fugro and Geotek for the Guangzhou Marine Geological Survey (GMGS), China Geological Survey (CGS), and the Ministry of Land and Resources of China. The expedition took place on the geotechnical drillship *SRV Bavenit*, which visited eight sites in the northern South China Sea (Zhang et al., 2007; Yang et al., 2008; Wu et al., in press) from April to June 2007. The project goal—to determine the gas hydrate distribution at as many sites as possible in the allotted time—required maximum flexibility in the drilling program. The strategy was to use pressure cores (FPC and FRPC) and conventional wireline piston cores to ground-truth wireline logs, and after confidence was developed in the downhole log interpretation, some locations were surveyed by downhole log alone.

Gas hydrate was detected in a thick layer (10–25 m) just above the base of gas hydrate stability at three of the five sites cored. PCATS pressure core analysis provided ground-truth for gas hydrate saturation, as well as gamma density, P-wave velocity, and X-ray images at *in situ* pressure. Gas hydrate occupied pores between silty clay sediment grains, in direct contrast to the hydrate-bearing clays cored off India, which contained hydrate at similar overall saturations but in distinct veins and layers. While surprising, this conclusion is based on the extremely high gas hydrate saturations (20%–40% of pore volume), the nature of the matrix (variably silty clay), the elevated P-wave velocities (over 2000 m s^{-1}) without change in the gamma density, and the smooth, predictable increases in downhole sonic velocity and electrical resistivity.

The distribution of gas hydrate in the Shenhu region, within the sediment column and at the grain scale, is unusually simple and uniform. Its presentation in a relatively homogenous layer, directly above the base of gas hydrate stability, is the type of distribution predicted from simple models of gas hydrate formation (Hyndman and Davis, 1992; Xu and Ruppel, 1999). However, a clear field example of such a gas hydrate distribution has not previously been reported. Similarly, the homogeneous, pore-filling, small-scale hydrate distribution found at Shenhu is the type of distribution typically used when modeling gas hydrate formation and dissociation in sediments of all grain sizes. Both of these characteristics would allow the gas-hydrate-bearing sediments in the Shenhu deposit to be used to test the assumptions and predictions, at various scales, of some gas hydrate models.

Korea, 2007

Ulleung Basin Gas Hydrate Expedition 1 (UBGH1) was South Korea's first large-scale gas hydrate exploration and drilling expedition in the East Sea (Fig. 1; Park et al., 2008). It took place from September to November 2007, aboard the multipurpose offshore support vessel *REM Etive*, which was converted to a drilling ship by Fugro Seacore using the heave-compensated R100 portable drill rig. The Korean National Oil Company (KNOC) and Korean Gas Corporation (KOGAS), advised by the Korean Gas Hydrate R&D Organization and the Korean Institute of Geoscience and Mineral Resources (KIGAM), contracted Fugro, Schlumberger, and Geotek to investigate five seismically identified locations for gas hydrate in the Ulleung basin (Stoian et al., 2008). After the previous expeditions, pressure core analysis was recognized as the key dataset to which all others could be referenced (Schultheiss et al., 2008b).

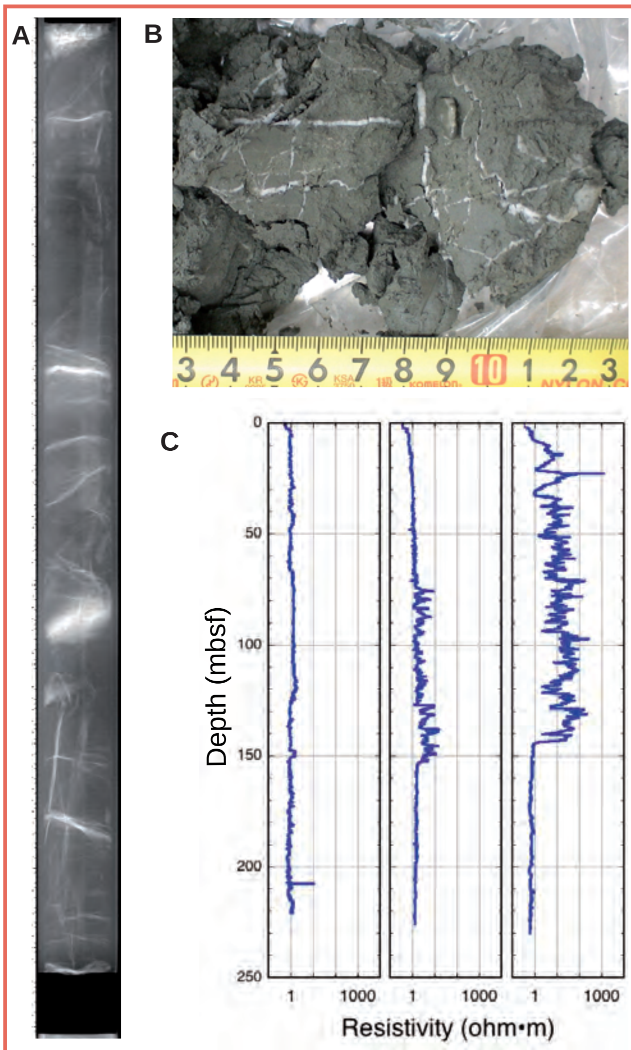

Figure 4. [A] X-ray image collected in the PCATS from Expedition UBGH-1 showing gas hydrate in veins and layers, similar to the core shown in Fig. 2 ; [B] picture of gas hydrate veins from another UBGH-1 core; [C] logging-while-drilling electrical resistivity data from the three "type" locations cored, showing resistivity profiles differing by orders of magnitude. Gas hydrate was present at all three locations.

Gas hydrate was detected at all three sites cored in the clay matrix as veins and layers, and as pore-filling material within silty/sandy layers. Both types of gas hydrate habit were observed in FPC and FRPC pressure cores via the PCATS datasets (gamma density, P-wave velocity, X-ray images), using a PCATS newly equipped with automated rotational and translational capability. The shipboard PCATS data showed that a number of cores contained a particularly dense network of gas hydrate veins (Fig. 4A). These cores were not depressurized onboard, but instead were transferred under pressure to HYACINTH storage chambers and saved for detailed post-cruise analysis.

At one site, a 130-m-thick gas-hydrate-bearing sedimentary interval of interbedded sands and clay was penetrated. This is one of the thickest gas-hydrate-bearing intervals to be documented worldwide. The gas hydrate saturation from analysis of pressure cores, which average over a one-meter sample, was 11%–27% gas hydrate by pore volume in this interval. Because much of the gas hydrate was in grain-displacing veins and layers, there was no obvious quantitative relationship between the electrical resistivity logs and the average gas hydrate saturation, though the overall magnitudes were correlated (Fig. 4C).

X-ray CT scanning of the saved pressure cores confirmed the PCATS data, showing a complex fracture structure within the sediment that was filled with gas hydrate. This information aided in the selection of locations for further geophysical testing inside cores relative to the sedimentological and gas hydrate structures. These specific locations were tested with the IPTC, using the direct-contact probes to measure P-wave velocity, S-wave velocity, electrical resistivity, and strength. The combined translational and rotational precision of the PCATS and the radial precision of the IPTC allowed probes to be inserted into the cores with millimeter accuracy. The preliminary data indicated that physical properties varied on a sub-centimeter-scale in these pressure cores containing thin hydrate veins (Park et al., 2009).

While five of these cores were depressurized to determine hydrate saturation during physical measurements ("mini-production tests"), some of the cores were preserved for further gas hydrate studies. Two of the cores that were tested were rapidly depressurized and portions stored in liquid nitrogen for further testing. In addition, the most lavishly-veined core was not tested invasively and remains stored under pressure, awaiting equipment to be designed for further pressurized analyses.

Future HYACINTH Developments

When a new technique appears, or an old technique is applied in a new location, new insights follow. The recent HYACINTH deployments have provided such new insights into the nature and morphology of natural gas hydrate (Holland et al., 2008). To continue these ground-breaking studies, we are making technological improvements to the HYACINTH system and hope to deploy it in exciting and diverse formations, on land and under the sea.

Over their development period, both the FPC and FRPC have been incrementally modified to improve their success at retaining pressure and the quality of the cut core. Over the last two years success rates for both tools has been 70%–80%. The success of such sophisticated tools is markedly improved when operated in a stable drill string. Experimentation with systems used routinely in geotechnical drilling, such as seabed frames in which to clamp the drill string, has shown that both the success rate and core quality improve relative to those taken in an unclamped string.

Like all equipment in a state of continuing development, the HYACINTH tools currently have some intrinsic limitations and inconsistencies, which are being addressed over time as funding and opportunities allow. The diameter of the core recovered by the two corers is 57 mm for the FPC and 51 mm for the FRPC, and developments have been planned to increase the diameter of the FRPC core to match that of the FPC for increased compatibility in downstream analyses. An increase in the length of the recovered cores (currently one meter) is also planned to ensure recovery of the target formations and to maximize the use of valuable ship time.

The ability to manipulate cores, take sub-samples, and make measurements—all at *in situ* pressures—were major objectives of the HYACINTH project. Like the coring tools themselves, the PCATS has been improved over the past few years and has major new improvements planned in the next few years. Non-destructive measurements of pressure cores in the PCATS have been vitally important as an immediate survey of the core, to determine if a successful core has been retrieved and to look for obvious signs of the presence of gas hydrate. PCATS measurements have also provided primary data on sediment-hydrate properties to ground-truth larger-scale measuremnts. The main analytical improvement that has been made to the PCATS system is the core manipulation capabilities, that now include fully automated translational and rotational control (±0.5 mm and ±0.5° of accuracy, respectively). A combination of precise rotational capability with high-resolution X-ray imaging provides three-dimensional X-ray visualization through the core that enables complex structural features to be examined in detail. This capability has been used to provide remarkable images, showing the complexity of gas hydrate vein networks that can exist in fine-grained sediments, as well as crucial clues to hydrate vein origin and growth mechanisms. In the future, CT software integration could enable PCATS to collect and display X-ray CT data along with the current high-resolution gamma density and P-wave velocity profiles.

Planned improvements to the PCATS infrastructure in the near future include lengthening the system to accept core up to 3.5 m long and active temperature control. In addition, a versatile cutter arrangement to subsection long

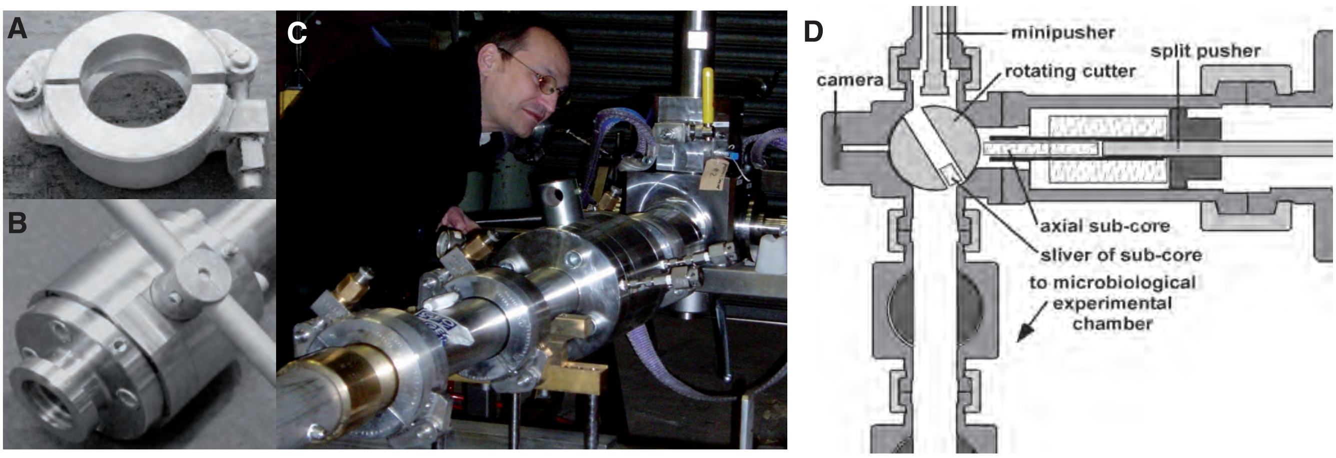

Figure 5. Interfacing third-party equipment to the HYACINTH PCATS. [A] Quick-clamp; [B] ball valve (65 mm internal diameter) and mating flange; [C] the DeepIsoBug, showing ball valves and quick-clamps in use ; [D] diagram of the complex subcoring and sampling mechanism at the heart of the DeepIsoBug. All manipulations are carried out under hyperbaric pressure equivalent to *in situ* hydrostatic pressure.

cores into custom lengths will allow further analysis or storage, as is most appropriate. Parts of a core might be depressurized on board ship, while other parts of the same core could be stored under pressure for shore-based studies. This increased flexibility will enable all cores to be more fully assessed and will further increase the value of every pressure core recovered.

PCATS was envisaged and designed as the midpoint, not the endpoint, of a full pressure coring and pressure core analysis system. Upstream compatibility to new coring tool developments and downstream compatibility to third-party equipment is paramount to its future evolution. The specifications for the HYACINTH mating flange, clamps, and ball valves used in the PCATS (Fig. 5) are publicly available, and any investigator may design "PCATS-compatible" pressurized equipment. Independent research scientists have already developed pressurized equipment that has been used with the PCATS and stored HYACINTH cores, including the previously mentioned IPTC and the DeepIsoBug (Schultheiss et al., 2006; Parkes et al., in press). The DeepIsoBug, designed to take aseptic slices of a subcore for use in pressurized microbial culturing, has prototyped some extremely complex core sampling mechanisms under pressure (Fig. 5D). There are also developments underway for other PCATS-compatible test apparatus to enable more sophisticated geotechnical measurements on pressure core samples.

The ODP and the IODP have been fundamental to the development of the HYACINTH tools and infrastructure. Since its last use for IODP on Exp. 311, the system has continued to be used and improved on commercially funded expeditions. With the restart of *JOIDES Resolution* drilling, the scientific community can reap the benefits of these commercial improvements in pressure coring and analysis, and will be able to realize its initial investment in these pressure coring and pressure core analysis systems.

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