Advances in Wireline Pressure Coring, Core Handling, and Core Analysis Related to Gas Hydrate Drilling Investigations

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Abstract

Further developments in both wireline pressure coring and rig-site pressure core handling & analysis since 2014 have resulted in a single, integrated borehole-to-laboratory pressure core solution for gas hydrate investigations. An overview of these developments and how they have contributed to both recently completed and future drilling expeditions is presented here. The value of routine pressure coring in other unconventional resource environments (in particular shale oil and gas) is likely to occur over the coming years now that an integrated, robust and fully tested package is available.

An Integrated Borehole-to-Laboratory Pressure Core Solution

In the 3 years since ICGH8 (Beijing, 2014) a number of significant offshore gas hydrate drilling expeditions have focussed heavily on the recovery of gas hydrate bearing cores at *in situ* pressures in order to characterize this unconventional hydrocarbon resource and to provide pertinent data to aid the design of production test wells. Continued demand for pressure cores has provided further impetus and opportunities to create what is now an integrated borehole-to-laboratory pressure core solution for all applications where advanced pressure coring & analysis is required on land or offshore. The recent expeditions, offshore China [1, 2], India [3], Japan [4] and the USA (yet to be completed at the time of writing) have exclusively used the PCTB, Pressure Coring Tool with Ball valve, to recover pressure core samples in unprecedented numbers that have been handled and analysis using PCATS (Pressure Core Analysis and Transfer System) and auxiliary compatible equipment.

Further development in the PCTB design and operational procedures have led to sustained improvements in performance. In particular, operational drilling parameters have been refined through experience in different formations while a design change redirecting the fluid flow through the tool during drilling has enabled higher flow rates to be used as and when required. Core recovery can be variable, and primarily depends on the formation properties being sampled, but sealing and pressure retention is now consistently above 70%. Core handling between the rig floor and PCATS has been optimized and simplified by using glycol-cooled cold shucks and baths to ensure the core samples in the tool stay within the gas hydrate stability field. PCATS core handling and analysis has been improved, enabling the 3.5 m long PCTB cores to be processed with maximum efficiency and reliability.

A cryo-freezing preservation system has been developed that enables core subsamples, up to 20 cm long and maintained at high pressure, to be preserved in liquid nitrogen. The system involves immersing and cryo-freezing a pressure core subsample in liquid nitrogen while still under pressure before releasing the pressure for longer term storage and transportation once the sample has been frozen. This development will allow many more pristine gas-hydrate-bearing samples to be shipped to different laboratories worldwide for specialist analysis that have previously had to contend with cryo-frozen samples of dubious quality because of the rapid depressurization process prior to cryo-freezing. An overpack transportation system has been developed to enable core sections up to 1.2 m long to be transported at a cold constant temperature (normally around 4-6 ˚C) and at full pressure (up to 35 MPa) worldwide. This has opened up the potential to transport precious 'undisturbed' samples from the drill site to the most appropriate specialist analysis laboratories in the world which has hitherto been impossible.

With the ability to transport 'undisturbed' pressure cores to shore based laboratories using the overpack system, further core handling equipment in the form of a 'mini-PCATS' has been designed and built enabling expert users to cut, handle and analyse pressure core samples in their own laboratories. Mini-PCATS can handle PCTB pressure core samples up to 1.2 m long and cut subsamples using either the guillotine or reciprocating saw cutting system for subsequent transfer into analysis test cells. A new K_0 permeameter test cell has been specifically designed to enable PCTB subsamples (up to 8 cm long) to be consolidated under triaxial conditions enabling permeability measurements to be made under *in situ* K_0 stress conditions that could simulate production scenarios with dissociating gas hydrate.

Pressure Core Collection

The goal of the Geotek pressure coring tools is to acquire core materials in a range of geologic formations and recover them to the surface while maintaining full *in situ* hydrostatic pressures. In this way, rocks and sediments that contain pressure-sensitive components, in particular gas hydrates, free gas, oil and other fluids, will be captured in their original relative locations without the damage to the host formation which would ordinarily be caused by expansion, phase changes and fluid migration in normal coring systems. Core samples that also retain *in situ* lithostatic stress would be ideal, but this goal is not considered practically feasible. Retention of the *in situ* hydrostatic pressure to ensure that the pore fluids do not expand during core recovery, preventing damage to the fabric of low permeability formations, and reapplication of the *in situ* lithostatic pressures in the laboratory when required is currently the best practical compromise. PCATS, PCATS Triaxial and the K_0 consolidation/permeability cell (see eponymous sections below) are designed to complement the pressure coring systems to achieve these objectives.

Pressure Coring Tool with Ball valve (PCTB III)

The latest version of the PCTB wireline rotary pressure coring system (PCTB version III) used by Geotek is a development from tool designs from Geotek Coring (formerly Aumann Associates) and Aumann-designed systems such as the Integrated Ocean Drilling Program Pressure Coring System [5,6], the JOGMEC PTCS (Pressure Temperature Coring System) [7] and the JOGMEC Hybrid Pressure Coring System [8]. Within the PCTB III there are a significant number of recent upgrades and features which have been field-proven to provide reliable pressure retention and good core recovery in the challenging conditions in which the tool is often deployed. These recent improvements have not changed the overall philosophy or operation of the tool but have significantly improved the ease of rig floor handling and have affected the range of operational conditions and formations in which the tool can be effectively used. Subtle changes to internal flow paths, latch mechanisms, and internal ball closure timing mechanisms have significantly increased the reliability and confidence with which the tool can be used in formations ranging from soft sediments to hard sedimentary rocks. A similar but larger-diameter coring tool, the HPTC III (High Pressure Temperature Corer), which is a development from the earlier PTCS, now operates on similar principles to the PCTB. It has been built and tested on land (see Fig. 10) but has not yet been used offshore.

Figure 1. Drawing showing the bottom end of the lower section of the PCTB.

Wireline coring enables continuous pressure coring to take place using multiple core barrels (autoclaves) and alleviates the need to trip pipe. A Bottom Hole Assembly (BHA) hosts the main drilling bit and mechanisms to lock the coring tools in place. Geotek uses a BHA that enables both the PCTB and other pressure and non-pressure-retaining coring tools, with various acronyms such as the HPCS, ESCS, APC, XCB, FHPC, FPC, and HRC/FRPC [8, 9, 10] to be used without tripping pipe, providing significant operational flexibility. The normal configuration of the PCTB III uses an extended cutting shoe that protrudes through the main bit at the base of the BHA. The extended cutting shoe acts as a pilot bit to cut and trim the core ahead of the main bit, which advances the borehole. This configuration enables the cutting and trimming core bit to be replaced without tripping pipe. An alternative 'face bit' version of the PCTB III is also available where the main bit on the BHA advances the hole while cutting the core at the same time, which may have advantages in some formations; in this version, alternative coring tools cannot be used. The different configurations are currently being tested to determine which version is most suitable for various lithologies.

The PCTB tool runs in a drill pipe with a minimum ID of 4-1/8" and collects cores that are nominally 51 mm (~2") in diameter and up to 3 meters (~10') long. It is rated to recover cores at pressures of up to 350 MPa (~5000 psi) and uses a powered ball valve closure mechanism for rapid actuation and positive closure of the core barrel. The HPTC tool is similar except that it runs in a larger diameter pipe (minimum ID of 6-5/8") and collects cores that are nominally 57 mm in diameter and up to 3 meters (~10') long.

Currently the PCTB III can be operated in formations with temperatures up to 230 ˚C (440 ˚F) and mud with flow rates through the tool of up to 2840 L/min (750 gal/min). A maximum wireline pull of 33 kN (~7,500 lbf) are recommended with a minimum wireline speed of 100 m/min (330 ft/min). Temperature and pressure are recorded continuously during deployment, coring, and recovery using data recorders located inside the autoclave and optionally within a 'rabbit' that is pushed up through the plastic liner by the core material. These data sets provide information about the pressure-temperature history of the samples collected, which is critical for gas hydrate studies.

The PCTB is composed of two assemblies: the lower assembly, that collects the core and retains pressure; and the upper assembly, containing the BHA landing shoulder and the wireline latching interface. The lower assembly in turn is composed of two sections: the autoclave, which houses the core and top-sealing ball valve; and the pressure section, which provides a nitrogen-charged, pressure-regulated system to maintain pressure on the autoclave after the core is cut and the ball is closed. Note that the nitrogen in the pressure section remains separate from the core in the autoclave and that only fluid pressure is transmitted between the sections. The upper and lower assemblies are combined to make up the complete tool at the drill floor.

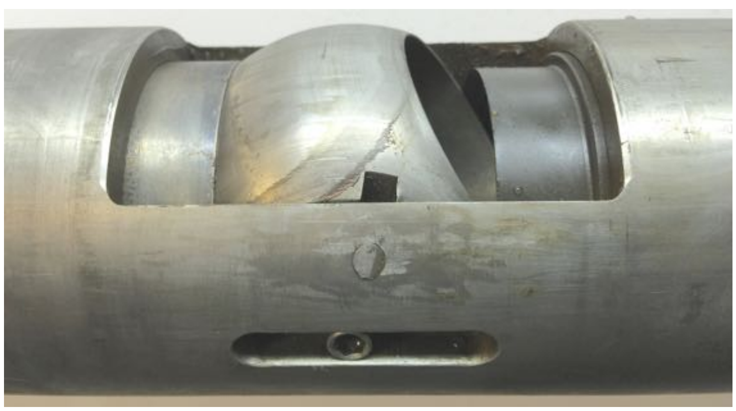

Figure 2. Photo showing the half -open ball valve sealing mechanism in the PCTB III.

Although the PCTB is locked into the BHA in order to transmit torque to the cutting shoe, the inner tube and plastic core liner assembly is suspended on a bearing to restrict the rotation of the core liner and core catcher relative to the formation, minimizing core disturbance. The standard core catchers used on the end of the plastic liner act as one-way valves, letting core enter the liner while advancing the hole, but retaining core material when the PCTB is recovered to surface.

Recovery of the PCTB begins as the BHA is lifted off the bottom of the hole. A pulling tool lowered on the wireline is used to latch onto the PCTB, which on lifting triggers the closing of the lower ball valve and the release of the nitrogen charge, sealing the core inside the autoclave. The pulling tool then releases the outer latch that enables the complete PCTB assembly to be pulled to the surface.

The upper assembly is separated from the lower assembly on the rig floor. The lower assembly is brought to the PCTB service laboratory (after soaking in a temperature-controlled cold shuck during gas hydrate investigations), where the autoclave is pressure-isolated and then separated from the pressure control section. The autoclave is prepared for core transfer to PCATS (see PCATS section) by installing the PCATS adapter onto the autoclave and is then moved to the PCATS laboratory, where the core is removed, analyzed, cut, and transferred to specialized pressure cells for analysis or transportation.

Figure 3. Autoclave section of the PCTB being prepared in the tool service laboratory.

Field Analysis & Sampling

Pressure Core Analysis & Transfer System (PCATS)

PCATS, the Pressure Core Analysis and Transfer System, is the crucial link between the borehole and the laboratory, providing a means to remove core from corer autoclaves, collect background data on cores, and cut sections of core and transfer them under pressure to transportation cells or specialized analysis cells. PCATS has been described in detail elsewhere [11, 12]. The essential concept and use of PCATS has not changed since its inception in the late 1990's when it was conceived as a system to maximize the scientific and technical value of cores recovered under pressure [13]. The key to its success was to make the transfer of core material from the coring tool to PCATS an essential design criterion of the coring tools, rather than attempt to retrofit an existing pressure corer.

In summary, PCATS can handle and process cores up to 3.5 m long, transferring them from compatible pressure coring autoclaves (e.g., the PCTB III or HPTC III) at pressures up to 35 MPa. Temperature is controlled (down to 4˚C) using glycol-cooled heat exchangers and circulating pressurizing water which can have tracers added to test for any core contamination effects during handling. Pressure cores are quickly assessed in PCATS for content using the integrated X ray imaging facility prior to being analyzed in more detail to provide accurate density and P-wave velocity profiles with centimetre-scale resolution. Full X-ray CT (computed tomographic) imaging can be performed with a voxel resolution of 100 μm and which has in the past revealed the intricate and complex nature of gas hydrates in fine grained sediments [14]. Once the core has been analyzed, it is normal to provide the client with a summary data set to enable a detailed cutting and testing plan to be determined for each pressure core. An example of this type of summary data and cutting plan is shown in Figure 4.

Whole cores can be temporarily cut and stored in 3.5 m long pressure storage chambers, or cores can be cut into shorter lengths and transferred into other chambers for rig site analysis or for transportation to shorebased laboratories. Gas hydrate investigations generally require some cores to be cut and analyzed on board to determine the gas hydrate concentration from depressurization or 'mini production' tests. Cores are stored and/or depressurized in a dedicated depressurization laboratory (see Depressurization Laboratory section).

As with the pressure coring tools, PCATS and its associated infrastructure has undergone development over many years and has now been used on 15 major offshore gas hydrate drilling expeditions. Recent improvements have all centered around reliability and speed of operation. Recent software improvements will enhance the speed at which full X ray CT can be acquired. This will be of significant benefit during drilling campaigns where pressure coring is the primary activity and 'time is of the essence'.

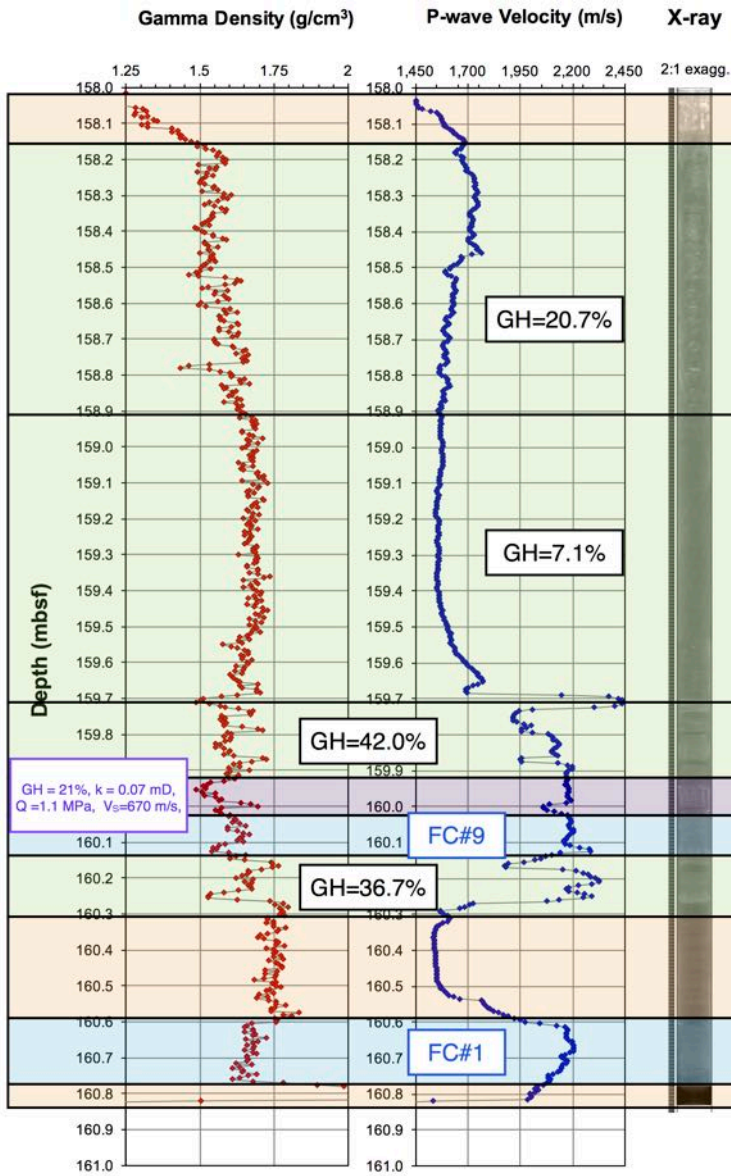

Figure 4. Illustrative PCATS nondestructive data and core cutting plan, showing use of nondestructive data set in further sampling and analysis planning.

Core Storage and Field Depressurization Laboratory

During gas hydrate pressure coring drilling expeditions there is always a logistical challenge of handling significant numbers of cores or core sections that are kept under high pressure and at cold temperatures, either on a temporary or permanent basis. Some cores are kept whole on a temporary basis (up to 3.5m long) within the PCATS laboratory but most are cut into core sections for either long term storage or for rig site quantitative depressurization.

Quantitative depressurization/degassing experiments normally take place from short sections of core up to 35 cm long in small storage chambers and are conducted in a controlled fashion to accurately quantify the total amount of hydrocarbon gas in all phases, including gas hydrate, within the subsamples. This enables the concentration (saturation) of gas hydrate to be determined as well as the overall distribution of gas hydrate within the sediment sequence. The pressure in the subsample chambers is slowly and incrementally reduced through a manifold and all the expelled gas and fluid are volumetrically recorded in bubble and gas chambers at each pressure increment.

Samples of gas are taken and analyzed throughout the depressurization process enabling the composition and concentration of gas hydrate in the sedimentary formation to be determined.

Analysis of the pressure-time-volume records from the depressurization steps can provide both kinetic and thermodynamic evidence for the presence of gas hydrate. Kinetic evidence of gas hydrate occurrence is seen in the pressure 'rebound', or the increase in pressure over time after a depressurization step. Thermodynamic evidence of gas hydrate occurrence comes from the degassing records of pressure vs. volume, where the volume increases (gas continues to be released) while the pressure remains constant, near that predicted for gas hydrate stability.

Core sections that are destined for shore based laboratories are normally stored in storage chambers that can hold sections up to 1.2 m long. These are stored locally in the storage laboratory and connected either to accumulators or a pressure maintenance system for security until they are offloaded at the end of the expedition. The latest core storage and field depressurization laboratory can store up to 30 storage chambers and houses four integrated depressurization stations inside a customized 20 ft ISO laboratory (Fig. 5).

Figure 5. Secure storage and depressurization laboratory for high-throughput quantitative core depressurization.

Pressurized Freeze Cell Using Liquid Nitrogen

On many gas hydrate coring or drilling expeditions, samples of gas-hydrate-bearing sediment have been preserved in liquid nitrogen (LN_2) for transport to onshore laboratories for further study. Transport of samples has been achieved using LN_2 cooled 'dry shippers' which is a well established process. Samples have been taken from either conventional, non-pressurized cores or from pressure cores that were depressurized rapidly. Both techniques have had only limited success in preserving the gas hydrate or indeed the structure of the core. The depressurization process (slow or fast) creates a significant degree of disturbance to the sample depending on many factors, including gas hydrate concentration and sediment type.

We have developed a new technique of preserving gas-hydrate-bearing sediment samples in LN_2 which ensures that all the gas hydrate within a sample is preserved and the physical degradation of the sample is minimized (Fig. 6). This new cryo-freezing technique involves cutting a suitable subsample (12-20 cm in length) in PCATS and transferring it to a sample storage chamber in the same way as other pressure core subsamples are taken. The water surrounding the sample is replaced with high pressure nitrogen (up to 250 bar) before the chamber is connected to the cryo-freeze cell, which is pre-filled with LN_2 and then pressurized with nitrogen to the same pressure as the storage chamber. When the ball valve connecting the two chambers is fully opened, the sample falls into the LN_2, still at high pressure. After about 2 minutes the sample is completely cryo-frozen and the pressure is released. The frozen sample is then removed from the pressurized freeze cell, transferred to a LN_2 dewar for storage, and shipped in a dry shipper to its final destination as has been done historically.

With this new technique the preservation method ensures that all the gas hydrate is preserved for subsequent analysis. We found in practice with the sediments from expedition GMGS4 (see Recent & Upcoming Uses section) that the core sample is largely preserved intact, although it does expand during the cryo-freezing process (Fig. 6).

Figure 6. Freeze cell in use on the GMGS4 expedition (above) and a typical sample after cryo-freezing (below).

Sample Transportation

Overpack Pressure Core Transportation

As the need for more sophisticated testing of samples taken from pressure cores becomes more prevalent the requirement to transport undisturbed samples to specialized laboratories has become a growing requirement. A number of post-expedition analyses of pressure cores stored and transported to local laboratories in storage chambers have taken place over the past few years [15, 16, 17, 18, 19, 20]. However, previous transportation of core samples in storage chambers has always taken place within the country where the samples have arrived at port. Pressurized samples in storage chambers have not been transported internationally because of different (and sometimes difficult) regulatory requirements associated with the shipment of these ‘dangerous goods’. Gas hydrate bearing cores can contain significant amounts of methane which of course is highly flammable and considered a hazardous cargo (HAZMAT class 2.1/ UN1971 flammable gas). Methane is also of course explosive at certain concentrations when mixed with air.

To overcome this difficulty Geotek has developed a comprehensive transportation solution that enables pressure core sections up to 1.2 m long to be safely transported anywhere in the world by sea or road whilst maintaining the *in situ* temperatures and pressures. To achieve these goals an ‘overpack’ pressure core transportation container was designed. The container itself is an explosion-proof refrigerated shipping container (to mitigate against any sparks during transit) that contains certified transport overpack cylinders that house the storage chambers containing the pressurized cores up to 1.2 m long. Overpack cylinders provide enough volume to accommodate all the methane gas in the unlikely event that the storage chamber leaks or ruptures during transit.

Geotek pressurized storage chambers are secured and shock-mounted within the overpack cylinders in all dimensions by a machined support structure, so there is no risk of damaging the overpack cylinder during transit. To avoid any possibility of creating an explosive mix within the overpack cylinder, the free volume within the overpack cylinder is purged with nitrogen once the pressurized storage chamber has been loaded. Any methane released into the overpack will mix with the nitrogen only. The first use of this system should see five pressure cores stored in Japan for over one year transported in their original condition to the USA for the United States Geological Survey (in transit at the time of writing).

Figure 7. Overpack cylinders containing storage chambers secured and shock mounted inside a specialized refrigerated shipping container.

Laboratory Subsampling & Specialized Analysis

Mini-PCATS

The Pressure Core Analysis and Transfer System (PCATS) is designed as a rig site facility for handling, analysing and processing pressure cores up to 3.5 m long. It can also be used as a shore-based facility for subsampling cores that have previously been analyzed, cut, stored and transported to shore. PCATS is a fully featured but relatively large facility (60 ft in length) with far more infrastructure and capability than is required for simply handling, subsampling, and transferring 1 m core sections that have previously been analyzed and cut by PCATS at the rig site. With pressure core samples being increasingly transported to shore-based facilities for detailed processing and experiments, a need for a simpler pressure core handling and sampling system was required. Consequently we designed and built a mini-PCATS system under contract to the University of Texas to provide them with core transfer and sampling capabilities for their Pressure Core Centre (UT PCC).

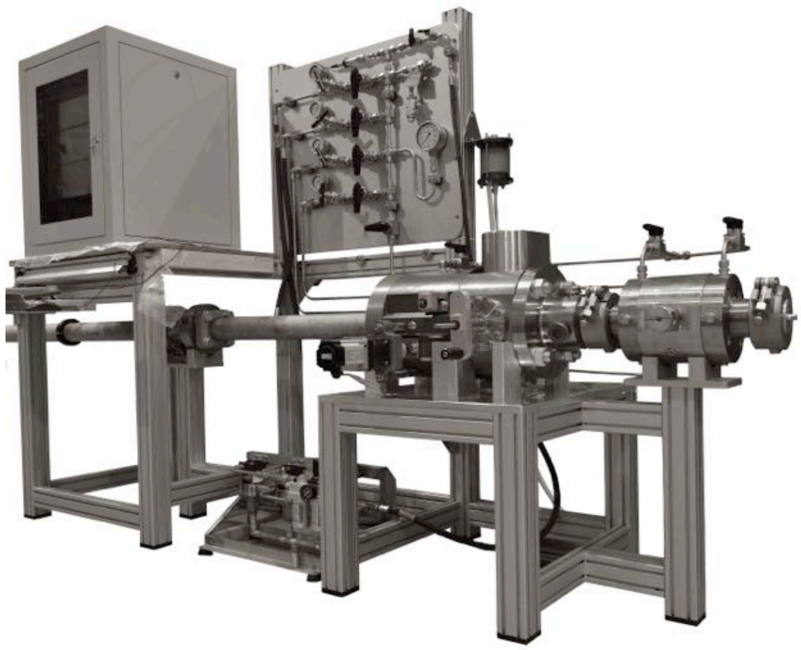

Figure 8. Mini-PCATS showing primary core cutting components. Far end of motor-driven manipulator (to left) not shown. Subsamples are moved into test cells or storage chambers (not shown) at right hand end.

Mini-PCATS is a smaller and simplified version of PCATS and is compatible with all pressure core storage chambers and other third-party equipment that uses the standard Geotek flange-clamp design. It enables core sections (up to 1.2 m long) to be extracted from storage chambers and accurately cut into subsamples (along with the plastic core liner) before being transferred into sample test cells (including the K_0 Permeameter; see K_0 Permeameter section) to measure physical properties whilst maintaining pressures of up to 35 MPa.

The core cutting function in mini-PCATS enables the core sample to be cut using a new design that incorporates both a rolling circular blade to cut cleanly through the plastic liner and a reciprocating saw blade to cut through the sediment/rock sample. The new techniques create 'square' ends to samples, which had occasionally been a problem with the earlier guillotine system, where brittle samples would fracture along bedding planes. Control of sample geometry is especially important for samples that are to be analyzed in test cells such as PCATS Triaxial or the K_0 Permeameter.

In PCATS, the integral X-ray system enables the cut ends to be examined prior to transferring samples into test cells. An X-ray system can be added to mini-PCATS, but currently a three-port viewing window has been incorporated that enables the user to not only have visual confirmation of exactly where the sample end is but also to examine the quality of the cut end. This enables the sample to be accepted or rejected as necessary.

PCATS Triaxial

The PCATS Triaxial system is a mechanical testing system designed specifically to enable both small and large-strain geotechnical tests to be performed on 'undisturbed' pressure core samples of soil or rock, along with direct-flow measurements of permeability. Samples are cut in PCATS and transferred into PCATS Triaxial for testing while maintaining full *in situ* hydrostatic pressures (up to 25 MPa). Consequently, gas-hydrate-bearing (or oil-and-gas-bearing) sediment or rock samples can be collected from deep within a formation and transferred to a sophisticated mechanical testing apparatus, at near *in situ* conditions, with the gas hydrate being maintained within its stability field. With full control of triaxial pressures in the apparatus, meaningful mechanical property and permeability data can be obtained. Recent modifications to the equipment have included the provision of viewing windows in the main pressure housing enabling the rather delicate process of sample transfer from plastic liner to thin rubber membrane to be directly observed.

For small-strain resonance testing, an electromagnetic drive unit excites the sample in a torsional mode to obtain the natural frequency of the sample and the attached drive mechanism. The shear moduli (and hence the shear wave velocity) of the sample can be derived from these measurements using suitable calibration techniques and wave propagation theory. Large-strain behavior of the sample is obtained using a standard triaxial testing configuration, which allows the stress-strain properties of the sample to be determined. A progressive uniaxial load is applied to the sample with axial deformation recorded as a function of the applied load. Permeability is measured by applying a pressure head across the sample while measuring the flow rate. This test apparatus has been previously described [21] and was recently used extensively offshore during both the NGHP02 and GMGS4 gas hydrate drilling expeditions offshore India and China respectively. Data from the GMGS4 expedition is reported in a companion paper [22].

To date, PCATS Triaxial has only been used offshore during pressure coring expeditions themselves. However, it is envisioned that in the future samples will be returned to shorebased laboratories where more time can be devoted to the testing process. More time is often needed, especially with finer-grained sediments, where the consolidation and permeability testing requires significant time that limits the number of tests that can be performed offshore. Development of the overpack pressure core transportation system (see Overpack section) as part of the overall 'borehole to laboratory' concept has made the extended testing of samples back in shore-based laboratories a practical reality.

K_0 Permeameter

To complement the PCATS Triaxial system, a new test cell has been developed with the specific aim of providing permeability data at *in situ* anisotropic (K_0) stress conditions in a simpler, less expensive test cell to enable higher sample throughput.

The overall K_0 system enables pressure core samples to be transferred directly into the K_0 Permeameter cell while maintaining *in situ* hydrostatic pressures (up to 35 MPa) throughout the sample cutting and transfer process. Once inside the cell the consolidation and permeability characteristics of the sample can be determined. During the testing process the sample is surrounded by a flexible rubber sleeve enabling the confining pressures and pore pressures to be independently controlled and hence effective stresses can be applied to the sample enabling *in situ* lithostatic pressure to be simulated. Samples 25-80 mm long can be selected and cut from stored PCTB pressure cores using either PCATS or mini-PCATS (see sections above) and then transferred into the K_0 Permeameter test cell. The cell is isolated using an integral ball valve, removed from mini-PCATS, and connected to an Axial Loading and Transfer System (ALTS). This combined unit enables the sample to be extruded from the liner into the flexible rubber sleeve mounted inside the cell. Once the sample has been extruded into the rubber sleeve under a constant pressure, the confining hydraulic stress and the vertical load (via the ALTS) can be applied as required to reconsolidate the sample to *in situ* stress conditions prior to direct flow permeability measurements being made through porous stones at the top and bottom of the sample.

Recent & Upcoming Uses

The driving force for the continued development of pressure coring technology has continued to come largely from national programs related to investigating gas hydrates as a potential future energy resource. In the last few years, drilling expeditions have taken place offshore India, China (two expeditions), and Japan. With 188 deployments of the PCTB pressure coring system during these expeditions–recovering over 200 m of pressure core material, most of which contained gas hydrate–a significant wealth of operational experience and knowledge has accrued.

In 2015 the India National Gas Hydrate Program Expedition 02 (NGHP-02) was conducted off the eastern coast of India [3] using the deepwater drilling vessel Chikyu. Pressure coring was a major component of the program, in water depths up to 2,815 meters, where the primary goal was to explore for highly saturated gas hydrate occurrences in sand reservoirs that would become targets for future production tests. The PCTB was deployed 104 times, recovering a record-breaking total of 156 m of pressurized core material from a single expedition.
Pressure core subsamples were quantitatively degassed to determine the gas hydrate concentration, mechanically tested on board using the PCATS Triaxial equipment, or rapidly degassed for direct visual observation and storage in liquid nitrogen. Selected longer core samples (~1m long) were stored at pressure in storage chambers for shore

based analysis at a later date. A few of these pressure core samples were stored in Japan before being transported in a new overpack transportation system back to the USA for analysis by USGS.

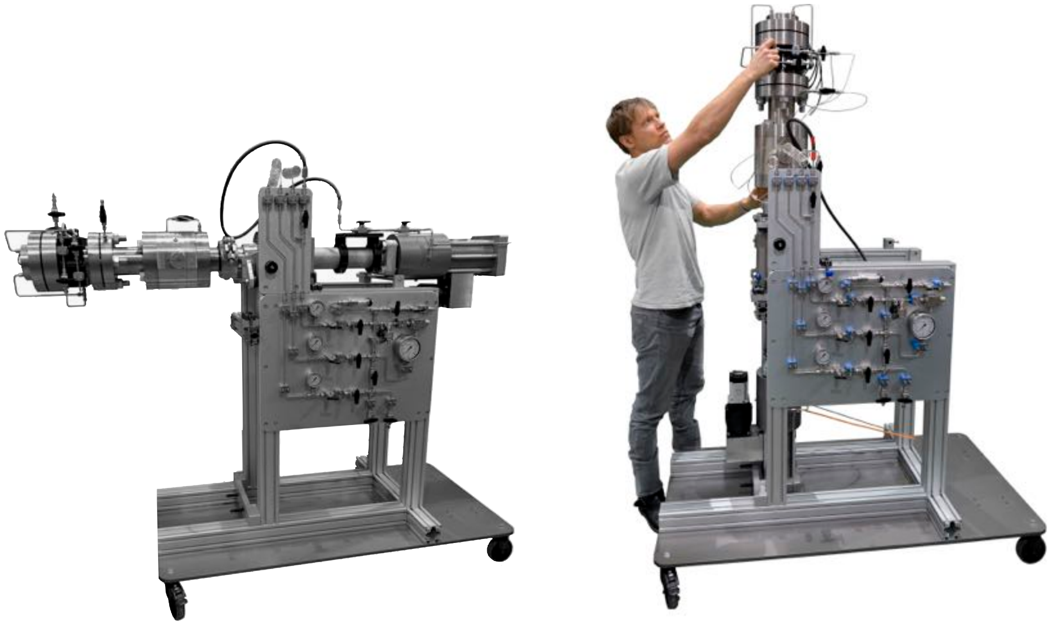

Figure 9. K_0 permeameter cell connected to the Axial Loading and Transfer System in its horizontal orientation for sample transfer and in its vertical orientation during sample analysis. Computer control system not shown.

China's Geological Survey/Guangzhou Marine Geological Survey (CGS/GMGS) completed their third and fourth gas hydrate drilling expeditions (GMGS3 & GMGS4) onboard the Fugro Voyager drill ship in the South China Sea in 2015 and 2016 respectively [1, 2]. These expeditions took place mainly in the Shenhu area, in water depths up to 1292 m, and relied heavily on pressure coring using the PCTB and pressure core analysis using PCATS and PCATS Triaxial to evaluate gas hydrate reservoirs for future development. A total of 126 m of pressure core was recovered from 57 deployments of the PCTB. Expedition results from pressure core analysis demonstrated that concentrated gas hydrate exists in clay-rich silt layers 20-90 meters thick, and that some regions of Shenhu show evidence of Structure II hydrate and recent hydrate formation.

Meiji University conducted a drilling/coring expedition in the Japan sea in 2015 [4] which used Geotek's conventional and pressure coring tools. The PCTB coring tool retrieved 27 pressure cores containing gas hydrates that were handled and analyzed on board using PCATS. The gas hydrate targets in the Japan Sea were not those dispersed in sedimentary sequences, as is the case in most gas hydrate drilling expeditions, but were concentrated within gas chimney structures that are up to 1 km in diameter and limited to sub bottom depths of around 100m. Within these structures massive deposits of gas hydrates are located and are thought to be an enormous resource potential.

Although not a gas hydrate drilling exercise, it is worth noting that in late 2015 a land based test of the PCTB in its two drilling configurations was performed at the Schlumberger Cameron Test and Training Facility. This program was undertaken for the University of Texas gas hydrate drilling project and was designed to test the effectiveness and efficiency of drilling and coring with the new PCTB III pressure core barrel. At the same time the larger diameter HPTC pressure coring tool was also tested at the Cameron facility for JOGMEC, illustrating that both of these tools can be effectively used in hard formations using the appropriate correct drilling parameters (Fig. 10).

It is anticipated that between the time of witting and the ICGH9 conference, the University of Texas Hydrate Pressure Coring Expedition 1 (UT-GOM2-1) will have been completed. This offshore drilling expedition (April/May 2017) is dedicated to the use of the PCTB in the Gulf of Mexico, Green Canyon Block 955. During this drilling expedition it is planned to take 20 pressure cores with a view to not only testing recent improvements/modifications to the tool but also to collect a significant number of pressure core samples for both on board and shore based analysis.

Figure 10. Sections of depressurized core, collected during the 2015 Cameron land test in a hard shale & carbonate formation using both the HPTC (57 mm diameter, upper photo) and the PCTB (51 mm diameter, lower photo) illustrating the effectiveness of these pressure coring systems in harder formations.

Conclusions

Significant development of wireline pressure coring tools and associated pressure core handling systems have taken place over the past two decades driven by funding primarily from national governments interested in understanding how gas hydrates might be exploited as a future hydrocarbon resource. Regular offshore drilling programs (most recently offshore China, India, Japan and the USA) have been a consequence of this funding, which has resulted in the development of a comprehensive integrated borehole-to-laboratory pressure core solution for any drilling application where advanced pressure coring and pressure core analysis is required. Although these applications have been almost entirely related to gas hydrates to date, the technology is equally applicable to other unconventional hydrocarbon resources especially applications related to shale oil and gas.

The workhorse wireline coring tool, the PCTB, has undergone continued development and 3-m-long samples can be cored in a wide range of sedimentary formations from soft sediments to hard cemented sands and shales. Pressure core handling at the rig site under controlled temperature and pressure conditions using PCATS, and associated infrastructure, enables multiple cores to be taken in succession without impacting rig operations. Nondestructive testing of cores (P-wave and density) together with structural analysis using X-ray CT visualization enables core sections to be appropriately and accurately selected before being cut and transferred into storage chambers for rig site or shore based analysis.

Samples can be transported to port either under pressure in storage chambers or after being cryo-frozen in liquid nitrogen using a newly developed techniques that freezes the samples while still at pressure. This ensures that the samples are minimally disturbed by the process and ensures that all the gas hydrate is captured. Transportation from port to the laboratory anywhere in the world has hitherto been a problematic because of regulatory issues surrounding the transport of these ‘dangerous goods’. A new technique whereby standard pressure core storage chambers are loaded inside overpack cylinders that it turn are loaded into a refrigerated, explosion-proof shipping container has overcome these issues enabling core sample to be transported to any laboratory worldwide. To further analyze pressure core samples in the laboratory a smaller system for handling pressure core samples has been developed (mini-PCATS) together with more advanced test cells for characterizing samples (K_0 Permeameter and PCATS Triaxial).

The integrated development of pressure coring tools in parallel with the design and development of pressure core handling and analysis equipment has resulted in a mature ‘borehole-to-laboratory’ technology that can be relied on to provide some of the key data required in the quest to exploit gas hydrates resources worldwide. Its value, use and application in other unconventional resources (in particular shale oil and gas) is yet to be fully appreciated but it is likely to occur over the coming years as market conditions for using advanced technologies improve.

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