EXTREME HPHT CORING, HANDLING AND ANALYSIS: SECURING THE VALUE CHAIN

John Owens, *Maersk Oil North Sea UK Limited*
Robert D. Evans, *Core Laboratories (U.K.) Limited*

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Napa Valley, California, USA, 16-19 September, 2013

ABSTRACT

The robustness of future field development investment decisions is commonly founded upon high quality core-based data. Data acquisition in extreme environments of high pressure and/or high temperature (HPHT) with pressures up to 25,000 psi and temperatures up to 400° F is particularly challenging. It requires not only specialist techniques but also many months of integrated planning and preparation to ensure a safe and successful operation. Thus, securing the value chain between well, rig, laboratory and application in subsurface models was identified as key to success.

A case history is presented based on a series of HPHT exploration wells drilled in the Central Graben of the North Sea (the “HPHT Heartland” of the North Sea). It provides an overview of the planning and execution of an extreme HPHT core handling and core analysis campaign from setting the initial information objectives, through the deployment of HPHT-specific solutions and subsequent application of the data in the static and dynamic models. From the project initiation, a holistic approach was adopted from detailed integrated planning, through execution and subsequent application. A key deliverable was the safe rig site operation whilst minimising chemical and mechanical damage to the core. The project was tailored to harsh winter conditions at surface and extreme HPHT bottom hole conditions. Fostering the extended team concept facilitated strong communications and the leveraging of niche skills which added significant value to the campaign.

Performance was analysed on each well. For wellsite operations, focus was applied to obtaining the best possible quality core by meticulous planning of customised coring techniques including the use of specialised mud tracers, surface handling methods and transportation procedures to minimise chemical and mechanical damage to the core. Subsequent laboratory processing and analysis methods required an integrated approach to deliver the required geological, petrophysical and reservoir engineering data objectives in a timely manner for the subsurface static and dynamic models. These were employed to support subsequent technical and business decisions. The lessons learned from each coring operation were applied to further improve efficiency through optimisation of operational design to secure the value chain.

INTRODUCTION

A key business and technical objective of exploration and appraisal projects is to safely deliver well information objectives. To ensure that potential Field Development Plan (FDP) investment decisions are not adversely affected by inadequate or unreliable (or lack of) basic data, safely delivering high quality data is a fundamental step in realising excellence in subsurface description and hydrocarbon volume quantification.

Key threats to the technical success of the core analysis programme were chemical and mechanical alteration of the core during the coring, tripping, handling, transportation and core analysis stages. During these stages, value can be eroded by causing chemical and or mechanical damage to the reservoir rock. The goal is to preserve the rock properties and to minimise damage (alteration) to ensure they are representative of the subsurface.

A number of principles were therefore at the forefront of protecting the value chain during planning the coring, core handling and core analysis programme:

- Ensure nobody is hurt at any stage of the project
- Minimise chemical damage to the rock
- Minimise mechanical damage to the rock

It was recognised at project initiation that diligent mitigation of the challenges posed by a conventional core analysis project would be required. In addition, special attention would be needed as the core would experience significant and rapid temperature and pressure changes at wellsite due to tripping out of hole from an extreme HPHT downhole environment to mid-winter surface conditions in the North Sea.

BACKGROUND

Success was defined as safely delivering the well information objectives. This required high quality data to be provided in a timely manner. Consequently, in the months prior to departure to the rig, intense onshore planning and preparation between the operating company and contractor companies had to be completed.

The HPHT definitions of Falcão [1] are used. An exploration and appraisal campaign was planned for the HPHT area of the UK Central North Sea [2] comprising two vertical wells and the potential for a number of sidetracks. Coring operations were to be confined to the primary objective 8½” hole where reservoir conditions were prognosed to be extreme or even nearly ultra HPHT. The vertical depths of each well varied but were generally planned to be about 17,500 ft. The principle adopted was to plan for the technically most challenging conditions but hope for more benign conditions.

The coring information objectives were established by operating company’s end-users as obtaining suitable material for lithostratigraphic description and correlation, formation lithology, porosity, permeability, fluid saturation and rock mechanics. These were to be fulfilled by acquiring minimally altered core in specific intervals and obtaining high quality measurements of porosity, permeability (ambient & in situ), grain density, water saturation, cementation and saturation exponent, capillary pressure and relative permeability. In addition, high quality slabbing was required to acquire good quality high resolution digital core images and mini-permeability data.

Having the same information objectives in the different wells created the opportunity to develop common ways of working, similar procedures and use of each coring operation as a learning opportunity for subsequent cores. Thus, a culture of continuous learning was embedded throughout the campaign. Specific focus was given to managing the interfaces between different contractors, operating company and rig so the core would experience a seamless continuity protecting the value chain and minimizing damage at all stages.

HSE

The project could not be deemed a success unless there were zero Health, Safety and Environmental (HSE) incidents. Core handling crews were to go offshore. Thus, from project initiation through to return of crews to base, safety was always an integral aspect of the planning. Special attention was given to the agreement of the core processing area on the rig deck, deconflicting rig and core processing activities and avoiding injuries to feet, back, hands and eyes during lifting, sawing, plugging, whole core preservation, etc. As a standard, risk assessment and hazard identification was tailored for each specific operation and documented via a detailed risk register highlighting the individual threats and their mitigation. This was reviewed with crews prior to departure for the rig and was also provided to the wellsite Drilling Supervisor for the pre-job safety meeting.

DECISION PROCESS AND INITIAL PLANNING

To ensure success in fulfilling end user’s requirements, a critical success factor was the early agreement of a structured plan and assignment of appropriate people and equipment. In support of this was alignment by all with the plan and the timeline.

Regular reviews were essential to keep everything on track and adapt to changes as required. Thus, a dedicated team was assigned with the objective of safely delivering the project objectives. The team consisted of experts with a strong background in HPHT technical preparation and operations. Key considerations included the timeline to core point of the first well, rig specific considerations, projected maximum formation temperature and pressure, hole size and planning for proposed deviated wells.

It was acknowledged from the time of project initiation that planning for success in extreme HPHT wells is not a trivial task. Thus, the kick-off meeting of the extended operator/contractor team was held five months prior to the first expected core point. The outcome was the agreement of the main project phases, associated deliverables, focal points and timelines tailored to the HPHT well information objectives.

ASSIGNMENT OF PERSONNEL

People are key to planning and delivering a successful project. To ensure continuity and develop the seamless interface, individuals within the extended team were assigned specific roles. The team included the operating company focal point, specialist technicians, and contractor management. All assigned personnel clearly understood the principles in the quality plan. This created a deeply rooted sense of personal ownership and responsibility for safe and successful project delivery.

PLANNING PRINCIPLES

Project planning principles were applied to the coring, core handling, transportation and core analysis campaign. An overview was maintained to ensure at each step the key threats along the value chain to the eventual core analysis data quality were identified and mitigated. An essential element was front-end loading whereby at project initiation the extended team reviewed the technical challenges posed by the information objectives and the solutions deemed necessary. A continuous learning cycle was applied comprising of the Planning, Execution, Application and Learning (PEAL) phases (Owens, [3]).

Planning is a multi-faceted preparation phase that includes the pooling of experience and the collation of applicable learnings from previous operations. This is followed by the Execution phase during which wellsite operations are conducted and core material brought to surface, processed, transported to the core analysis facility and core analysis undertaken. The Application phase is the period of time when reviews of operations are undertaken, preliminary core analyses data delivered and applied to subsurface realisations (both preliminary and subsequently more detailed models). During the Learning phase reviews are held to consider continuous improvement challenges such as the identification of data gaps, data quality and operational efficiencies. These can then be applied during the next Planning phase iteration.

Early in the planning stage, staff with HPHT expertise were brought together to ensure solutions tailored to the project challenges were deployed. These included equipment selection and wellsite operational procedures. This formed the basis of a shared “road map” whereby the equipment inventory was assembled allowing for a rig deck plan of the core handling processing area to be agreed with the rig. Front-end loading the project with the available expertise identified best practices to establish the best way forward. This proved an excellent foundation for success providing numerous efficiencies that reduced wasted effort. However, it was recognised that throughout the whole campaign there would be learnings that would be captured via the continuous improvement cycle.

HPHT CORE HANDLING AND CORE ANALYSIS CHALLENGES

To minimise irreversible chemical and mechanical damage to HPHT cores, a number of specific threats had been identified from previous experience of such projects. The primary threat was from chemical alteration due to reactions with the high density oil based muds (OBM) required to safely drill the wells. Often the optimal drilling mud is suboptimal for core analysis. As safety takes precedence, core damage was a secondary consideration even though vital to avoid. Thus, it was decided to use Deuterium oxide (D2O) tracer in the OBM water phase to evaluate the integrity of the Dean-Stark Sw measurements. CMT-1000™ (a partially deuterated hydrocarbon OBM tracer) was added to the oil phase to better understand if OBM invasion had occurred in the hydrocarbon leg of the reservoir. Both tracers were measured using the Dean-Stark fluid extracts.

Another threat was the potential for the core to react with the atmosphere. Mitigation was required for two key challenges. Firstly, upon reaching surface, the core is much warmer than the ambient temperature, particularly during the North Sea winter. Connate water can evaporate resulting in reduced Dean-Stark water saturations. Secondly, the potential exists for core reactions with the atmosphere resulting in oxidation and hence irreversible changes in wettability. This could adversely impact measurements of saturation exponent, capillary pressure and relative permeability with subsequent consequences for the FDP.

A number of solutions were considered. One method was to bring the core barrel above the mud line within the riser to cool and relax for several hours. This had three disadvantages; namely that the core was still soaking in the OBM with the associated threat of potential invasion and core/OBM chemical reactions, the HPHT drilling rig was idle with a significant associated cost and there was a concern with increased time exposure to risks associated with well stability. These threats were addressed by bringing the core to surface under controlled trip conditions, removing the inner barrels and transferring the core in the 30 foot long inner barrels with end caps fitted to be submerged in Blandol® baths where it could cool. Thus, the twin threats to the value chain of reactions with the atmosphere and loss of connate water due to evaporation were reduced.

WELLSITE CORE HANDLING PROCEDURES AND EQUIPMENT DEFINITION

The wellsite procedures depended on a combination of services from the coring contractor, the core handling contractor and the H2S safety contractor. The presence of H2S in the area was considered a low probability and, if present, low concentrations would be expected. Nevertheless, integrated in the planning, procedures and wellsite operation was that the H2S safety contractor would monitor for H2S concentrations.

In addition to the HPHT challenges, specific care was given to minimising mechanical damage during surface handling. The core was parted at the end of each inner barrel using a screw-operated shearing guillotine rather than by hammering action. Whilst hanging in the derrick, a core handling cradle was carefully fixed to the inner barrels so that during lowering and rotation to the horizontal and resting on rig floor the inner barrels and core were not allowed to flex. Once end-capped, each inner barrel containing core was lifted out of the cradle and into the Blandol® bath using a four lift point spreader bar to minimise bending. The combination of cradle and spreader bar proved simple to use and very effective in minimising core flexing and hence mechanical damage.

Following recovery of all the inner barrels to the Blandol® bath and making-up of the next BHA, attention turned to core processing. The first 30 foot inner barrel and core was removed from the Blandol® bath using the spreader bar and loaded onto a cradle with integral rollers. The core was measured and wellsite Gamma Ray log acquired. The inner barrels and core were sawn with a 85° cut into 3 foot lengths and the core removed for marking. The purpose of the 85° cut is in addition to the parallel marker pen marks to safeguard the accurate realignment of the core pieces. A further example of preventing mechanical damage was that no chipping of the core by wellsite personnel was permitted for core description. Detailed offshore core descriptions provided no benefit in this campaign and could have led to both delay in processing and damage to the core.

It had been previously determined that 1 foot long SCAL preserved samples would be obtained from the last foot of every second 3 foot long section of cut core. Dean-Stark plugs would be cut offshore, just above the where the SCAL sample would be taken to provide a proxy insight into the likely properties of the SCAL sample. Blandol® was to be used as the core plug bit lubricant and air would cool the trim saws. Prior to preservation, the SCAL samples were to be digitally photographed to provide a temporary record before they were opened for analysis. The Dean-Stark plugs were to be wrapped in cling film, aluminium foil and packed in labelled foil bags. On selected wells, hotshot plugs were twinned with alternate Dean-Stark plugs. Whole core 1 foot long geomechanical samples were to be acquired and preserved from representative lithologies as per SCAL samples but with a distinguishing label. The reason for preserving the geomechanical samples was to prevent the core drying out and altering the rock properties.

The unpreserved core was to be repacked into its inner barrel with labelled wooden dummies replacing the removed SCAL and geomechanical samples as protection during transportation. Core was then to be packed in core crates with foam sections to prevent and reduce shocks and movement while in transit. The core was to be sent by next boat to harbour and then road transport to the core analysis facility. In addition, lagged fluid samples of the OBM were planned to be taken at different stages before and during the coring operation along with samples of the D2O and CMT-1000™ tracers were to be packed and shipped with the associated core. Shock monitors were also to be deployed in the shipment to identify where high shocks which could cause mechanical damage were occurring during transportation and hence learn how best to avoid them in future.

For every 180 foot of core, there was a significant amount of material to be stored on the rig. This was exasperated since up to four cores per well were planned. Consequently, in advance of the planned operational execution, senior representatives of the contractor crews visited the rig together to agree with senior rig personnel where to place the core processing area and the significant associated equipment inventory. Consideration was given to minimal trip hazards, no overhead working of cranes, adequate light, access to compressed air for saws and plugging machines plus electricity for wax baths.

EXECUTION: WELLSITE CORE PROCESSING

The extended team prepared and agreed a single document containing the fully integrated step-by-step procedures covering the time from when the tracers were introduced to the mud system (prior to reaching core point) through to the core reaching the core analysis facility. At each step, the responsible contractor was identified. The procedures were written from the perspective of safeguarding HSE requirements and minimising value erosion by ensuring the mechanical and chemical integrity of the core.

The procedures document was supplemented by a HSE core processing area checklist to be completed to the satisfaction of the senior contractor representatives, OIM and Drilling Supervisor prior to beginning operations. A HSE risk register with associated mitigations was provided. This was reviewed at the pre-job tool box talk with a summary document of individual roles and responsibilities. The focus was ensuring a clear understanding that the objective was a safe operation with minimal erosion of the value chain associated with this extremely important resource. A very useful approach was the core handling crew gave a brief “show-and-tell” to the rig crew explaining what they did and why. This resulted in an appreciation by the rig crew of why core should be moved with care and hence gained their even greater cooperation.

EXECUTION: CORE ANALYSIS

A comprehensive core analysis programme was planned to achieve maximum value from the available core material. The laboratory work flow is summarised in Figure 1.

The hot shot plugs were partially cleaned for 2 days, dried and porosity and permeability determined. After this analysis the hot shot plugs were fully cleaned, dried and porosity and permeability re-determined as part of the routine sample set.

As the cores were received in the laboratory, the Dean-Stark water saturation plugs cut at the wellsite also arrived. The Dean-Stark plugs were placed into the Dean-Stark glassware apparatus without delay. In order to help quantify the effects of invasion on the core, the Dean-Stark plugs were drilled and preserved at the wellsite. Extracted waters from these plugs were analysed by continuous-flow isotope ratio mass spectroscopy. The natural background level of D_2O in formation water is ~150 ppm and the target OBM water phase concentration was ~500 ppm to provide a good contrast. Lagged mud samples taken once every 30 feet during coring provided measurements of the actual OBM water phase D_2O concentration.

The 4” diameter whole core was received at the laboratory in aluminium liners that had been cut into 3 feet lengths at the wellsite and had been securely packed into plastic core crates. As mentioned previously, with each shipment of core from the wellsite a digital shock logger had been placed into the plastic crates. The data from the shock loggers were downloaded and examined to check for any shocks that might have occurred during the transportation of the core from the rig to the laboratory.

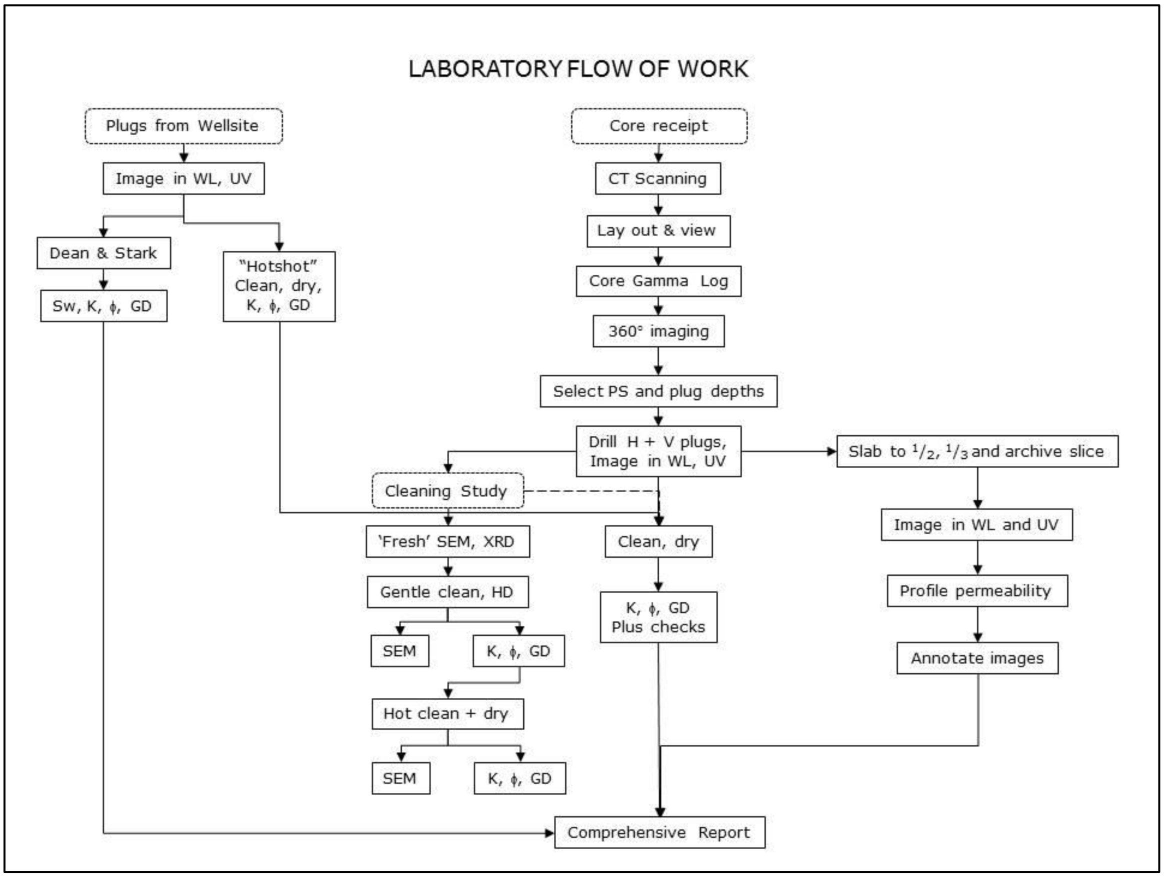

Figure 1. Laboratory core analysis flow of work

It had been noted by the wellsite engineers that some of the core appeared to be stuck inside the aluminium liners. To investigate if fracturing had occurred in these sections it was decided to CT scan these core sections. All SCAL samples were also CT scanned.

All of the core was pushed out of the aluminium sleeves and wiped to remove oil base mud. Depth markings and orientation lines were applied to the core surface. Spectral Core Gamma Ray measurements were then performed over the entire core interval and, from the raw data, total gamma and the concentrations of Potassium, Uranium and Thorium were determined. Prior to each run a standard with known total gamma ray and the spectral components was measured to check the equipment was in calibration.

Routine plug sampling depths were selected and both 'horizontal' and 'vertical' plugs of 1½" diameter were drilled and trimmed. Before cleaning the routine samples in solvents, a cleaning study was carried out to determine how various cleaning and drying techniques could impact on potentially sensitive minerals that may be present in the cores. Several samples underwent X-Ray Diffraction analysis to determine mineralogy, particularly clay mineral content. Scanning Electron Microscopy analysis was carried out before and after different scenarios of cleaning using a variety of solvents at various temperatures together with variations of controlled humidly drying and hot oven drying. The results of this cleaning/drying study allowed the optimum techniques to be selected for cleaning and drying all the plugs to minimise damage (i.e. changes to the rock fabric).

Before all plug samples were cleaned each individual plug, including the wellsite Dean-Stark and the hot shot plugs, were imaged in white light (WL) and Ultraviolet (UV) light. The objective was to secure a digital record of the plug including heterogeneities and fluorescence as a permanent record and audit trail.

The next step in the analysis programme was to perform 360° imaging of the entire cored section (minus the sealed preserved samples). The core surface was thoroughly cleaned prior to imaging. Standard high-resolution capture (WL) was acquired over the entire cored interval for application to detailed sedimentological studies. The resultant digital files were also processed to create lower resolution 3 foot images.

A variety of samples were taken for subsequent for rock mechanics, biostratigraphy, geochemistry, palynology and petrology analyses and noted in a Core Master Inventory. This recorded details of all samples, when they were taken and where they were sent.

Once all routine plugs had been cut, the core was slabbed in half using tap water as the saw lubricant to show the maximum dip on the slabbed surface. One half of each 3 foot section was placed flat side down on a plastic tray. Depth strips, plug sample labels and preserved sample labels were adhered to the tray at the relevant positions adjacent to the core. Clear resin was poured around the core. When the resin had fully set the inverted core was slabbed again to leave a thin slice set in the resin trays and the remaining $^{1}/_{3}$ free slice. The slabbed core sections set in resin were then digitally imaged using the core scanning system. White light images were captured by scanning individual resin trays and UV images captured using an SLR camera and processed to create digital UV images. The core was lightly cleaned to remove surface dust and rock flour before profile permeability measurements were performed.

The cleaned and dried routine plug samples were each placed in an UltraPore™300 Pycnometer system to determine Grain Volume. The system uses Helium gas and Boyles Law to ascertain grain volume. The system is fully automated with all pressure readings and calculations performed by computer, thus eliminating any transcription errors. In addition to calibration checks, every tenth sample was re- measured for quality control. Bulk Volumes of the plug samples were measured by mercury immersion utilising Archimedes principle. Careful attention was paid to the calibration of the weigh balance, and the calibration of the thermometer used to measure mercury temperature. Pore Volume was calculated by subtracting grain volume from bulk volume. Pore volume expressed as a percentage of bulk volume gives helium porosity.

All the plug samples were subjected to permeability measurement using the CMS-300™ unsteady state system. The hydrostatic sleeve confining pressure was 800 psi. The CMS-

300™ is an automated permeameter/porosimeter that measures permeability by a transient pressure fall off technique. As wide ranges of flow velocities, gas densities and mean pore pressures are obtained from a single transient pressure fall off, Klinkenberg (or slip-corrected) permeability, the Klinkenberg gas slippage factor, and the Forchheimer internal resistance coefficient can all be calculated directly from the time-pressure data.

LEARNINGS

The development of the “extended team” concept bore fruit in the subsequent analysis programmes applied to subsequent wells in the campaign. After wellsite operations and at key times during the core analysis of each well, reviews were used to compare what was planned versus what actually happened and where improvements could be applied. The objective was to deliver continuous improvements in terms of HSE and data integrity.

Leveraging the skills of the extended team in the exacting planning for the first well allowed the avoidance of subsequent duplication where unnecessary. E.g. the cleaning and drying study for the first well allowed for a rapid mineralogical check on cores from the subsequent wells and consequent implementation of the optimum cleaning and drying regime for plugs to be applied. An additional advantage leveraged throughout the campaign was continuity of personnel and the use of the same procedures which required only minor updates during the campaign. Thus, what was initially deemed an extremely challenging operation became “routine” in so far as it was repeated. However, clarity was always maintained that extreme HPHT operations are challenging and focus on HSE and high quality was paramount.

The value of continued use of D2O during the campaign was considered. Early results demonstrated that for the majority of samples there was no invasion. However, some plugs demonstrated varying degrees of water phase contamination. The value of the D2O was therefore to provide insights and confidence into which Dean-Stark water saturations were robust and hence could be applied in the petrophysical modelling and those that should be eliminated.

Attention then turned to the question of oil phase contamination. A relatively new service was the availability of CMT-1000™. It can be used to identify invasion of the oil phase filtrate into the core. It was added to the drilling mud at a low concentration as it can be detected down to 5 ppb. The concentrations determined from Dean-Stark samples were used to calculate core fluid saturations and to identify if the core could be reliably used for wettability-sensitive (i.e. uncontaminated) laboratory testing. Additionally, it was also used to help quantify OBM filtrate contamination of formation test fluid samples.

In this project, the CMT-1000™ indicated that the only significant oil phase invasion was in high permeability zones. In lower permeability zones, oil phase invasion was minor and in most cases zero. It is concluded that with mud solids particle size optimisation based on core studies, invasion could be better controlled in future wells.

RESULTS

A detailed audit trail for each well was reported in digital format. The objective was to provide a comprehensive and integrated permanent audit trail record containing the specifications of the analytical programme and resultant data. A goal of the core analysis report was to be sufficiently comprehensive to afford the “forensic” geoscientist of the future all the specifications necessary to fully investigate the analytical programme and the resultant data in this reservoir characterisation effort.

The results of all the various core analysis components from wellsite to laboratory were presented with the report being a “complete specification”. It included a detailed account of the wellsite core handling, core receipt in the laboratory and sampling techniques listing exact depths of the various sub-samples procured for various specialised analyses. It included the detailed pre-cleaning study objectives, deliverables and conclusions, detailed explanations of the various analytical techniques with the exact specifications of the equipment, tolerances, calibration traceability, etc. The actual data were reported in tables, statistical analyses, graphs with the complete digital photographic record of all the core material (360^o images, plugs, etc.). The Core Master Inventory was appended.

CONCLUSIONS

An extreme HPHT case history of core handling and core analysis has been presented focussing on the value chain from setting the initial information objectives, the subsequent planning and execution through the deployment of HPHT-specific solutions. From the project initiation, a holistic approach adopted a line of sight to secure the value chain from detailed integrated planning, through execution and subsequent application to subsurface descriptions.

The key deliverables were the safe rig site operation whilst minimising chemical and mechanical damage to the core to obtain a representative, best in class core data set. The project was tailored to harsh winter conditions at surface and extreme HPHT bottom hole conditions. Fostering the extended team concept facilitated strong communications and the leveraging of niche skills added significant value to the campaign. With high confidence in the results, the data was then applied to the static and dynamic models which are essential to future field development plans.

ACKNOWLEDGEMENTS

The authors would like to thank the management of Maersk Oil, Britoil, JX Nippon, Eni UK and Core Laboratories for permission to publish this paper. The authors are indebted to the contribution of expertise by Steve Duguid, Andy Dunk and Alan Swanson. The authors would also like to thank all those who have shared their HPHT experience and have contributed to helping safely deliver HPHT well information objectives.

REFERENCES

[1] Falcão, J.L. “Curso de Perfuração de Poços HPHT”. *Universidade Petrobras, Salvador,* outubro de 2007.

[2] Milton-Worssell, R. “Potential to Production – Conventional HPHT (300˚F 10,000psi) to Extreme HPHT (350˚F 15,000 psi) on the UKCS”. *HPHT Arena 2009, A One Day Workshop Dedicated to the North Sea’s Hottest Plays,* 11th December 2009.

[3] Owens, J. “HPHT Formation Evaluation : Planning For Success – A Structured Approach”. 2013. *In press*.