X-Ray Computed Tomography 3D virtual plugging – value of the technique in challenging case studies.

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Abstract. 3D X-ray Dual Energy Computed Tomography (3D DECT) is a common practice performed in the laboratory for most oil and gas exploration companies at the initial stages of a core analysis study. Some of the main objectives behind the scanning of whole core sections inside the inner barrel include the visualization, identification and evaluation of features and attributes such as drilling induced damage, fractures, lamination, mineralogy, mud invasion, rock structure or core stabilization. More specifically a special core analysis (SCAL) study requires homogeneous, representative, and non-damaged cylindrical plug samples for advanced core analysis experiments. Application of the virtual plugging 3D digital investigation approach can increase the core plugging success rate and sample representativeness, optimize the efficiency of the rock sampling process and improve data quality, resulting in considerable benefits for companies involved in advanced core analysis programs. In this publication we present real case studies on cores from the Norwegian Continental Shelf (NCS), where the rock lithology and structure posed a significant challenge for the core sampling process - mainly due to heterogeneities, hummocky crossbedding, and poor degree of consolidation. Applying the 3D CT Virtual Plugging methodology allowed the analysts and engineers to drill multiple, properly oriented core samples with an increased plugging success rate. This was performed without inducing unnecessary damage to the core material by recognizing precisely where and how to effectively drill the cylindrical samples. This technique has been proven extremely beneficial in increasing sampling success rate/representativeness and subsequently has enabled the operator to perform a more reliable and accurate core analysis data acquisition program for reservoir evaluation and modelling.

1 Introduction

During the last decades, a substantial amount of industry effort and time has been dedicated to the development of different technologies (from the field to the laboratory) to address and resolve challenges related to best practise and protocols for core handling, preservation, and subsampling. Especially in complex lithologies such as those seen in heterogeneous, laminated and poorly or unconsolidated cores.

X-ray Computed Tomography (CT) is a well-known and a fifty-year mature technique (developed under the leadership of Sir Godfrey Hounsfield in 1971 in Great Britain). Since 1974, CT scan methodology has been developed in many areas of geology, core analysis and digital rock characterization.

It refers to computerized imaging procedures that uses a series of X-ray beams to produce images of a cross-section of the scanned body or object and a 3D image. Used mainly for the medical sector it has been used in the oil and gas imaging market since the early 1980s [2] with incremental interest from the industry since then. At the beginning, medical scanners availability was restricted to medical centres and advanced clinics however after several years there was seen a slow incorporation of scanners from petroleum engineering research departments [3].

Computed Tomography (CT) is a non-destructive imaging technique which uses X-ray electron beams to visualize the internal structure of core material and is based on the fundamentals of density contrast, taking advantage of various levels of X-ray adsorption.

In core analysis and rock characterization studies, the application of X-ray CT scanning techniques, mainly with 2D visualizations has been in use for many years, this includes the investigation and evaluation of full-diameter sample sections to determine coring induced damage, core orientation relative to bedding for core handling, core sampling, and processing (e.g., slabbing), identification of lithological heterogeneities and discontinuities such as fractures and nodules.

3D and Dual Energy CT (DECT) based characterization for core analysis applications include evaluating core quality, identifying, and quantifying bulk lithology, measuring density and porosity, integrating CT-derived density and porosity with log-derived data, depth matching, quantifying heterogeneity detection of fractures, visualization and evaluation of mud or additive fluid invasion [8].

In more recent years, X-ray 3D DECT data on whole core samples has been successfully utilized and integrated with other core screening techniques such as CoreDNA®, IR Hyperspectral and UV hydrocarbon spectroscopy for rock

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and fluids characterization measurements at an early stage in the core analysis program.

Advantages:

Because CT is a non-destructive measurement, it has become common in technical applications, for instance, rock material characterisation to evaluate structural features without removing it from the inner tubes, to maintain the core integrity and reduce the risk of mechanical damage related to laboratory core handling.

In addition, 3D CT images provide integration with logs by using the axial CT images in combination with the borehole logging images (BHI). As with any other technology, the new CT scanner models allow advancement in spatial definition, scan speed, artifacts reduction (e.g., beam hardening) and image quality resolution which allows new applications.

Another potential characteristic is the core screening and tri-dimensional visualization of inhomogeneities to observe any structural damage that might occur in the reservoir core during different stages in the core handling and processing workflow (Figure 1). Or a representation of the orientation of visible and non-visible natural fractures [5].

There is also a possibility to determine fluid distributions within core material thanks to the contrast density difference between high density drilling mud components (e.g., Barite) and reservoir fluids.

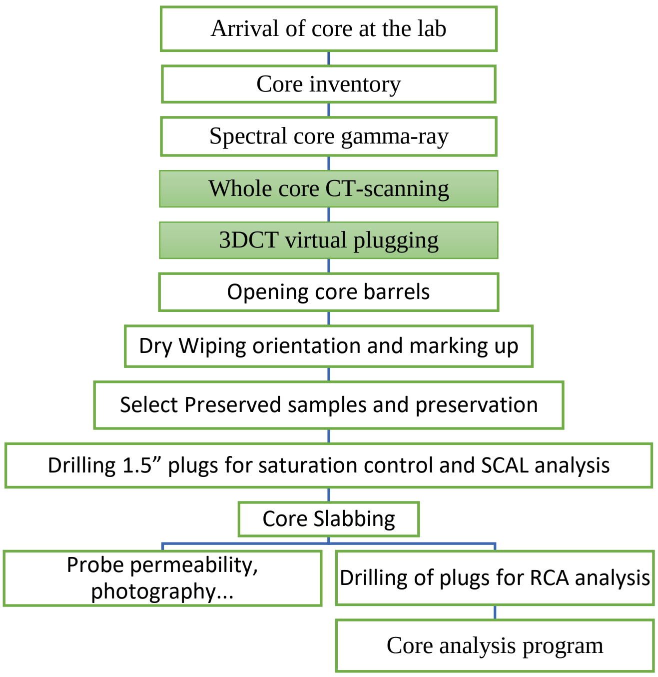

Fig. 1. Core analysis workflow example and CT scanning and 3DCT virtual plugging program steps.

One of the main strengths of this methodology is the capability to work at the initial stages in the core analysis program, when images generated enable the selection of plugging locations before the core is extruded from the inner barrels. In some circumstances, this task is critical because of the nature of the rock (i.e.: highly fractured, fragile, vugular, heterogeneous). Therefore, the initial CT images become an indispensable source of information for early core sampling screening, evaluation, and orientation using the CT numbers and standard deviation in Hounsfield (HU) units [9, 11].

In the past, with the older single slice X-ray CT-scanners, only one single image could be produced per rotation. Nowadays, with the modern 7th generation multidetector 64 or 128 slice CT machines (which means shorter scan times with a larger volume coverage) we can acquire multiple highly detailed images in one rotation reducing the scanning time per meter from minutes to few seconds (Figure 2).

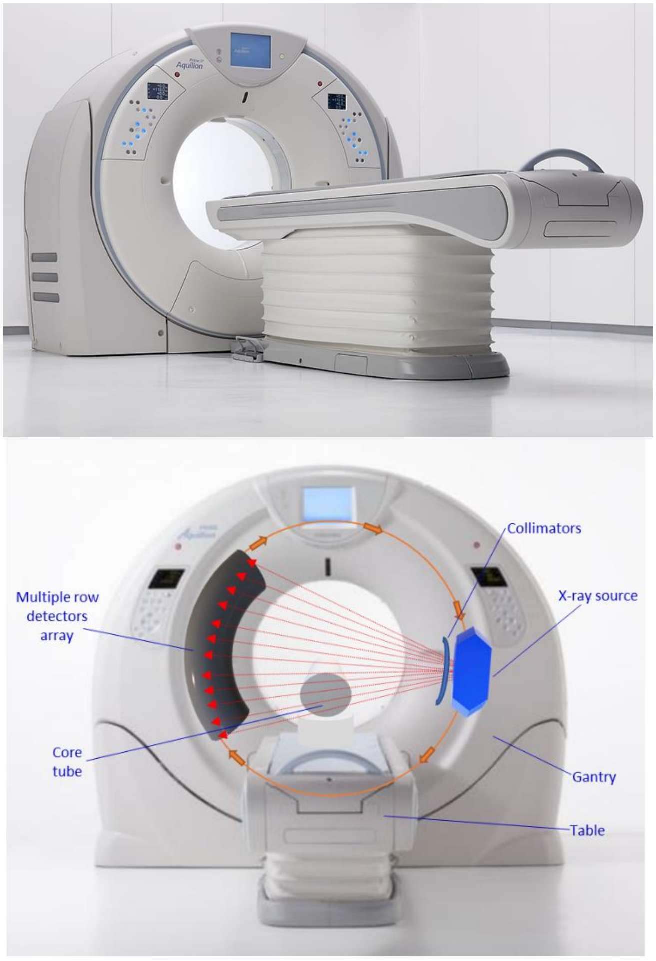

Fig. 2. Toshiba Aquilion Prime 160-slice medical CT scan equipment and location of the main components and multiple rows of detectors.

The commercialization of the first generation of 64 slice scanners with dual source helped the industry to develop the DECT methodology, not only for better image resolution but also to translate the radiodensities into additional parameters such as photoelectrical factor (Pe or PEF) atomic number (Z) and bulk density (RhoB) [10], for core-to-log calibration. This method also introduced the capability of using CT data for early-stage mineral modelling and mapping.

CT scanners can also be used to observe changes in rock structure and properties (mineral dissolution, scaling, wormholes development) by image comparison before and after core flooding experiments such as acid stimulation treatment [12]. The same CT technique is also applied in 2-phase immiscible flooding tests under pseudo reservoir conditions with the use of dye contrasts to enhance visualization from the extracted CT images or in combination with other techniques such as NMR in 3-phase fluids saturation determination [6].

Limitations:

CT is based on the degree of attenuation (or radiodensity variation and atomic number) of X-rays passing through a material. A standard medial Computed Tomography scanner has an ease-of-use limitation as it requires the modification of the pre-defined radiodensity configurations (i.e.: head, lungs, bones) into specific rock radiodensity intervals requiring calibration using core material analogues, such as outcrop rock. Different procedures have been published in the last decade as this calibration methodology has a critical impact in the Dual Energy Computed Tomography data analysis [13].

The efforts to quantify and improve the accuracy of Computed Tomography scanning techniques have been successfully deployed up to a certain level. This is in principle related to X-ray physics and to the maximum image reconstruction we can obtain in the laboratory from medical CT scanners where the 2D slices spacing or slice thickness range is normally no less than 0.2-0.3 mm (200-300 micron) according to manufacturers and equipment specifications.

This spacing is determined by the number of rows of detectors in the z-axis of the scanner (i.e.: 16, 32, 64 or 128 slice CT). Therefore, the medical CT end-user cannot acquire ultra-high-resolution images to identify features like microfractures, internal grain distribution, quantification of clay content, pore volume or ganglion connectivity at the microns and sub-microns scale. For this high-resolution 3D type of analysis, a much smaller sample size and the use of a higher resolution advanced industrial X-ray machine micro- or nano X-ray CT is required.

The two main parameters that potentially control the CT image quality are the voltage (which affects the extent of X-ray penetration) and the current (which determines the number of photons that can be generated) and each laboratory has their own procedures in selecting these parameters depending on the type of rock and core barrel characteristics. Max voltage and current are also directly dependent on how advanced the CT machine is, and modern models are expensive. This is one of the reasons why, the availability of the latest state of the art CT in commercial core analysis labs is limited and therefore they need to utilise CT equipment located in medical clinics or local hospitals. This normally requires additional transportation from the laboratory to the CT location, with an increased risk of core damage, additional handling, packing and logistics. Most of the clinics and hospitals only allow use of their facilities outside normal working hours when these locations are closed for patients. In addition, they might not be able, or willing to adapt their protocols for core scanning purposes and modify CT voltage and current due to safety restrictions (dose reduction protocols) or internal policy procedures and concerns.

2 Objectives and challenges

The X-ray CT technique detects the attenuation of X-rays passing through an object and is dependent on bulk density and effective atomic number. The X-ray attenuation is mapped in Hounsfield units and converted to CT numbers, in each voxel of a CT image of the object, where:

$$\text{CT number} = ((\mu c - \mu w)/\mu c) \times 1000$$

The μc is the calculated X-ray attenuation coefficient and μw is the attenuation of water [1].

3D Computed Tomography is one of the first tasks to be performed once the core inner barrels or core tubes arrive at the laboratory as this is a necessary technique to quickly characterize and understand the rock integrity and the fluids and drilling mud located inside and around the core. This knowledge is essential to select locations for plugging and the final purpose is to obtain the most homogeneous, representative samples possible with the optimum diameter, length ratio as it has high importance for special core analysis (SCAL). Core analysis measurements performed on heterogeneous, micro fractured or obliquely laminated samples will provide unreliable results and consequently generate a misleading petrophysical data correlation and interpretation.

Heterogeneous, poorly consolidated, and unconsolidated sandstones reservoirs contain an important percentage of oil volumes around the world. To improve the understanding of displacement physical mechanisms controlling the fluid distribution, saturation, and transport through the porous media, it requires in some cases very extensive core analysis programs. These studies must be performed on the best possible cylindrical shape plug samples (e.g., the most accepted size by the industry: 1.5” diameter and 3” length).

It has been discussed in the literature [4] the problems with this type of rock material where plug samples tend to collapse or break apart even if the laboratory uses liquid nitrogen as the drill bit lubricant. The frozen core thaws and loses competence and matrix stability very quickly [7].

In this paper we will describe the procedural steps applied for cylindrical plug sampling of two sandstone lithology cores from the Norwegian Continental Shelf (NCS) with different geological characteristics, where a specific 3D virtual plugging method using X-ray Computed Tomography was evaluated to validate the proposed added value of the technique to the core sampling program for Special Core Analysis (SCAL) measurements.

The Computed Tomography has also potential benefits for complicated carbonates and heterogeneous multi-layer shaly sandstone formations where disciplines such as rock mechanics and core analysis demand the specific selection and use of large core sections for full diameter core measurements. Virtual plugging can also be a good complimentary technique when there is a need to drill smaller or shorter samples (i.e.: mining and side track wells with a whole core diameter below 3 inches).

The main objectives for the different case studies are summarized as follows:

2.1 Case 1

In this case the main purpose of this application was to test if the virtual plugging methodology could increase the rate of success during the plugging operation by obtaining representative cylindrical plugs with the correct final size (1.5 inches in diameter and maximum length allowed for further laboratory petrophysical measurements).

The presence of sensitive clays in some reservoir intervals and the importance of obtaining an accurate reading of water saturation content by Dean Stark laboratory measurements suggested to avoid freezing the core and drill 1.5-inch diameter plugs with liquid nitrogen. This reduces the risk of possible rock texture and clay structural damage due to water liquid-solid expansion. Previous cores drilled in the same area also show a poorly consolidated characteristic, making the core freezing methodology and plugging operation extremely challenging with very low rate of success.

2.1 Case 2

Due to the complex heterogeneous rock structure and the presence of cross-bedding laminations from sedimentary hummocky stratification, most of the core plugs drilled from a close well were disqualified for advanced core analysis because of non-parallel orientation to visible bedding.

The main objective in this case was to use the virtual plugging methodology to properly select, orientate and obtain suitable true horizontal laminated samples by avoiding non-representative features and trying to reduce the number of drilling attempts in a heterogeneous and fragile-poorly consolidated core. The customer also requested to maximize the number of plugs due to the large number of different SCAL analysis planned for each specific depth interval and lithofacies.

3 Methodology

In this study the X-ray CT images were acquired in Stratum Reservoir Stavanger (Norway) using a seventh-generation Toshiba Aquilion Prime helical 160-slice CT medical scanner (Figure 2). Using a multiple energy level of dual energy CT with different voltages and current of 135kV/100mA and 50kV/300mA on example 1 while the lab run single energy CT with 135 kV/350 mA for example 2, in both examples the AIDR dose reduction, beam hardening correction and *Bone* protocol for image reconstruction was applied. The spatial resolution was approximately 1 mm with a minimum slice thickness of 0.3 mm (after image reconstruction) registering the whole length of the core and core inner barrel.

X-ray Computed Tomography can create 3-dimensional models by volume rendering the axial and longitudinal 2D slices, it is possible to generate these models in any spatial axis. This follows the principle where the internal structure of an object can be reconstructed from multiple projections of it. In addition, with most of the current commercial software available, different shapes can be created to focus on the volume of interest to identify and therefore by using a virtual cylinder with a diameter of 38.1 mm (1.5 inches) the operator was able to obtain the digital version of a plug for core analysis.

This workflow (Figure 3) can be performed with both, the single energy or dual energy CT technique and it needs a commercial CT visualization and image processing software for digital rock characterization, for these specific studies we used Thermo Scientific Avizo™ Software.

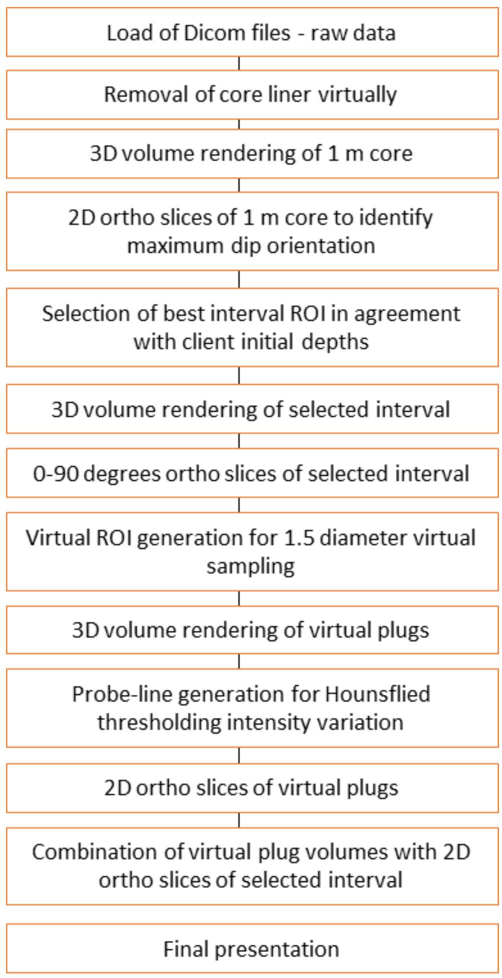

Fig. 3 Simple software workflow for 3DCT virtual plugging.

The process starts with data loading and the virtual removal of the aluminum or fiber glass core inner barrel to obtain a better image contrast. Then, a selection of a small piece of 20-

30 cm length from the whole core was performed as this was the main region of interest (ROI) for the study (Figure 4).

The software visualization dashboard is then adapted and optimized to visualize all the 3D directions of the digitally rendered volume.

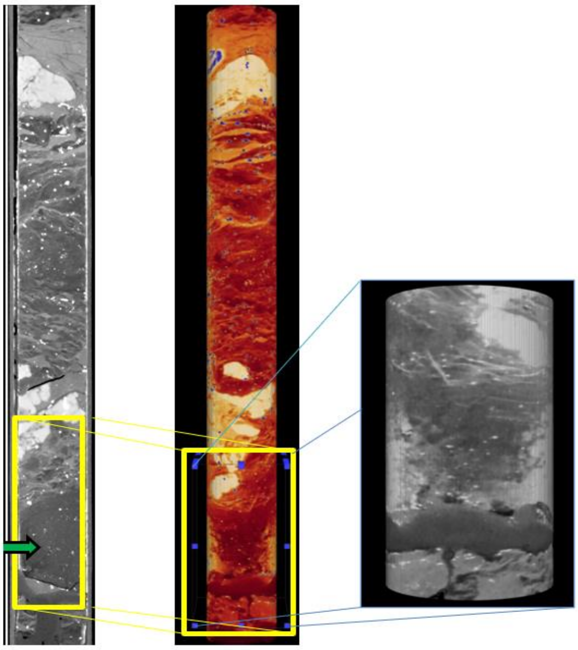

Fig. 4 Selection of best interval and volume rendering creation.

At the same time, the operator could observe the interior ortho slices in XY, YX and XZ axis that will allow the early identification of any small features and structures which cannot be observed only with the three-dimensional core volume visualization (Figure 5).

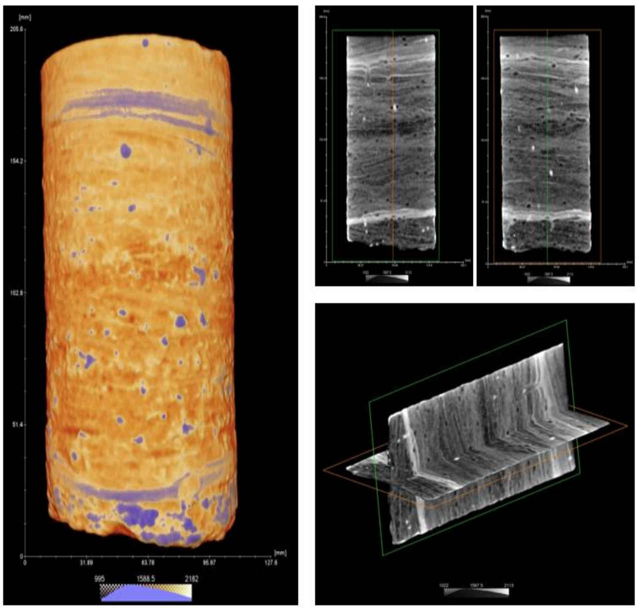

Fig. 5. Example of 2D ortho slices from a selection interval.

At this stage in the workflow, the software allows the generation of a small cylinder (Figure 6) that will extract only the portion of the core that is inside the cylinder volume while eliminating the rest of the image information. By creating a new volume rendering, the virtual plug is generated, and it can again be presented as a 3D volume and with the corresponding 2D slices in all orthogonal XYZ directions.

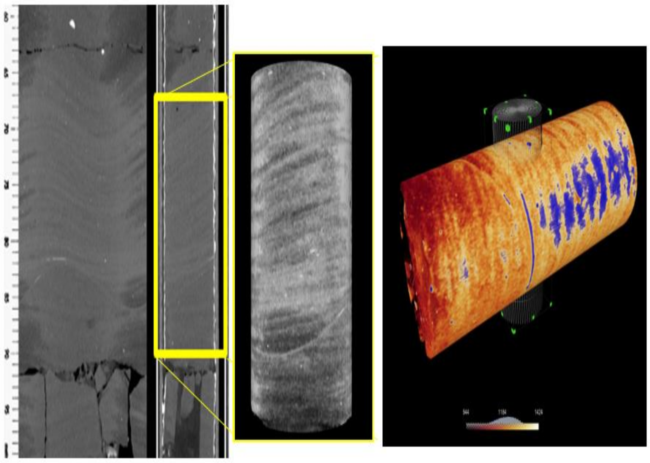

Fig. 6. Virtual plug location following maximum dip angle.

It is important to mention that the cylinder used must be placed perpendicular to the maximum dip orientation (if visible) otherwise the results of the virtual plugging could be erroneous and generate misleading spatial information. This was especially difficult to perform on case study 2 where the amount of crossbedding with high density variation of local depositional angles made the plug location selection more challenging (Figure 7). The virtual plugging process needed multiple attempts to obtain the most suitable samples location/orientation and at the same time maximize the number of plugs per selected core section.

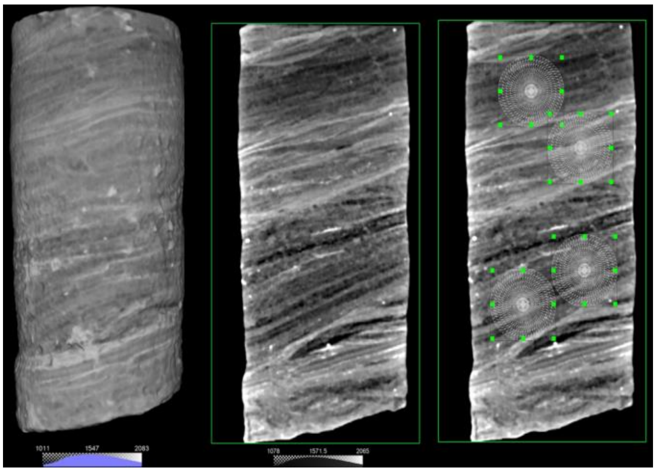

Fig. 7. Virtual plug location following maximum dip angle.

The X-ray CT density colormap or color scale recommended for this type of study might vary depending on operator needs (contrast, intensity, brightness, resolution, and color combination). The authors suggest a standard gray scale, glow, or physics (Figure 8) as they are the optimal options to quickly identify key features such as fractures, microfossils, or high-density minerals.

The colormaps are connected to the individual data field but can also be displayed for all the images and volumes if necessary. In addition, the interval data of different radiodensities in Hounsfield units obtained for each data set should be also included together with the CT images for better visualization of density variation and what has been the threshold boundary values selected by the operator.

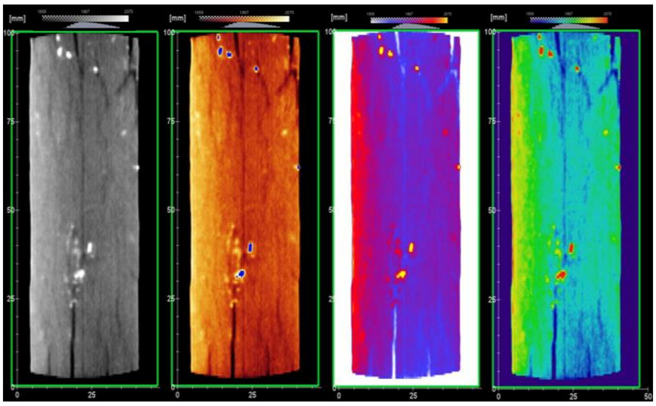

Fig. 8. Example of colormap options for different type of features visualization.

Another option that can be included when performing the virtual plugging assessment is a quick inspection and evaluation of samples heterogeneity with an intensity profile or Hounsfield units' profile (HU).

This HU CT density profile can be constructed along a line (simple linear thresholding for quantitatively examining intensity values across certain data sets) or by taking the whole virtual plug volume. For this study, the authors applied the first method for both cases with an intensity profile plot of a line probe (Figure 9) positioned in the middle of the virtual plug sample.

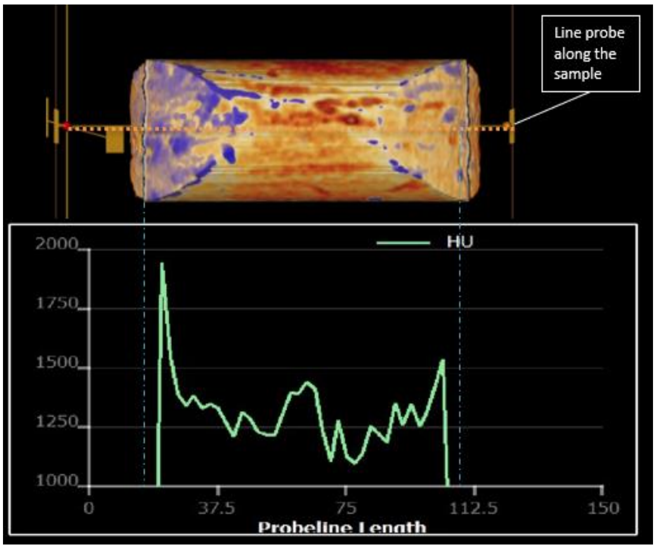

Fig. 9. Example of HU intensity plug profile by line-probe.

One of the last steps to perform is the combination of the virtual plug generated together with the ortho slices from the selected interval to obtain a general outline of the final 3D density variation and sample quality expectations (Figure 10).

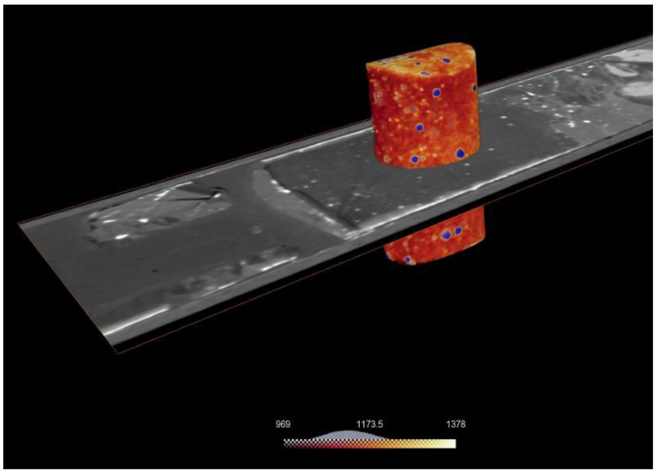

Fig. 10 Visualization of 3D virtual plugs and 2D selected interval core slice.

4 Results

4.1 Core Plugging Case 1

The four inches diameter core was preserved inside fiberglass barrels and stabilized with gypsum offshore due to the fragile nature of the 1-meter cored sections cut at the wellsite (Figure 11). The core sections were properly handled and carefully transported in metal crates with stabilizing foam material inserts to minimize and prevent any mechanical shock during core shipping from the rig site to the laboratory.

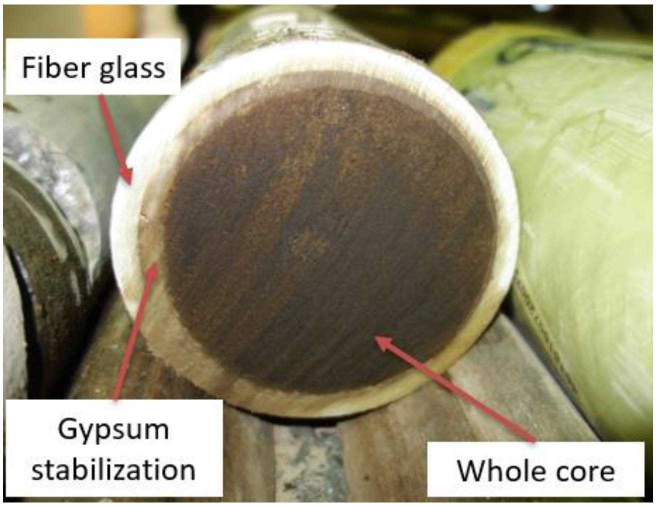

Fig. 11. Example of case study 1 inner core section view.

After the core arrived at the laboratory facility, X-ray CT scan was performed prior to Spectral core gamma measurements with the core still inside the fiberglass inner liner to avoid any evaporation and core material alteration due to additional exposure to air (e.g., oxidation). The virtual plugging technique commenced immediately after the first lengths of core were reconstructed, showing the heterogeneity of some of the intervals pre/selected initially (Figure 12).

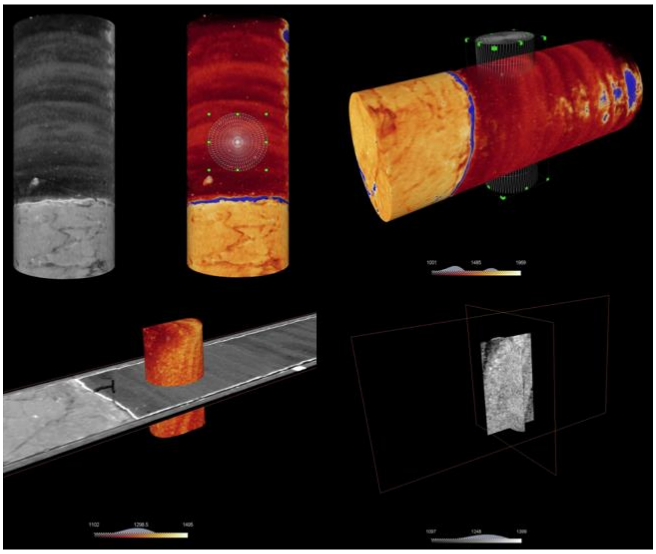

Fig. 12. Example of case study 1 with plug orientation process.

Once virtual plugging was completed, the laboratory proceeded to cut the small sections of the core (Figure 13) and open the fiberglass inner liner by drilling a 2-inch diameter window, this allowed to access to the standard 1.5 inches diameter drill bit to take the sample, the entire process was performed without using any coolant fluid.

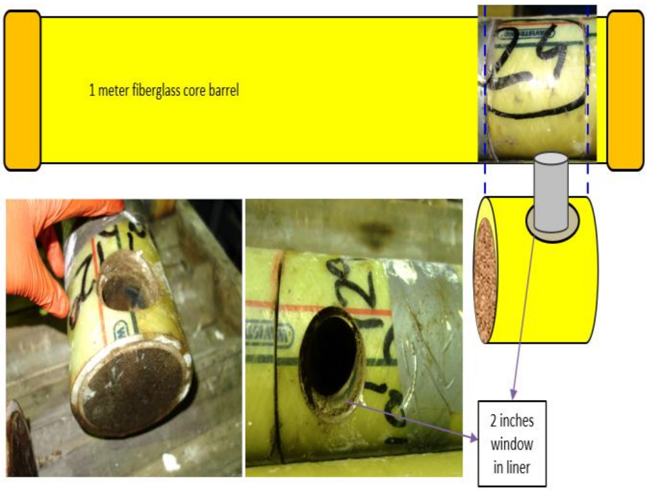

Fig. 13. Schematic drawing of fiberglass barrel and plug drilling.

Once the 1.5 inches plugs were safely collected, the samples were immediately mounted with rubber sleeves, metal end-stems and loaded in core holders for further SCAL analysis. The sampling operation was extraordinarily successful with only two samples partially broken after extraction due to extremely fragile nature of the core material.

4.2 Core Plugging Case 2

The core was received from the wellsite encapsulated in aluminum inner barrels, no core stabilization was performed offshore, and the core barrel annulus was filled with only oil-based drilling mud. After the core surface was cleaned and the selected intervals identified, the team re-oriented the core according to the information obtained from CT scans (Figure 14). The plugging in this case was performed using mineral oil as drill bit lubricant.

The core orientation process for this case was particularly challenging as the detection of heterogeneities or crossbedding lamination observed in the core surface varies internally with different dip angles. The virtual plugging methodology helped the laboratory technicians to quickly identify the location and orientation of the pre-selected plugs before drilling.

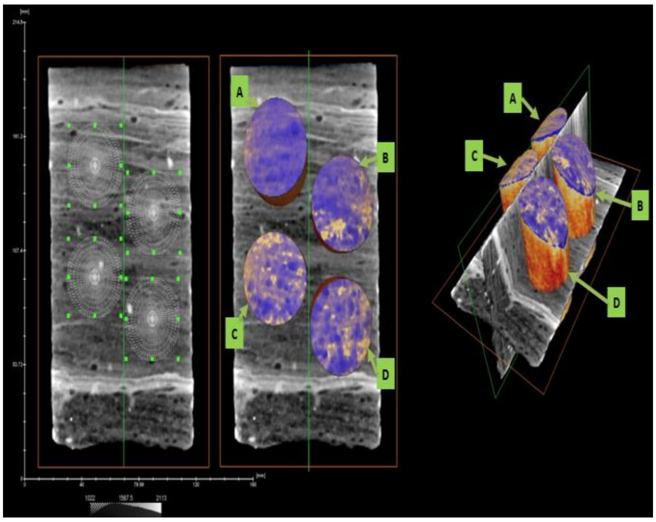

Fig. 14. Example of case study 2 with plug orientation process.

After plugging, and before sample preparation (cleaning and drying) a digital image of each plug was acquired under white light conditions (Figure 15). By comparing the different plug images, it is possible to visualize the challenges in identifying sample laminations and heterogeneities only from the simple evaluation of core samples by visual inspection.

The plugging operation was a complete success with no damaged or broken samples after whole core sampling. This approach helped to obtain a suitable and high-quality set of plugs for each specific rock type and for further advanced analysis originally planned such as capillary pressure, electrical properties, and relative permeability measurements.

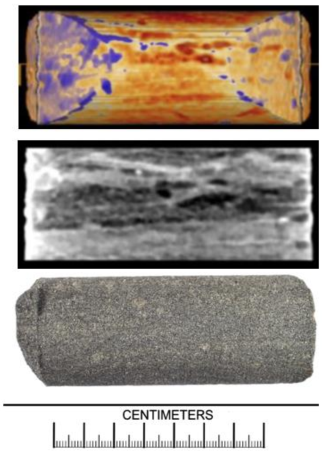

Fig. 15. CT plug image using virtual plugging and White light photo comparison.

Conclusions

- This study has shown step by step how 3D X-ray CT virtual plugging methodology has been a paramount step in the design of a core analysis workflow by improving core plugs quality, representativeness, and an increased rate of success during whole core sampling operations. This early-stage screening approach allowed the execution of a successful petrophysical measurements SCAL program for lithologically complex, heterogeneous, and poorly consolidated sandstone reservoirs.

- We have demonstrated the capability of the 3D CT virtual plugging technique in two scenarios where the imaging of whole core samples was crucial for obtaining the most suitable and representative plugs for Special Core Analysis. The combination of standard Computed Tomography on whole core and the 3D CT virtual plugging technique represents an ideal and consistent approach for an improved early-stage core characterization, evaluation on lithological challenging cores.

- It is recommended to implement a similar laboratory methodology and protocols when the core has been stabilised at the wellsite and cannot be easily extruded from the inner tube making it difficult to properly orient the core by looking at the visible bedding and/or when the formation is very heterogeneous or highly laminated.

- 3D virtual plugging requires an investment in commercial software for digital rendering visualization, image segmentation, and analysis as the standard tools. Software modules used for conventional CT scanning in hospitals or clinics are not well adapted to the final fit-to-purpose of virtual plugging for core analysis.

- This technique can be implemented efficiently in a shorter timeframe (e.g., a few hours) after the whole core section within the inner barrel has been received at the laboratory facility and CT scan and 3D images have been reconstructed. The virtual plugging information can be evaluated in close collaboration with the customer at early program stages to agree on final plug depths selection, expected samples quality and proper orientation.

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