UNCERTAINTY REDUCTION IN THE EVALUATION OF POORLY CONSOLIDATED, THIN BEDDED CORE USING X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

Thin layer sedimentation and poorly consolidated rock are common features in many reservoirs. We have used X-ray Computed Tomography (X-ray CT) on whole core, in fibreglass or aluminium sleeves, to tackle three significant problems relating to estimation of the reserves in these reservoirs, namely:

- to detect and quantify the thin sandstone layers (width of the order of a few cm).
- to reduce the uncertainties in porosity measurements
- to obtain porosity information of adequate resolution.

The advantage of X-ray tomography is the possibility to analyze the cores without removing them from the inner tubes and therefore without subjecting them to mechanical stress which could jeopardize their integrity.

The thickness of the layers, often in the range of a few centimetres, and the unconsolidated nature of the material usually does not permit accurate petrophysical characterization with conventional core analysis techniques due to the difficulty in taking representative plugs.

Moreover, the best resolution available from wireline porosity measurements is only about 30 cm. Using X-ray CT we were able to determine the porosity variation at high resolution using only a few reference standard measurements to calibrate the CT scale and integrating the resultant bulk density values with other data (such as grain density and fluid saturation) coming from routine core analysis and NMR relaxometry measurements.

Subsequent comparison with the sedimentological description on sleeved and slabbed core confirmed the success in identifying both position and dimension of thin sandstone beds. Porosity data revealing significant variations with respect to conventional measurements will be shown in real cases.

INTRODUCTION

Turbiditic sequences with interbedded sand and shales in centimetric to metric thick levels is the main reservoir type for gas production in the Adriatic Sea.

The vertical resolution of the traditional logging tools is insufficient to define the productive levels in the context of thin bedded formations. More complex evaluation models must be used, based on data from wireline tools having vertical resolution that is comparable with the thickness of the layers. However, although lithology differentiation can be obtained downhole with a resolution of a few centimetres, the best resolution available for wireline porosity measurements is about 30 cm. This is not adequate for pore volume evaluation in reservoirs of this kind.

In these cases, high resolution studies of core provide important additional input to the determination of the petrophysical characteristics.

Unfortunately, another typical problem is the poor consolidation of core. These lithologies represent a big challenge as far as handling, plugging and conventional core analysis is concerned [1].

The quality of core analysis data is dependent on the condition of the core material used in the laboratory. Many works have been published on this subject suggesting and discussing different approaches to stabilize the unconsolidated cores in order to obtain representative plugs and thus reliable experimental results, including: freezing [2-3], resin injection [4], gypsum injection [5] and elastomer sleeve [6].

However, these techniques are not easily available worldwide and the results are rather questionable or conflicting [7].

Moreover, in thin bedded reservoirs, the size of the layers is often unsuitable for conventional core analysis.

For these reasons, a new approach has been developed based on X-ray Computed Tomography (X-ray CT) measurements on preserved cores directly in their inner tubes. In fact, an important advantage of X-ray CT is that the poorly consolidated core can be assessed and measured prior to removal from its protective sleeve (fibre glass or aluminium), plugging or other induced mechanical damage. This work describes the improvements of the methodology presented in a previous paper [8].

BACKGROUND

The principle on which X-ray CT is based is the attenuation which an X-ray beam undergoes on passing through a rock [9]. This attenuation depends on the density of the minerals which form the rock according to Beer's law:

$$I = I_S \cdot e^{-\mu \cdot L} \qquad (1)$$

where I is the intensity measured at the detector, I_S the initial intensity of the incident X-ray, L the length (or thickness) of the material penetrated and μ is the linear attenuation coefficient which is related to the density of the material being studied.

In fact, in the presence of a homogeneous material, Beer's law becomes:

$$I = I_S \cdot e^{-(\mu/\rho)\cdot \rho L} \qquad (2)$$

where μ/ρ is the linear attenuation coefficient per unit of mass and ρ is the density of the material.

In practical applications, the attenuation coefficient measured by X-ray CT is a numerical value, called *CT number*, calibrated in accordance with an international standard (Hounsfield units, H [10]) in which the attenuation value of water is equal to zero and that of air equal to -1000 H. Using appropriate attenuation standards with known density, it is possible to correlate the CT number with the bulk density of the rocks. But the attenuation coefficient of the rock, although directly related to bulk density, is also influenced by mineralogical composition, thus the relationship between CT number and bulk density is potentially lithology dependent. This is an issue to be considered later.

PROCEDURE

In this work the X-ray images were acquired with a fourth-generation medical CT scanner using a single energy level of 130 kVp and 100 mA. The spatial resolution was about 0.5 mm with a minimum slice thickness of 1 mm. To obtain reliable results, the scanner was carefully calibrated to optimise the “beam hardening correction”.

The experimental procedure provides the acquisition of a preliminary overview image (radiograph scan) of the core taken through the full thickness without removing the core from its sleeve.

From this preview scan, some useful information can be obtained, as shown in Figure 1 :

- quality of coring (whether or not mechanical damage, mud invasion, etc. occurred)
- lithology changes
- dimension and orientation of beds

As already mentioned, X-ray CT describes the variation of the linear attenuation coefficient, or CT number, of the rock. It is preferable to extract this quantitative information from tomographic slice images transverse to the axis of the core.

Tomographic scans of slice width 5 mm are usually taken at 10 mm intervals along the length of the cores but this value (depth resolution) can be adjusted to the scale of the layers (observed in the overview image) with a minimum slice thickness of 1 mm. Our CT scanner takes four seconds to acquire the data for reconstruction of a slice image so the measurement time is about 10 min. per metre. The quantitative measurements on the images are restricted to intact rock avoiding man made artefacts such as coring damage and mud invasion (see Figure 2).

Data can be obtained even from damaged sections since the measurements can be made on any small intact fragment of rock. From each slice, an average CT-number is obtained representing the average attenuation coefficient of the rock.

The linear attenuation factor is directly proportional to the density of the core; thus a linear correlation can be found between CT number and bulk density. Using a few reference materials (attenuation standards) with a known bulk density, the calibration curve is obtained. It is important to choose uniform reference materials with a mineralogical composition as similar as possible to the investigated lithology [11]. Calibration scans must be acquired with the same scanner setup (slice thickness, energy, acquisition time, etc.) and in the same conditions as the core samples (i.e. reference materials inside an aluminium or fibreglass sleeve).

For the applications shown in this work, four sandstones were used, having similar mineralogy but different bulk densities (Figure 3). The calibration is focussed on the sands as the shales are not important in terms of storage and productivity.

Applying this correlation to each slice, and therefore to each CT number, a bulk density value is obtained every centimetre.

After the removal of the core from the inner tubes, some core plugs (1 inch diam.) are immediately collected both in sand and shale layers. Grain density is measured using an

Helium pycnometer, while the fluid saturation(*) is estimated using NMR relaxometry and/or conventional extraction on core plugs. Usually these values are not effected by the errors caused by the plugging of the samples.

A mean grain density and fluid saturation value for sand and shale is determined for each metre of core. The porosity is then calculated using the well-known equation:

$$\Phi = \frac{\rho_{grain} - \rho_{bulk}}{\rho_{grain} - \rho_{fluid} \cdot S_{fluid}} \qquad (3)$$

where ρ_{grain} is the grain density, ρ_{bulk} the bulk density, ρ_{fluid} the fluid density and S_{fluid} the fluid saturation , as reported in Figure 4.

RESULTS

Applying equation 3 over the entire length of the core, a continuous porosity profile (CT porosity log) is obtained with a vertical resolution of the centimetre scale. The variation of the porosity describes the thin layers of the core and it is in very good agreement with the sedimentological description carried out on the sleeved and slabbed core. In Figure 5, two examples of one-metre core crops are shown.

As expected, the comparison with porosity data coming from conventional core analysis confirms that conventional measurements tend to overestimate the porosity of sand layers (with differences up to 4-5 p.u.) because of the poor representativeness of the core plugs. As already mentioned in the introduction, with these unconsolidated lithologies getting intact core plugs is a very difficult task and the samples often lose their integrity during the plugging process.

In any case, as shown in Figure 6, conventional plug measurements are not capable of describing in detail the porosity variation of the core.

In addition, by calculating an average porosity of the shale zones and using this datum as a cut-off value, it is possible to estimate, in the cored interval, a "net/gross" to be compared with that obtained from the well logs.

CONCLUSIONS

- X-ray CT is a non-invasive method to evaluate poorly consolidated cores in their inner tubes.
- It offers a quick and reliable method of providing bulk density and porosity data in thin bedded lithologies.
- CT porosity measurements on poorly consolidated cores are more accurate than conventional plug measurements.
- Quantitative data can be obtained with a depth resolution, appropriate to the scale of the sequence, which cannot be achieved by other methods.
- This is a significant improvement for refining the storage estimates of unconsolidated, thin bedded reservoirs.

(*) Liquid fluid (brine, oil) detectable by NMR

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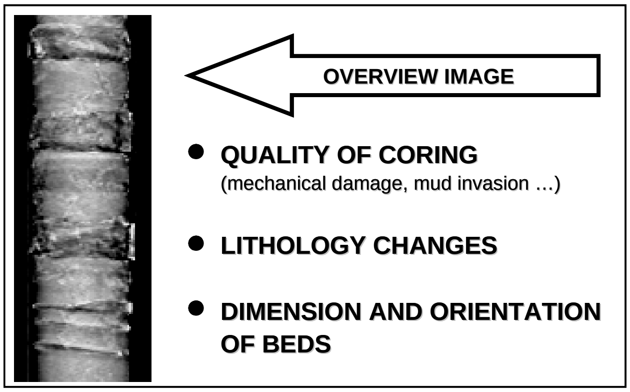


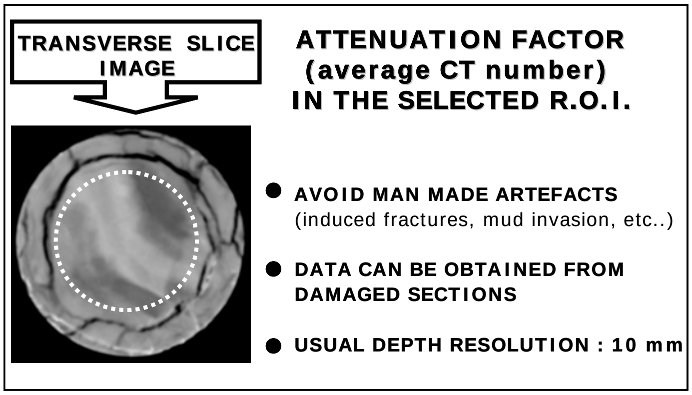
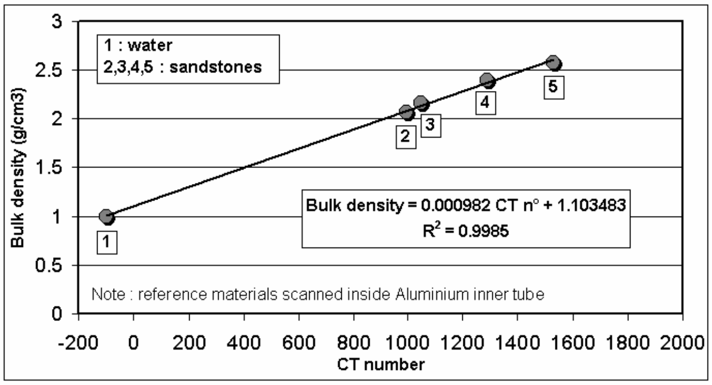
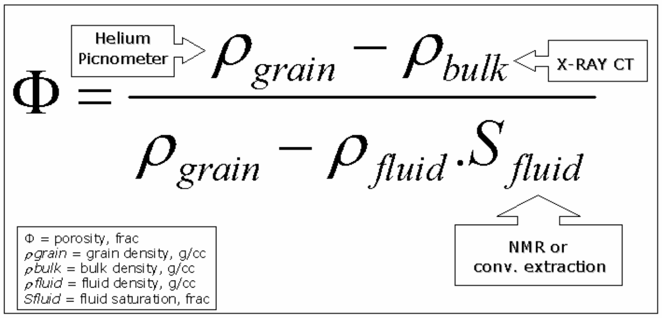


Figure 1. Visual information.

Figure 2. Quantitative information.





$$\Phi = \frac{\rho_{grain} - \rho_{bulk}}{\rho_{grain} - \rho_{fluid} . S_{fluid}}$$

Figure 3. CT number – Bulk density correlation.

Figure 4. Porosity calculation.

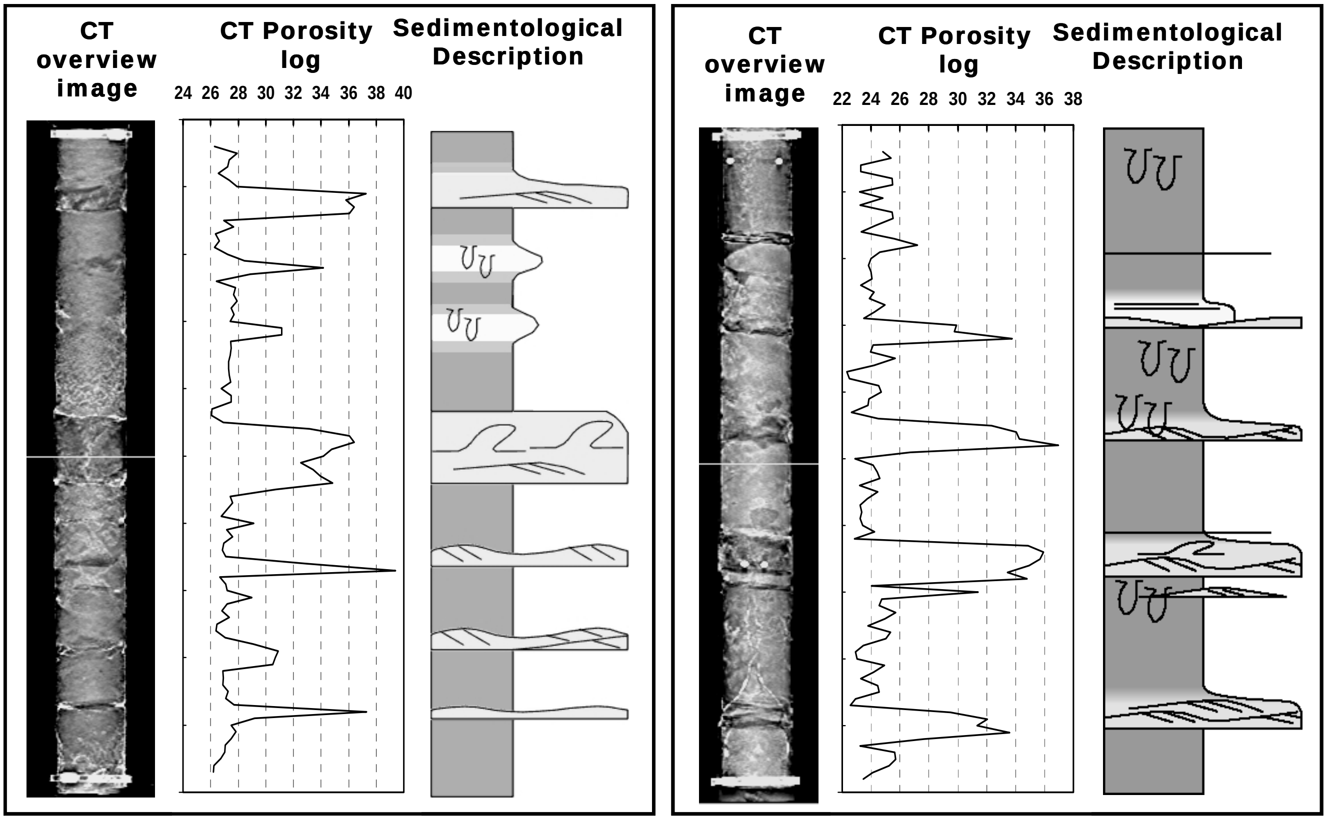


Figure 5. CT Porosity log and Sedimentological description.

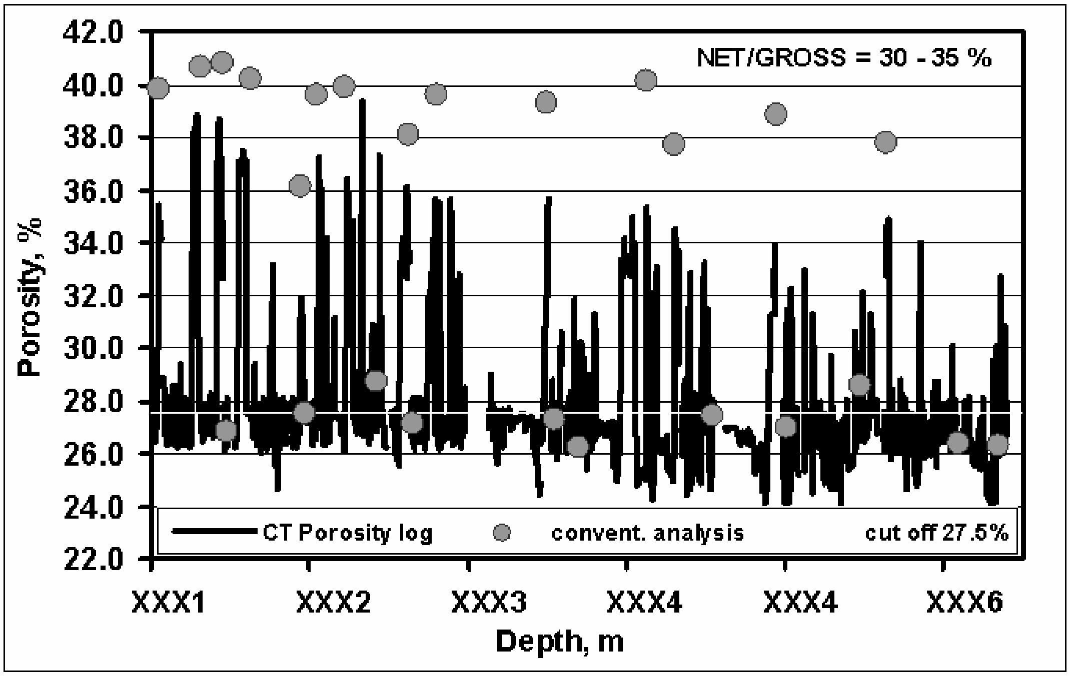


Figure 6. Conventional and CT porosity comparison with “net/gross” estimation.