The use of high-resolution 3D X-ray microtomography in carbonate reservoir studies

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Aims. To understand complex carbonate reservoirs, it is necessary to study the different mineral phases building up the reservoir rocks and their relation with size, shape and connectivity of the available pore space. Moreover, understanding early and late diagenetic processes responsible for the creation of different pore types and the quantification of this wide variety in pore types is important (vital) for the reliable prediction of the reservoir quality in carbonate reservoirs. Traditional petrographical techniques (microscopy of thin sections, including cathodoluminescence and fluorescence microscopy and scanning electron microscopy (SEM)) limit the observations to two dimensions. This paper illustrates how high-resolution 3D X-ray microtomography can give insights in the 3D characterization and quantification of mineral phases and petrophysical characteristics of complex carbonate reservoirs. In particular, two case-studies are presented: Khuff carbonates (yielding a high oomoldic porosity with different degrees of dolomitisation and anhydrite cementation/replacement), and hydrothermal dolomites (to calculate the amount of post-hydrothermal pore occluding calcite to define the original pore distribution). For the latter, the coupling of 3D imaging data with more conventional petrographical techniques is illustrated by a new calibration method. The potential of 3D X-ray microtomography to understand the spatial variability in petrography (rock fabric and texture, mineralogy, grain contacts, pore structure) and petrophysical parameters is discussed.

Method. The SkyScan 1173 was used to visualize rock plugs. The use of a stable 8W-source of 40 to 130 keV with spot size smaller than 5 micron allows to study samples with high attenuation coefficients (like rock samples). Combined with the use of a flat panel detector (2240 by 2240 pixels) whereby the glassfibres are lead-coated to assure a longer live time when high-energy X-rays are used, reservoir features (mineralogy, rock fabric and texture, pore structure) can be studied in great detail. This set-up (combination source-detector) reduces beam hardening drastically, making the quantification of different mineral phases and pores easier, and avoiding the use of time-consuming dual-energy techniques (Remeysen and Swennen, 2008). To scan 2D thin-sections (for calibration studies) the SkyScan 1172 X-ray microtomography scanner was used. The samples were scanned with an X-ray microfocus tube with a tungsten reflection target using a voltage of 60kV and the maximum current at this setting (167µA for the 10W source). In order to cut off the lower energy part of the X-ray spectrum, a 0.5µm Al filter was used. In this way a better contrast in the X-ray shadow images (judged from the glass plate carrier) was obtained and beam hardening artifacts were reduced. The X-ray camera was set to the highest resolution (2096 by 4000 pixels, no binning). A frame averaging of 8 and a rotation step of 0.2° was used in order to retrieve enough signals from the thin layer. The sample was rotated over 180°.

Results.

Khuff carbonates
Khuff carbonates are well-known for their high oomoldic porosity. Basically, it is a porous intraclastic (oolitic) pack- to grainstone (Figs. 1 & 2). Locally the rock is dolomitised and a whitish pore blocking poikiliotopic anhydrite phase is clearly visible (Fig. 1). The
dolomitisation, responsible for the creation of an intercrystalline porosity, and the pore blocking anhydrite will affect the pore network (porosity, permeability) and other petrophysical parameters (i.e. acoustic and elastic properties, micromechanics of grain contacts, capillary pressure). Figure 2 represents the 3D reconstruction of such carbonates. The red and the dark blue colours correspond respectively with anhydrite and dolomite (Fig. 2B-C) and the light blue with porosity (Fig 2A). The brown colour in Figure 2A-B-C corresponds with calcite. It is obvious that from these reconstructions volumetric contributions of different minerals as well as sample homogeneity/heterogeneity can be deduced. The quantification of 3D volumes is necessary for advanced Pore Network Modelling.

Figure 1: A. Thin section representing high porous oomoldic grainstone with isopachous rim cements. B. Thin section illustrating a partly dolomitised relict grainstone, with pore blocking poikiliotopic anhydrite. C, An and D represent respectively calcite, anhydrite and dolomite.

Figure 2: 3D reconstruction of the Khuff sample (Skyscan 1173), with repartition of calcite (brown), anhydrite (red), dolomite (dark blue) and porosity (light blue)

Hydrothermal dolomites: case study for a new calibration procedure
Hydrothermal dolomites are complex carbonate reservoir types. Microtomographic scanning allows quantifying and distinguishing the amount of post-hydrothermal pore occluding calcite from the dolomite phases (Fig. 3). This is necessary to understand the intercrystalline dolomite pore distribution. To distinguish calcite from dolomite is complex and not that straightforward due to similar attenuation coefficients of both minerals. However, scanning directly 2D thin sections enables a more consistent quantification of similar rock constituents and might be an important calibration procedure in the interpretation of 3D CT-data. Moreover, this approach can be seen as an important step in the development of an adequate “up-scale” methodology bridging the gap between 2D and 3D petrography, each
characterized by different scales and resolutions. Figure 3 represents how calcite and porosity can be segmented on scanned 2D thin sections.

**Figure 3:** Microtomographic scanned thin section (Skyscan 1172) of hydrothermal dolomites, representing (after segmentation) the pore-occluding calcite phase, the porosity created by microfractures and the intercrystalline porosity.

**Conclusion.** It can be concluded that X-ray microtomographic scanning has a lot of potential to become a common tool to better understand complex carbonate reservoirs. The possibility to quantify mineral phases and pore networks, as well as the estimation of petrophysical properties based on such 3D quantifications is an important development. The coupling of 3D imaging data to scanned 2D thin sections (i.e. a microtomographic approach of classical petrographical microscopy) is an important calibration step.

**References.**