

# Evaluation of Rock Properties and Rock Structures in the µ-range with sub-µ X-ray Computed Tomography

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## SUMMARY

High resolution X-ray micro CT has become a very powerful tool for 3D analysis of core and rock samples. The results can be obtained in a non-destructive way and yields to conclusions for a better understanding of rock structures, mineral composition and fluid flow in the pore space just to name a few.

Tendencies of modellers to analyse rock properties at scales going down to µm and even nm forces the industry to develop appropriate equipment for sub-µ applications. The examples chosen in this paper emphasize the capability of the used X-ray  $\bar{C}\bar{T}$  systems to fulfil modellers' requirements and cover different fields of investigation like reservoir rocks, volcanology and palaeontology with resolutions down below 1 µm.

The described method enables geo-scientists to receive 3D models of their rock samples at sub-µ scale with extraordinary contrast resolution and opens them not only new possibilities in modelling research but also can speed up all further rock analysis by properly choosing slices for thin sectioning as an example. Furthermore not only palaeontologists will appreciate that they are able to virtually cut their valuable samples for visualization without any physical destruction at all.

Key words: Rock Physics, X-ray CT, Reservoir Rock Analysis, Core Analysis

## **INTRODUCTION**

In recent years high resolution X-ray Computed Tomography (CT) for geological purposes contribute increasing value to the quantitative analysis of rock properties. Especially spatial distribution of minerals, pores and fractures are extremely important in the evaluation of reservoir properties. The possibility to visualize a whole plug volume in a nondestructive way and to use the same plug for further analysis is undoubtedly currently the most valuable feature of this new type of rock analysis and will be a new area for routine application of high resolution X-ray CT in the near future.

The paper outlines new developments in hard- and software requirements for high resolution CT. It showcases several geological applications which were performed with the phoenix nanotom and recently phoenix nanotom m, the first 180 kV nanofocus CT system tailored specifically for extremely high-resolution scans of samples up to 240 mm in diameter and weighing up to 3 kg with voxel-resolutions down to <300 nm.

# **HIGH-RESOLUTION COMPUTED** TOMOGRAPHY

In many fields like biology, geology or engineering, CT with nanofocus X-ray sources allows the researcher to explore sample structures into the sub-micron regime. In recent years major steps in important hardware components like open microfocus or even nanofocus X-ray tube technology on the one side and the development of highly efficient and large flat panel detectors on the other, allowed the development of very versatile and high resolution laboratory CT systems like the phoenix nanotom m (GE Sensing & Inspection Technologies). Electromagnetic focusing of the electron beam allows generating X-ray beams with an emission spot diameter down to well below one µm which is essential for CT examination with voxels-sizes in the sub-micron range. These characteristics with respect to spatial resolution principally allow CT measurements which valuably complement many absorption contrast setups at synchrotron radiation facilities [Withers 2007; Brunke et al. 2008; Kastner et al. 2010].

In order to cover the widest possible range of samples the CT system has to be equipped with an X-ray tube, manipulation stage and detector which allow in the sum a detail detectability in the sub-micron range. Therefore the phoenix nanotom m is equipped with a 180kV/15W X-ray tube with adjustable spot size  $< 0.9 \,\mu\text{m}$ . The spot size predominates the image sharpness for extreme magnifications (for details see e.g. Brockdorf et al. 2008). On the other hand, the X-ray tube can generate up to 15 Watt power at the target and enables the penetration of high absorbing geological samples like ore.

The manipulation system is based on granite stone to ensure optimal mechanical accuracy and long term stability of the setup. Together with a high precision rotation unit, samples can be moved and rotated with extremely high precision. On the detection side a unique 7.4-megapixel GE DXR flat panel detector (CsI scintillator) with an active area of 307x240 mm2 is used. The extremely high dynamic range of > 10000:1, combined with 100µm pixel size and a 1.5x virtual detector (i.e. 461 mm detector width) give rise to a wide variety of experimental possibilities.

# BENTHEIMER SANDSTONE: MINERAL ANALYSIS

The first example shows a typical reservoir rock of the North German Basin a so-called Bentheimer sandstone (sample diameter Ø 5 mm) scanned with 1 µm voxel size to extract information about the distribution of mineral components in the matrix. In fig. 1b is shown the 3-D distribution of three rock phases (quartz yellow, feldspar orange and pyrite blue). The pores and clay particles (less dense materials) are faded out in this visualization. The orange coating around the quartz grains is weathered quartz and has similar density as the feldspar (plagioclase). Analysing the volume in quantitative manner yields extremely valuable 3D information for the petrologists.



Figure 1 a+b. 3-D visualization (a) with greyscale and (b) after segmentation of different rock types (different colours see above)

## PYROCLASTIC ROCK: MINERAL STRUCTURES AT HIGHEST RESOLUTION

As a next example a very porous pyroclastic rock ( $\emptyset$  3 mm) from Etna (Sicily) has been examined at a resolution of 1  $\mu$ m on the phoenix nanotom m (see fig 2) showing the possibility to study the spatial variation of mineral structure within the accuracy of 1 micron. The resulting volume data can be used in general to produce extracted surface data for any CAD application and furthermore for FEM modelling for hydrogeological purposes.





Figure 2a+b. 2-D images through the reconstructed volume of a pyroclastic rock (view width: (a) 1.4 mm and (b) 520  $\mu$ m). (a) shows a cross section of the whole sample and the right image (b) gives a very detailed impression of the internal grain structure, measured wall thickness 1.8  $\mu$ m.

# MARINE MICROFOSSILS: A 2-mm-LARGE NUMMULITE

The last examples (fig. 3+4) shows a specimen of Nummulites, a 2-mm-large marine microfossil from the Lower Eocene of Belgium, about 53 million years old.

The sample ( $\emptyset$  3 mm) was scanned with 1.6 µm voxel size and figures 3 and 4 show impressively that such an nondestructive investigation at pore scale is possible with no doubt and that evaluation of tomographic slices enables modelling at micron range.



Figure 3. Virtual cut through the 3D reconstructed volume of a Nummulite. The pore space is faded out to visualize the amazing fractal structure of this fossil.



Figure 4. Zoom into a tomographic slice through the volume of the Nummulite sample to measure pores as small as 2 microns  $(2.3 \ \mu m)$ 

## CONCLUSIONS

Since density transitions usually indicate boundaries between materials or phases, CT data is usually intuitive for geoscience professionals to evaluate. Due to the digital form, 3D data can be used for quantitative analysis as well as for a variety of measurement and visualization tasks.

Powerful software enables rapid reconstruction and visualization of the volume data allowing the user to extract and view internal features and arbitrary sectional views. The phoenix nanotom m is the first 180 kV nanoCT system featuring voxel resolutions of less than 300 nanometers (< 0.3  $\mu$ m). The nanotoms ability to deliver ultra high-resolution images of any absorbing internal object detail at virtually any

angle caters to even the most complex geological and petrological applications.

The phoenix nanotom m was designed with the primary goal of meeting the unique needs of high-resolution computed tomography and comes standard with a 180 kV high-performance nanofocus tube equipped with a diamond window for optimized electron density, 7,4-Megapixel GE DXR digital detector, and high speed reconstruction unit for the processing of the volumetric data. The 180 kV high power nanofocus tube enables the inspection of even high absorbing materials such as ore, while the large DXR digital detector and a 1.5-position virtual detector enlargement enable extreme high resolutions and optimal flexibility for a sample range from 0.25 mm to 250 mm diameter.

Today's high-resolution X-ray CT with its powerful tubes and great detail detectability lends itself naturally to geological

trological applications. Those include the nonerior examination and textural analysis of rocks ermeability and porosity, the study of oil n reservoir lithologies, and the analysis of nd density distribution in sediments – to name

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