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Qualitative and quantitative investigation of microstructures within porous rocks by using very high resolution x-ray micro-CT imaging

Gerhard Zacher[1], Matthias Halisch[2], Peter Westenberger[3], Samaresh Changdar[4]

Summary

Today's high-resolution X-ray CT with its powerful tubes and great detail detectability lends itself naturally to geological and petrological applications. Those include the non-destructive interior examination and textural analysis of rocks and their permeability and porosity, the study of oil occurrences in reservoir lithologies, and the analysis of morphology and density distribution in sediments – to name only a few. Especially spatial distribution of pores, mineral phases and fractures are important for the evaluation of reservoir properties. The possibility to visualize a whole plug volume in a non-destructive way and to use the same plug for further analysis is undoubtedly the most valuable feature of this type of rock analysis and is a new area for routine application of high resolution X-ray CT. All presented geological CT volume evaluations were performed with GE's phoenix nanotom, a 180 kV/15 W nanofocus CT system tailored specifically for extremely high-resolution scans of samples weighing up to 3 kg with voxel-resolutions down to < 300 nm.

In our first sample we will show a typical reservoir rock scanned with 1 µm voxel size to characterize the pore space and to extract information about the distribution of mineral components. The segmented in-situ porosity could be easily used for fluid flow modelling purposes, to predict permeabilities and complex flow processes within these structures. Next, a very porous pyroclastic rock has been examined at a resolution of 5 µm. The data set has been analysed with the Avizo software tool XLab Hydro. The resulting velocity field can be visualized whereas the colour mapping visualizes the velocity's magn itude. The resulting volume data can as well be used to produce surface data for any CAD application and furthermore for FEM modelling for hydrogeological purposes.

Keyword: *micro-CT imaging*

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 mineral phases, pores and fractures are important for the evaluation of reservoir properties. The possibility to visualize a whole plug volume in a non-destructive way and to use the same plug for further analysis is undoubtedly the most valuable feature of this type of rock analysis and is a new area for routine application of high resolution X-ray CT.

The paper outlines recent 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

[1]GE Sensing & Inspection Technologies GmbH, Niels-Bohr-Str. 7, 31515 Wunstorf, Germany
[2]Leibniz Institute for Applied Geophysics, Stilleweg 2, D-30655 Hannover, Germany
[3]VSG • Visualization Sciences Group, Wernigeroder Str. 129, 40595 Düsseldorf, Germany
[4]GE Oil & Gas India, 402, 4th Floor, C Wing, Delphi, Hiranandini Park, Powai, Mumbai, IN
Email: samaresh.changdar@ge.com

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 1 µ m and even below, 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 [1], [2], [3].

In order to cover the widest possible range of samples, the CT system is equipped with an X-ray tube, a manipulation stage and a detector, which allow in the sum a detail detectability in the sub-micron range. The phoenix nanotom m is equipped with a 180 kV/15W X-ray tube with an adjustable spot size of down to < 0.9 µ m, since this parameter predominates the image sharpness for extreme magnifications [4]. On the other hand, the X-ray tube can generate up to 15 Watt power at the target and enables penetration of high absorbing geological samples and mineral phases, respectively. The manipulation system is based on granite to ensure optimal mechanical accuracy and long term stability of the setup, including a high precision sample rotation unit. On the detection side a unique 7.4 megapixel GE DXR flat panel detector (CsI scintillator) with an active area of 307 x 240 mm is used. The extremely high dynamic range of > 10000:1, combined with 100µ m pixel size and a 1.5x virtual detector (i.e. 461 mm effective detector width) give access to a wide variety of experimental possibilities.

Bentheimer Sandstone: Complex Qualitative and Quantitative Analysis

The first example shows a typical reservoir rock of the North German Basin a so called Bentheimer sandstone (sample diameter 5 mm) scanned with 1 µ m voxel size to extract (e.g.) information about the distribution of mineral components, as well as to characterize the pore space within for petrophysical applications. In fig. 1b the 3-D distribution of three rock phases (quartz yellow, feldspar orange and zirconia blue) is exemplarily shown. The pores and clay particles are faded out in this visualization. The orange coating around the quartz grains is weathered quartz and has similar density as the feldspar. Analyzing the volume in quantitative manner yields extremely valuable 3D information for the petrologists. Especially the investigation of microporosities (e.g. caused by clay or dissolved mineral phases) within porous rocks (fig. 2) has become of great interest for the oil and gas industry in terms of enhanced reservoir characterization and oil and gas recovery from these types of void space. The segmented in-situ porosity could be easily used for fluid flow modelling purposes, to predict permeabilities and complex flow processes within these micro-structures.

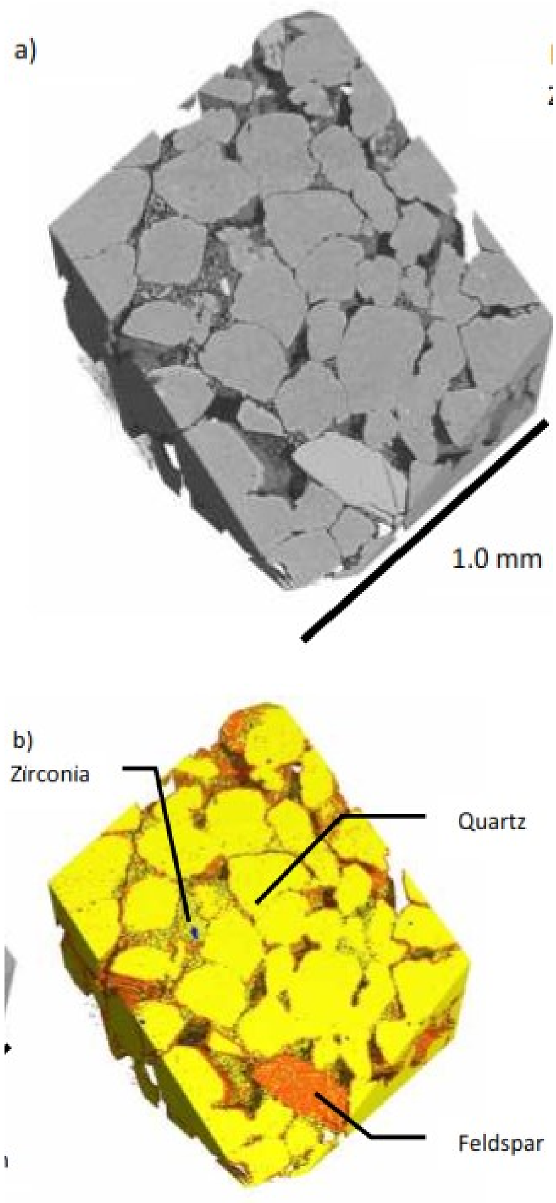

Figure 1: 3-D visualization with greyscale (a) and after segmentation (b) of different mineral types.

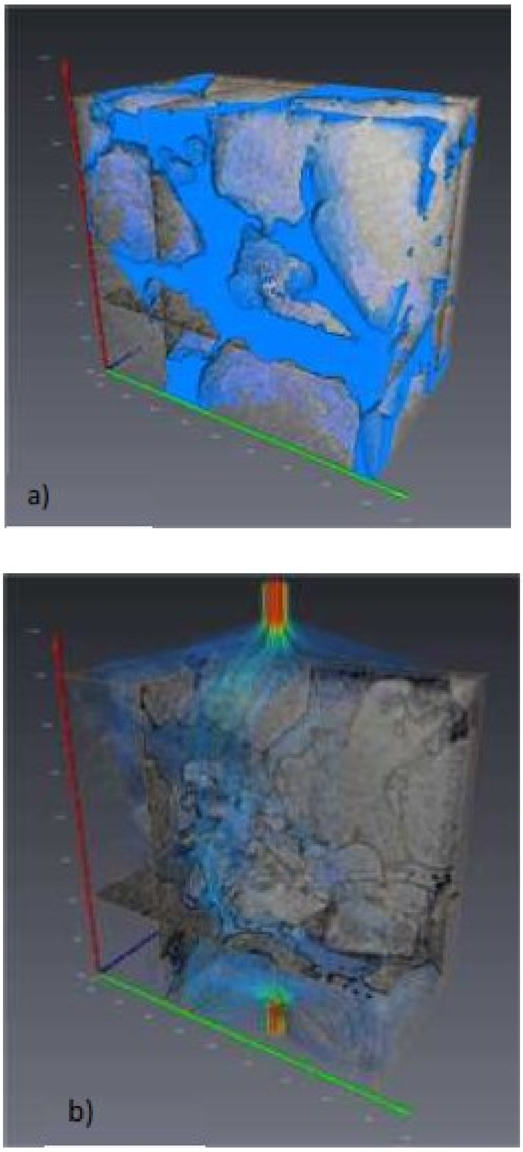

Figure 2: 3-D visualization of segmented microporosity within the scanned Bentheimer Sandstone (a) and streamline visualization of fluid flow (b) within this void space derived by Avizo (VSG).

Pyroclastic Rock: Mineral Structures at Extremely High Resolution

Next, a very porous pyroclastic rock (Ø 3 mm) from Etna (Sicily) has been examined at a resolution of 1 µ m on the phoenix nanotom m (fig. 3) showing the possibility to study the spatial variation of mineral structure within the accuracy of 1 micron. The resulting volume data can be used to produce surface data for any CAD application and furthermore for FEM modelling for (e.g.) hydrogeological purposes.

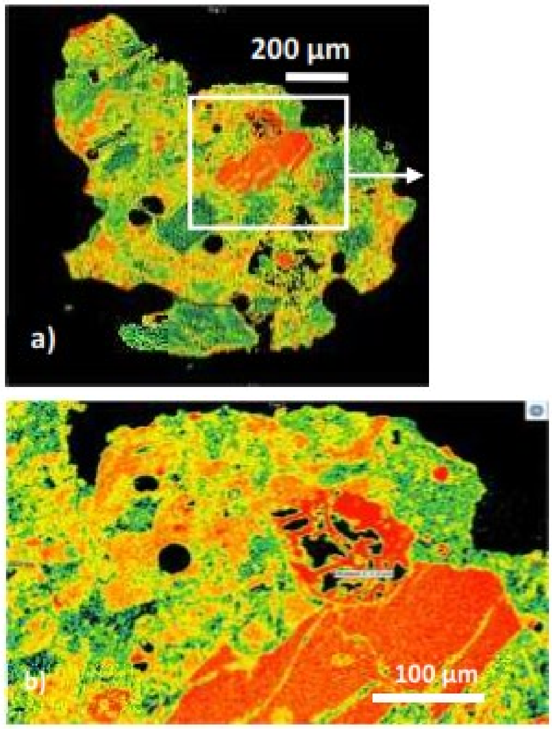

Figure 3: 2-D images through the reconstructed volume of a pyroclastic rock (view width: (a) 1.4 mm and (b)520 µm). (a) shows a cross section of the whole sample and the right image (b) gives a very detailed impression of the internal grain structure, measured wall thickness 1.8 µm.

For another rock sample from Etna, a scan with 5 µ m voxel resolution has been performed (fig. 4a). The data set has been analyzed with the Avizo software tool XLab Hydro for simulation of the fluid flow through this highly porous material. The resulting velocity field can be visualized (fig. 4b) using a technique called “line integral convolution” (LIC) whereas the colour mapping visualizes the velocity’s magnitude.

Summary

Since density transitions usually indicate boundaries between materials or phases, CT data is 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 tha 300 nanometers. The ability of the nanotom CT system 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 and petrophysical applications.

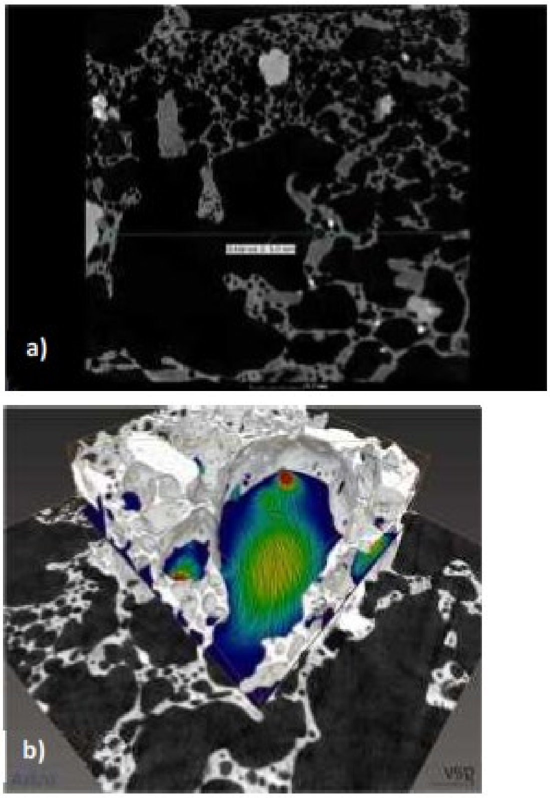

Figure 4: (a) 2-D image through the reconstructed volume of a pyroclastic rock (view width: 5 mm). The right hand image (b) visualizes in 3D the results of fluid flow modelling performed by Avizo software.

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, 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 in diameter.

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References

Brunke, O., Brockdorf, K., Drews, S., Müller, B., Donath, T., Herzen, J., Beckmann, F., 2008. „Comparison between x-ray tube-based and synchrotron radiation-based µCT" in Developments in X-Ray Tomography VI, edited by Stuart R. Stock, Proceedings of SPIE, Vol. 7078.

Withers, P., 2007. "X-ray nanotomography", Materials Today, 10(12), 26-34.

Kastner, J., Harrer, B., Requena, G., Brunke, O., 2010. "A comparative study of high resolution cone beam X-ray tomography and synchrotron tomography applied to Fe- and Al-alloys", in NDT & E Int. vol 43, pages 599-605.

Brockdorf, K. et al., 2008. "Sub-micron CT: visualization of internal structures" in Developments in X-ray Tomography VI, edited by Stuart Stock, Proceedings of SPIE, Vol. 7078.