QUALITATIVE AND QUANTITATIVE INVESTIGATION OF MICROSTRUCTURES WITHIN POROUS ROCKS BY USING VERY HIGH RESOLUTION X-RAY MICRO-CT IMAGING

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ABSTRACT

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 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 permeability and complex flow processes within these structures.

Next, two very porous pyroclastic rock samples have been examined at a resolution of 1 and 5 µm. One data set has been analysed with the Avizo software tool XLab Hydro. Besides permeability tensor, porosity and pressure drop, the resulting velocity field of the fluid particles can be directly visualized whereas the colour mapping indicates the velocity's magnitude. The resulting volume data can be used to produce surface data for any computer-aided design (CAD) application and furthermore for FEM modelling for hydrogeological purposes.

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 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 variable sized 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- and the development of highly efficient and large flat panel detectors 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 generation of X-ray beams with an emission spot diameter down to 1 µm 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].

The phoenix nanotom m is equipped with a 180 kV/15W X-ray tube with an adjustable spot size down to < 0.9 µm. Since this parameter predominates the image sharpness for extreme magnifications [4], it allows a detail detectability within the sub-micron range of about roughly 1/3 the achieved spot size. 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 granite-based to ensure optimal mechanical accuracy and long term stability of the setup, including a high precision sample rotation unit (up to 7200 slices per 360°). 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 100 µm 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 called Bentheimer sandstone (sample diameter 5 mm) was scanned with 1 µm voxel size to extract the information about the distribution of mineral components, as well as to characterize the pore space for petrophysical applications. In fig. 1 the 3-D distribution of three rock phases (quartz yellow, feldspar orange and zirconia blue) is exemplarily shown. The pores and clay particles are voided in this visualization. The orange coating around the quartz grains is weathered quartz and has similar density as the feldspar. Analyzing the volume in a quantitative manner yields extremely valuable 3D information for petrologists. Especially the investigation of microporosities (e.g. caused by clay or dissolved mineral phases – here: void space in range / size of voxel resolution) within porous rocks (fig. 2a,b) 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 spaces. The segmented in-situ porosity could be easily used for fluid flow modelling purposes, to predict permeability and complex flow processes within these micro-structures.

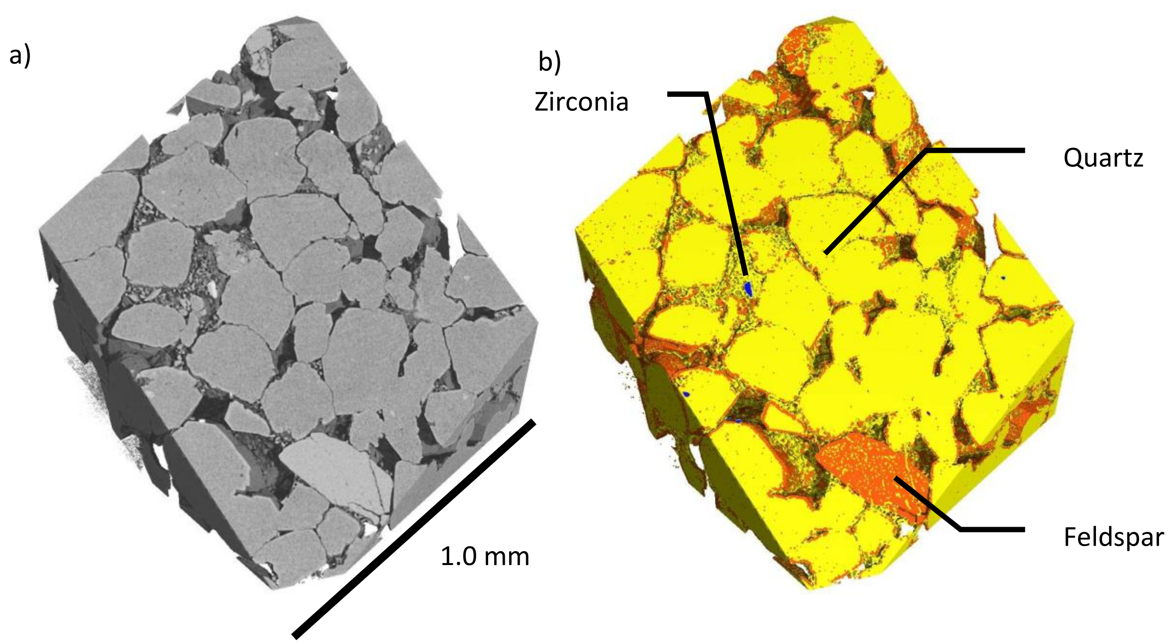

Figure 1: 3-D visualization with greyscale (a) and after segmentation (b) of different mineral types.

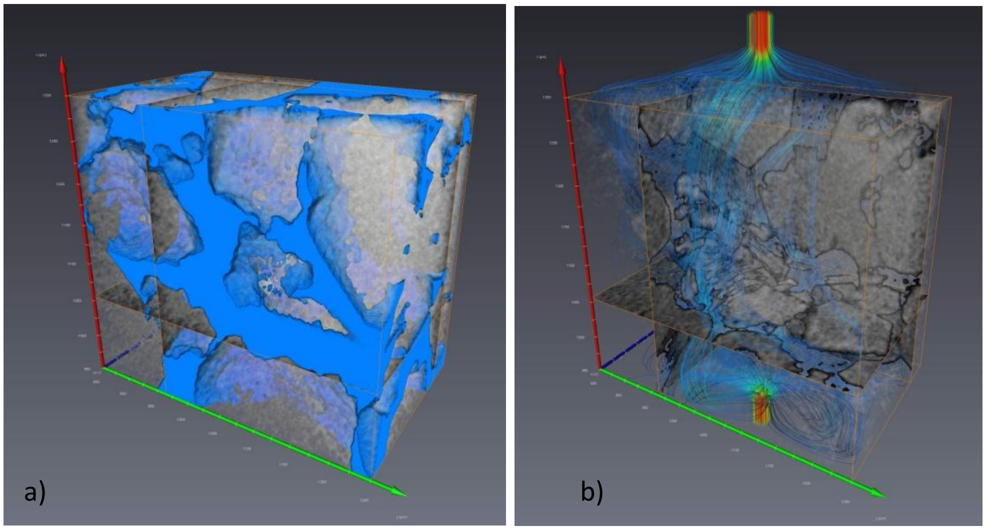

Figure 2: 3-D visualization of segmented microporosity within the scanned Bentheimer Sandstone (a) and streamline visualization of fluid flow (b) within this void space derived by Avizo (VSG).

PYROCLASTIC ROCK: MINERAL STRUCTURES AT EXTREMELY HIGH RESOLUTION

Next, a very porous pyroclastic rock (Ø 3 mm) from Etna (Sicily) was examined at a resolution of 1 µm 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.

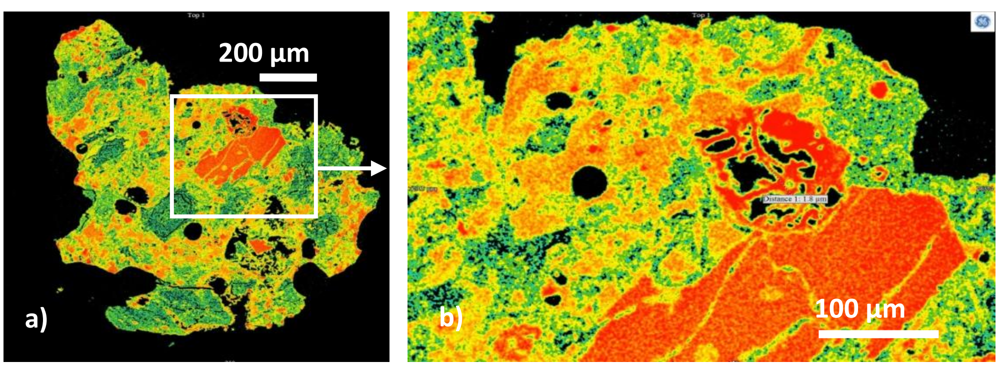

Figure 3: 2-D images taken from the reconstructed volume of a pyroclastic rock (view width: (a) 1.4 mm and (b) 520 µm). (a) a cross section of the whole sample and the right image (b) demonstrates a very detailed impression of the internal grain structure, measured wall thickness 1.8 µm.

For another rock sample from Etna, a scan with 5 µm voxel resolution was performed (fig. 4a). The data set was 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. The LIC algorithm works by convolving a random noise image along the projected field lines of the incoming vector field using a piecewise-linear hat filter. The synthesized texture clearly reveals the directional structure of the vector field inside the cutting plane.

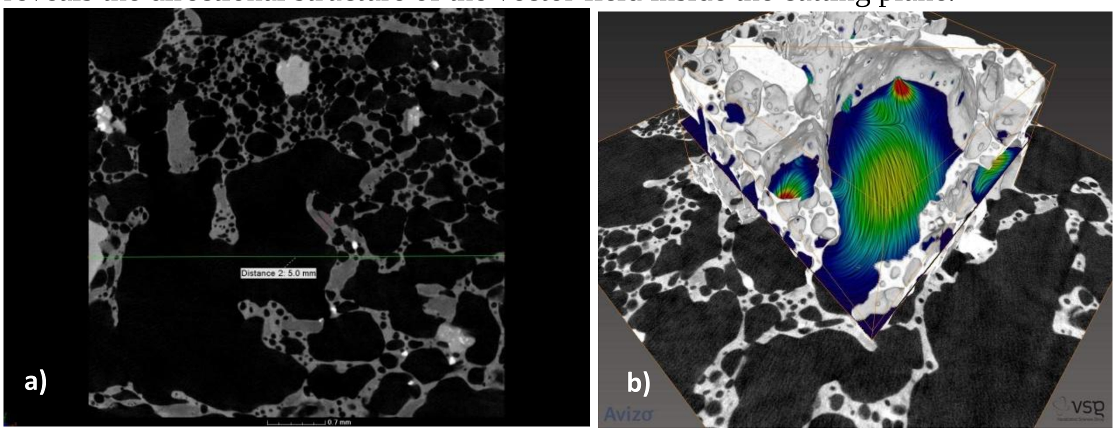

Figure 4: (a) 2-D image taken from the reconstructed volume of a pyroclastic rock (view width: 5 mm). The right hand image (b) visualizes in 3D the results of fluid flow modelling performed by Avizo software.

CONCLUSIONS

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 than 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 petrophysical applications. This enables scanning small core plugs (5-10mm diameter) with a voxel resolution of 1 µm and to achieve high contrast results within 2 hours scan time and only 5 min reconstruction time. Powerful software tools like Avizo (vsg) can be further used not only to visualize the 3D data set, but also to perform segmentation, modelling and last but not least visualization of the modelled data.

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

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