

3D Modeling of Fracture Flow in Core Samples Using μ -CT Data

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Introduction: Standard permeability measurements are performed on plug samples recovered from drill cores through insertion of gas at high pressure. Since these methods are tailored to “normal” porous rocks and fractured samples frequently disintegrate during the measurement process or even during sample preparation, permeability values are difficult to obtain this way. Micro Computed Tomography (μ -CT) offers a non-destructive opportunity for assessment of porosity distribution. The present study investigates the possibilities of numerical modelling for calculation of permeability on the basis of these porosity models.

μ -CT Data Acquisition: The distribution of fractures in the core samples was assessed using μ CT, where similar to CT used in medicinal application multiple X-ray images of one sample are recorded. From these records a 3D image of the fracture distribution can be reconstructed. The resolution of the resulting image is in the range of about ten to hundred μ m, depending on the size of the sample. The workflow of data acquisition is displayed in Figure 1.

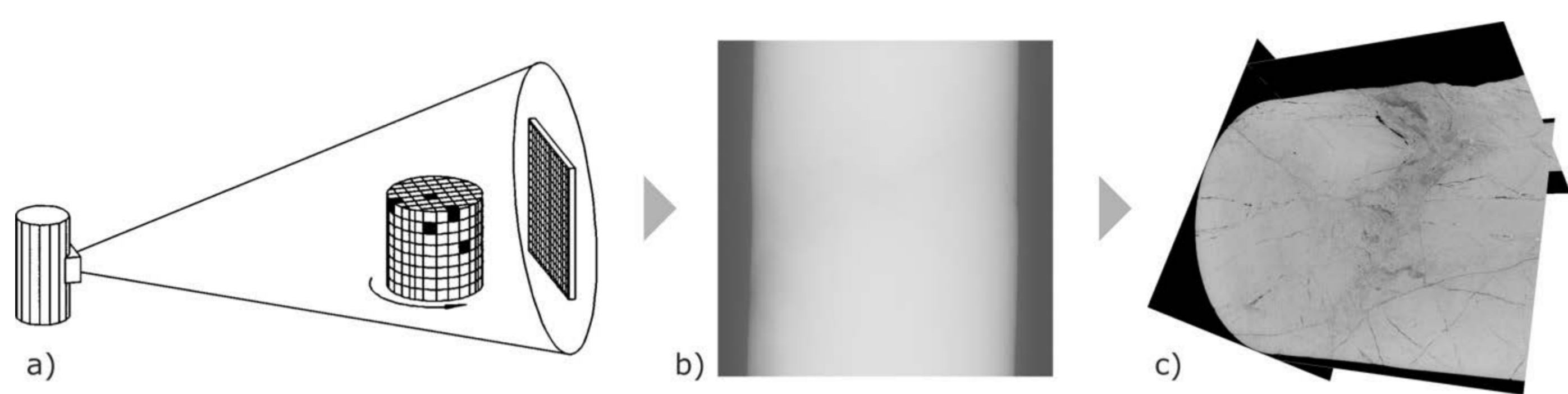


Figure 1. a) Schematic drawing of a cone beam scanning setup. The sample rotates stepwise within a cone-shaped X-ray beam, generated by the X-ray source. For each rotational step, a so-called radiogram is recorded by the detector [1].

b) Example of a radiogram, representing one single rotational step in the μ CT scan. All radiograms of the μ CT scan are combined by a process termed reconstruction into 3D volumes and/or 2D stacks of slices.

c) Slice-based representation of one of the used samples after reconstruction.

Meshing: After reconstruction, the datasets need to be segmented and binarised to serve as input for “Iso2Mesh”, an open-source Matlab toolbox for creation of surface as well as volumetric meshes from 3D images [2]. First, a surface mesh on the basis of an isosurface is created and subsequently populated with tetrahedrons. The output of Iso2Mesh are two Matlab-variables: One containing the node coordinates and the other containing the element list of the tetrahedral mesh. Using this information a “nastran” file can be written that can be transferred to COMSOL. Using the new “Box selection” technique it is possible to split the boundary in a way, that inflow/outflow boundary conditions can be set on opposing sides of the model to stimulate fluid flow in the three space dimensions (see Figures 2 and 3).

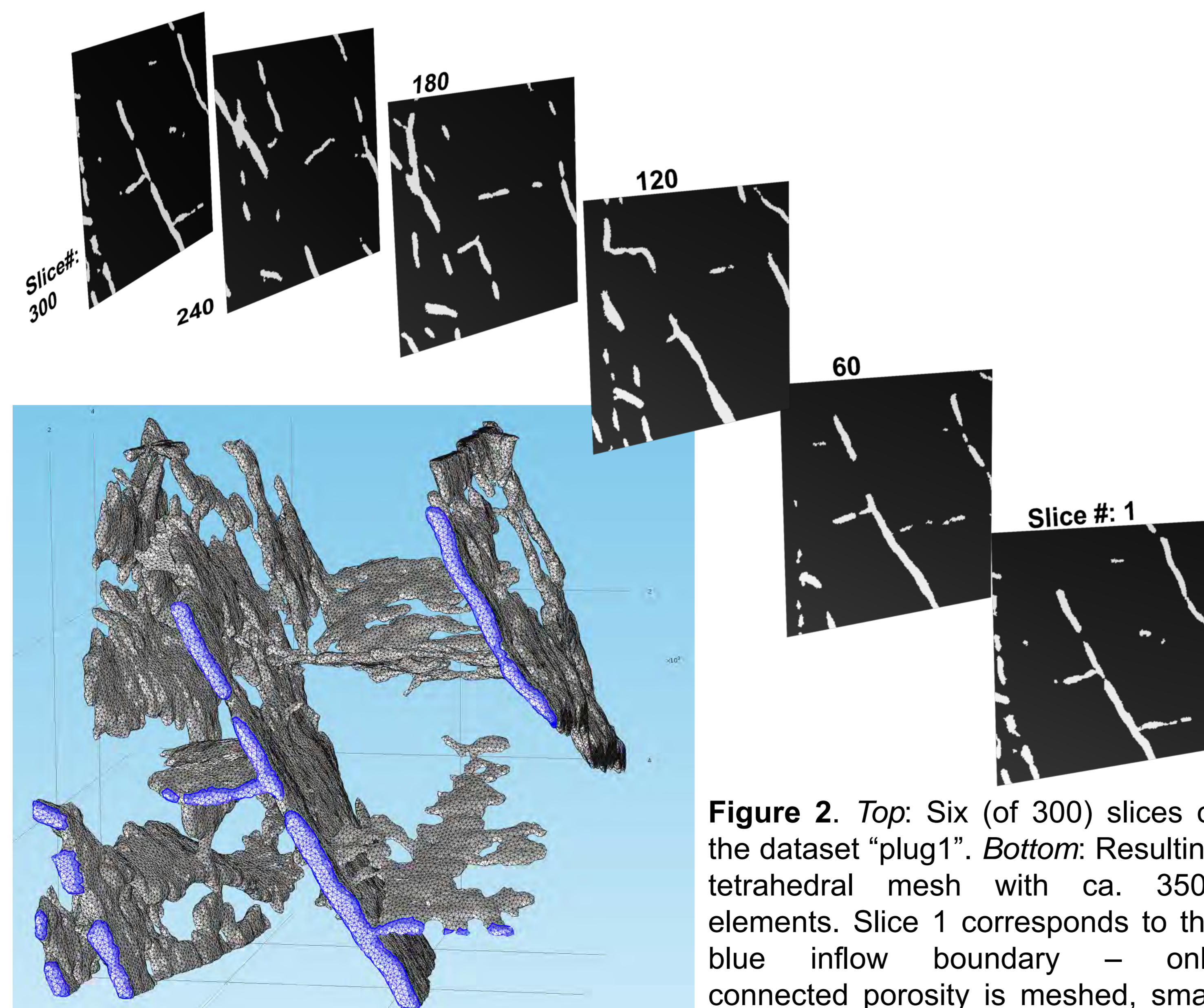


Figure 2. Top: Six (of 300) slices of the dataset “plug1”. **Bottom:** Resulting tetrahedral mesh with ca. 350k elements. Slice 1 corresponds to the blue inflow boundary – only connected porosity is meshed, small features are neglected.

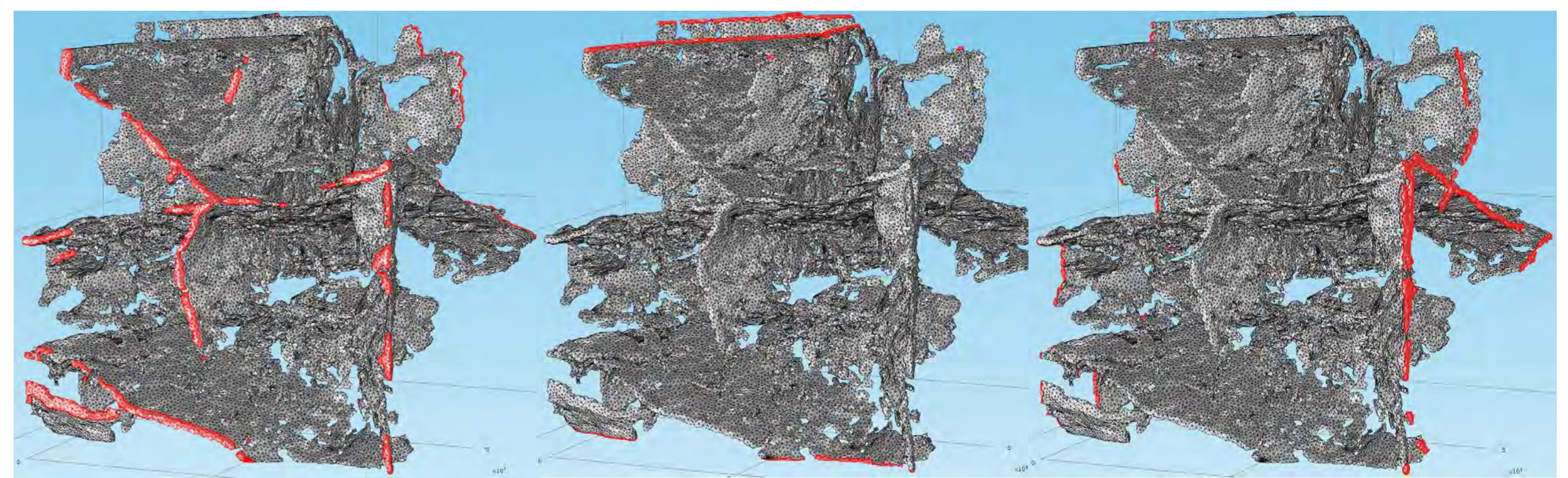


Figure 3. Tetrahedral mesh (ca. 500k elements) created from a larger (and much more complicated) dataset. Red: In-/ outflow boundaries.

Flow calculation is carried out using the ‘Creeping flow’ module in COMSOL. Flow is induced through a pressure difference on two opposing boundaries using a “constant pressure boundary condition”. Prior to steady state solving, a short (3 sec) transient study step with a ramped boundary condition is solved, to provide consistent initial values. The idea is to calculate the directional permeability values according to Equation 1:

$$K = \frac{Q \cdot \eta \cdot l}{\Delta p \cdot A} \quad \text{Equation 1: } K - \text{permeability [m}^2\text{]}, Q - \text{total flow rate [m}^3\text{/s]}, \\ \eta - \text{dynamic viscosity [Pa}\cdot\text{s]}, p - \text{pressure [Ps]} \text{ and } A - \text{total cross-sectional area.}$$

Permeability calculation: The total flow through the model (Variable ‘Q’; see Equation 1) is the integral of the normal velocity component over the cross-sectional area. Assuming incompressible flow, the total flux Q is a conserved quantity and can be evaluated statistically through averaging in multiple slices. Furthermore the permeability can be evaluated using different dynamic viscosity values (e.g. air, water, crude oil, etc.). The normal velocity component is exported on a regular grid (100³ points). Thus the calculation of Q is reduced from an integral to the sum of all normal velocities at all export nodes of one slice multiplied by the square of the spacing of the regular grid.

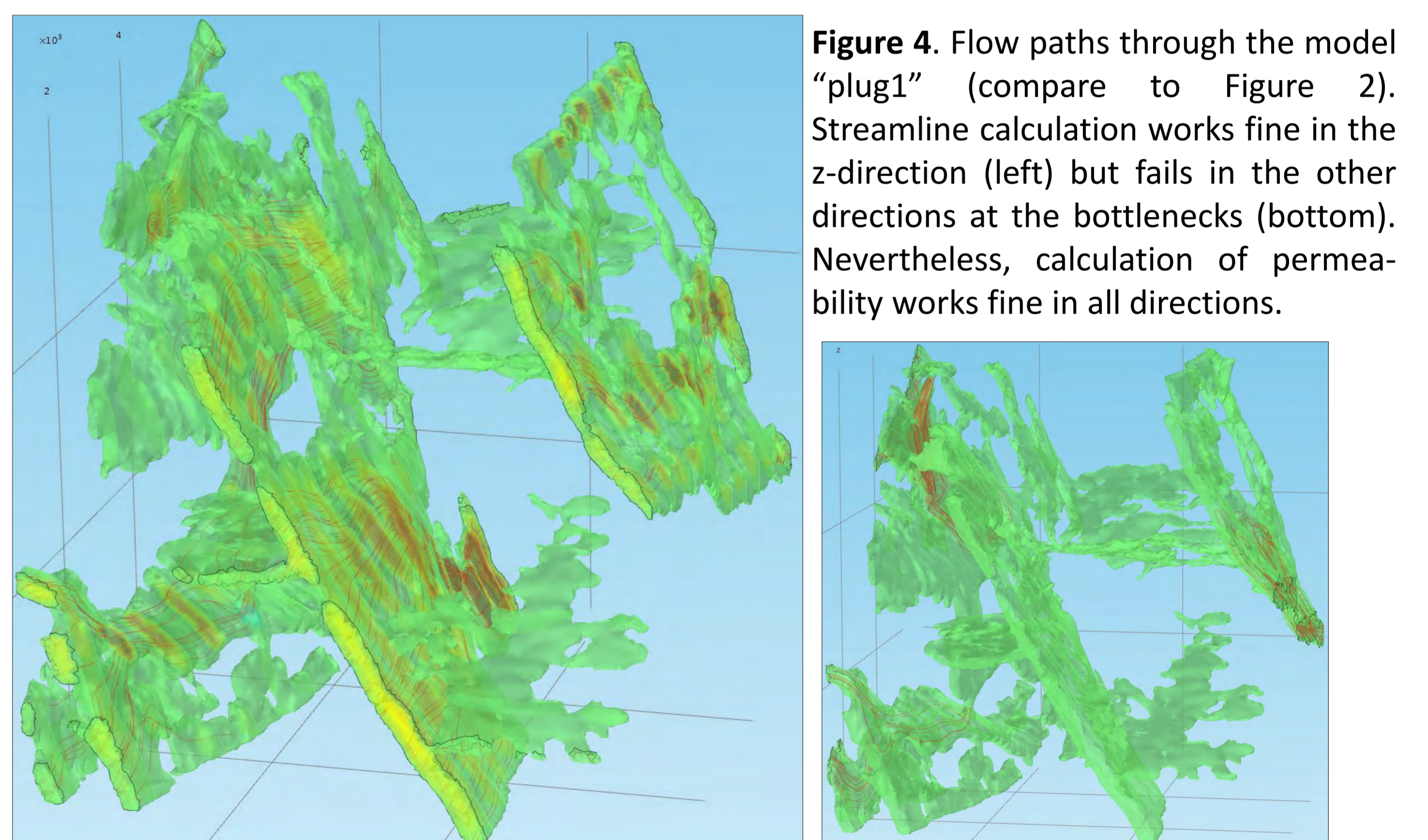


Figure 4. Flow paths through the model “plug1” (compare to Figure 2). Streamline calculation works fine in the z-direction (left) but fails in the other directions at the bottlenecks (bottom). Nevertheless, calculation of permeability works fine in all directions.

Results: The primary results of the present study are permeability values for the core samples according to the three space dimensions. The results will be validated via laboratory measurements of the corresponding samples. Additionally we will be able to analyse the discrete flow paths and pressure variations inside the models. The final aim is to find a method for upscaling the so-achieved results towards reservoir size and derive universally valid conclusions for the fluid flow in fractured reservoirs.

References:

1. Klobes et al., 1997, Rock porosity determination by combination of X-ray computerized tomography with mercury porosimetry. Fresenius' Journal of Analytical Chemistry, 357(5): 543-547.
2. Qianqian and Boas, Tetrahedral mesh generation from volumetric binary and gray-scale images, Proceedings of IEEE International Symposium on Biomedical Imaging 2009, pp. 1142-1145, 2009