PS Using X-Ray Microtomographic Imaging to Conduct Fluid Flow Simulations on Porous Media*

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Abstract

In recent years, X-ray micro-computed tomography (µCT) has become an important and useful tool for characterizing the 3-D internal microstructure of porous media. Although the materials used in different fields of study will have varying compositions, the methods and techniques utilized in µCT are very similar. The aim of this presentation is to identify these similarities by comparing a master's thesis study dealing with the permeability of a sample composed of FeS melt and solid silicate to studies done in the petroleum industry on reservoir rocks.

The purpose of the master's thesis study was to test the hypothesis that shear deformation enhances the connectivity and permeability of Fe-S melt within a solid silicate (olivine) matrix. A 250-ton hydraulic press was used to heat and torsionally deform the sample through six steps of 180° rotation, while µCT was used to obtain in-situ 3-dimensional images of the sample at each step. The resulting digital volumes were processed and permeability simulations utilizing the lattice Boltzmann method were performed to determine the effect of shear deformation on connectivity and permeability within the sample.

The image acquisition, image processing, and data analysis techniques utilized in this study are very similar to those used in the petroleum industry. The major image processing technique performed on the digital volumes in this work was binarization, wherein the melt (fluid) and non-melt (matrix) are identified and segmented (i.e. separated). This same process of segmentation

is conducted on digital volumes of reservoir rocks obtained via μCT, although the phases are different (e.g. cement, oil, gas, brine, and/or open pore space). Also similar to this work is that μCT images of reservoir rocks can be used to determine the porosity, pore connectivity, and permeability of a sample via fluid flow simulations, with quantitative results that can be obtained utilizing techniques such as the lattice Boltzmann method. The main goal of μCT use in the petroleum industry is to aid in predicting the producibility of a reservoir pay zone. μCT has proven to be a valuable tool for determining the properties of porous media, no matter the composition or end goal.

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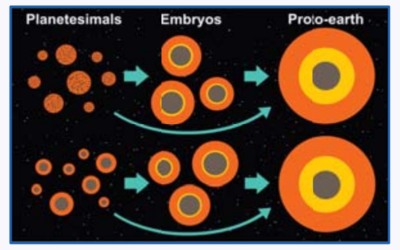
Argonne National Laboratory – Advanced Photon Source

Master's Thesis Research Overview

The effects of shear deformation on planetesimal core segregation: Results from in-situ X-ray microtomography



Relevance: Understanding the mechanisms of core formation in planetesimals furthers the knowledge we have of our own planet

Background:

- Earth formed by the accretion and collision of rocky bodies 10's-100's of kilometers in diameter called planetesimals
- Hf-W chronometry constrains their core formation to only 1-3 My
- Heat Produced by the decay of ^{26}Al likely melted the metallic portion
- Therefore, the expected mechanism of core formation in planetesimals is inter-granular percolation of the metallic melt through the solid silicate matrix (**fig. 1**)
- However, once ~5 vol% melt is left in the mantle, it no longer percolates and becomes stranded in the solid silicate matrix
- Deformation caused by large impacts may have aided in interconnecting this remaining melt, draining it to the core

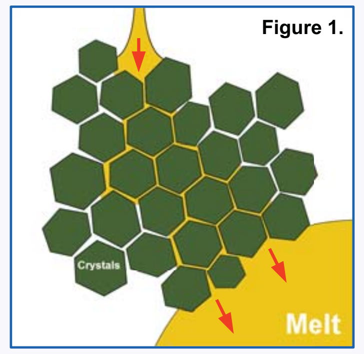


Figure 1.

Objective: Determine if shear deformation increases the melt interconnectedness, and thus the permeability, of a model planetesimal, resulting in rapid and efficient core formation

Experimental Methods:

Piston Cylinder Synthesis – Starting material of powdered olivine + 4.5 vol% troilite (FeS) sintered to attain textural equilibrium in a piston cylinder for 20 hours at 1 GPa & 1250°C

Deformation & Imaging* – Performed at Argonne National Laboratory's synchrotron at the Advanced Photon Source using a Drickamer press to create shear strain (**Fig. 3**) at high pressure and temperature (~2 GPa, 1100°C) and X-ray microtomography to image the sample *in-situ* throughout its deformation (**Fig. 4**, sample assembly)

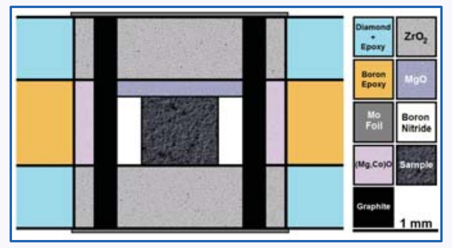


Figure 4.

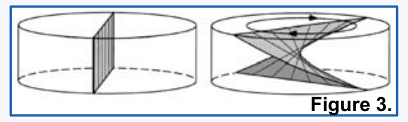


Figure 3.

Results*: X-ray Tomographic (XTM) images processed for the sample at 6 varying degrees of deformation (0°,180°,360°,540°,720°,840°); then permeability simulations were run on each of the resulting digital volumes through 2 flow directions (**Fig. 5**) using the lattice Boltzmann method

- Backscatter electron images were taken of an undeformed sample and the deformed sample in order to verify that an accurate representation of the sample's texture was being made during the processing of the XTM images

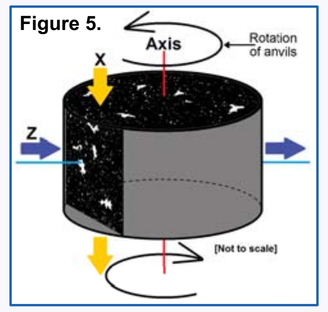


Figure 5.

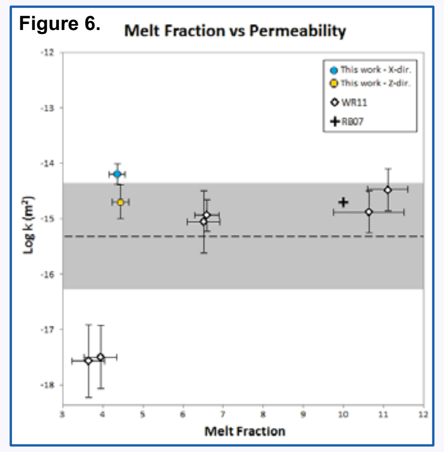


Figure 6.

Conclusions: Permeability did not appear to increase or decrease significantly with increasing deformation, and each permeability value was within 1σ of one another

- **Figure 6.** - The results from this work are comparable to the range of values from previous studies (Roberts et al., 2007, Watson & Roberts, 2011)

Implications: Permeabilities then used to directly calculate migration velocity of a sulfide melt through an olivine matrix

- Migration velocity = 0.40 cm/yr
- ~3.3 cm/yr necessary for core formation within the 3 My constraint
- However, migration velocity is highly dependent upon grain size

*Discussed further in panels 1 & 2

A Closer Look at X-ray Microtomography

What is X-ray Microtomography?

Also called micro-computed tomography (µCT), it is a technique that is used to characterize the 3-D internal microstructure of materials in a nondestructive manner at micron-scale spatial resolution (Landis & Keane, 2010)

X-ray Source: Laboratory-scale methods are available, however synchrotron-based radiation is utilized when the high quality imaging of a dense sample is required

- A synchrotron produces high-intensity, storage ring generated X-rays by accelerating charged particles (electrons) through a magnetic field (**Fig. 7**)
- Synchrotron X-rays were necessary in this work because they are able to penetrate the high density sample + sample assembly

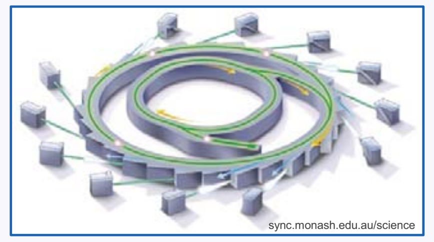
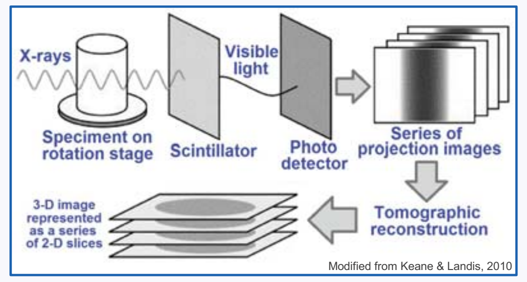


Figure 7. Schematic drawing of a synchrotron showing the paths of the particles within the storage ring and beamlines



µCT Image Collection: The sample is loaded onto the rotation stage and X-ray beams travel from the source, through the sample (+ assembly), to the detector where they are recorded as individual radiographs

Figure 8. Schematic illustration of the µCT acquisition & reconstruction process

µCT Image Processing:

Reconstruction – IDL scientific visualization software

- 2-D slices were centered and ring artifacts were smoothed
- The raw files were then exported as a stack of images in .TIFF movie format (**Fig. 9**)

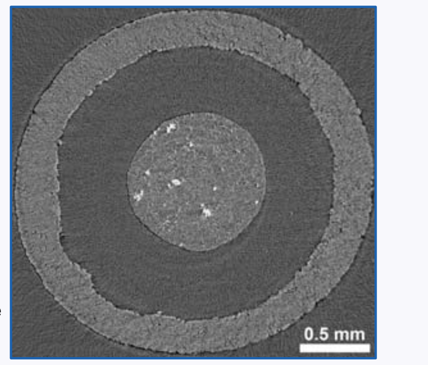


Figure 9. Reconstructed µCT "slice" of the sample (center) + surrounding assembly

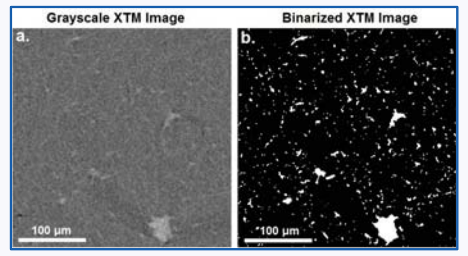


Figure 10. (a) A gray-scale µCT image slice and (b) the same slice binarized

Binarization – ImageJ image processing and analysis software

- The images were cropped & then thresholded into "melt" (white; FeS) and "non-melt" (black; olivine) regions (**Fig. 10**)
- Alternatively, white "melt" can be seen as pore space in the matrix
- The image stacks were then converted into digital volume files in MATLAB® in preparation for permeability analysis

SEM Analysis – µCT images were compared to backscatter electron (BSE) images (**Fig. 11**) in order to verify that the binarization process was successful in accurately reproducing the sample's texture

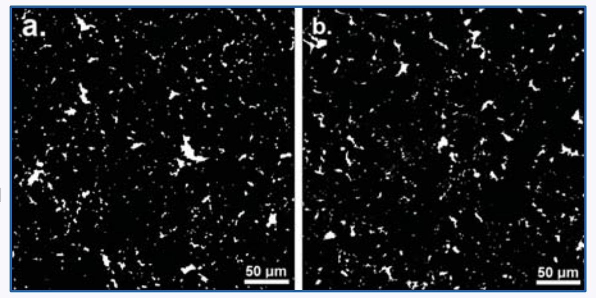
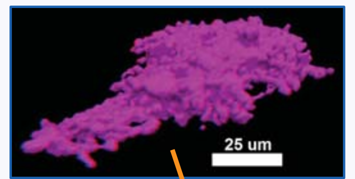
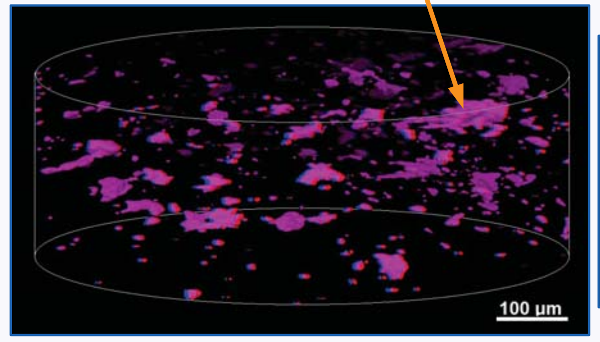


Figure 11. (a) A binarized µCT image of the sample and (b) a binarized BSE image of the fully deformed sample

Figure 12. 3-D view of the sample ~halfway through deformation, with inset showing the details of 1 FeS "blob"





3-D Visualization – Used the application Paraview to analyze the sample in 3 dimensions (**Figs. 12, 13**)

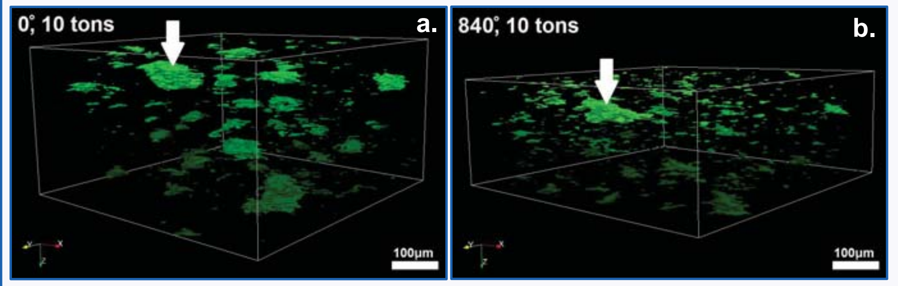


Figure 13. The sample (a) Undeformed & (b) fully deformed; arrow pointing to same FeS "blob"

Relevance to the Petroleum Industry

Why use µCT in the Petroleum Industry?

Understanding porous media flow and transport, especially multi-phase flow, is of great importance to oil recovery processes and can be measured and analyzed quantitatively, in a non-destructive manner, utilizing µCT methods in tandem with fluid flow simulations

- µCT core analysis can aid in predicting the producibility of a reservoir pay zone
- Serves as a benchmark against which other methods can be calibrated (e.g. well logs)
- Smaller rock samples (e.g. formation cuttings) can be used instead of whole cores
- Only non-destructive technique that can provide reliable information, in 3 dimensions for opaque porous media, about pore-scale processes relating to subsurface flow

Methodology: The µCT image acquisition, processing, and analysis techniques performed in the petroleum industry are very similar to the those used in this thesis work; although at lower pressures and temperatures and often utilizing a tabletop CT scanner

- The acquisition of the µCT images for industry purposes can be done using lower intensity, lab-based X-rays due to the lower density of the samples and ambient imaging conditions
- As with the FeS melt + solid olivine binarization in this work, the images are processed such that different phases (e.g. grains, cement, oil, gas, brine, pore space) can be identified and separated (i.e. segmented) accordingly (**Fig. 14**)
- Can also obtain info about grain size, shape, and matrix

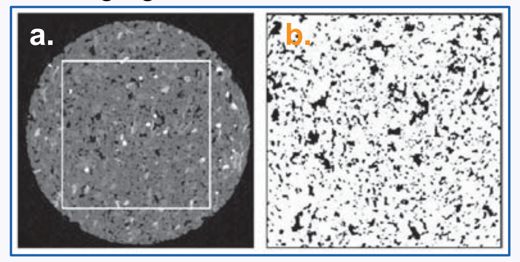
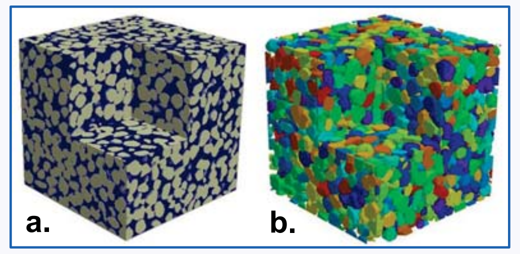
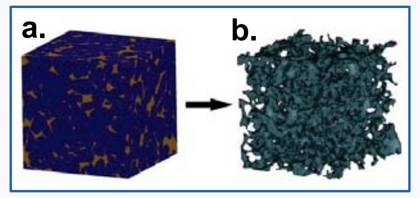


Figure 14. (a) A µCT slice of a dry sandstone sample (4mm diameter) & (b) a binary image of the square region in (a) with black pixels representing pore space and white the solid (Nakashima et al., 2004)

- **Figure 15.** - A 3-D reconstruction of a sandstone sample, with (a) showing a binary image in which the pores are blue and the grains are gray, and (b) showing isolated sand grains that have been colored to aid in differentiation of particles (pore space transparent) (Thompson et al., 2006)





- **Figure 16.** - A 3-D reconstruction of a sandstone sample, with (a) showing a binary image in which the pores are brown and the grains are blue, and (b) showing the pore space within the sample (Zaretskiy et al., 2010)

Simulating Fluid Flow: As in this work, the µCT images can be used to determine the porosity, pore connectivity, and permeability of a sample via fluid flow simulations

- Measures of formation factor & capillary drainage pressures can also be obtained
- Results show good agreement to conventional laboratory measurements
- As in this work, results are quantitative and can be obtained utilizing the lattice Boltzmann method (LBM) since samples are characterized at the pore scale
- The LBM operates under the assumption that larger-scale processes are governed by these small-scale phenomena

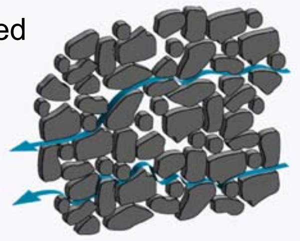
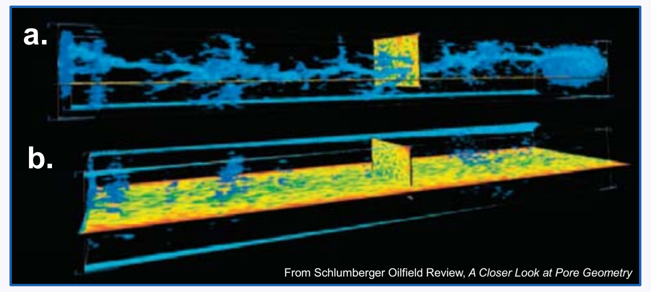


Figure 17. Schematic illustration of the flow of a fluid through a porous medium (from gcsu.edu)



- **Figure 18.** - Using µCT imaging to study the effects of heterogeneity on carbonate matrix stimulation using acid injection. (b) Before and (a) after acid injection, with porosity increasing after acidizing. In these images pore space is rendered opaque and surrounding material transparent

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