The National IOR Centre of Norway

Three-dimensional imaging and pore-scale modelling of carbonate rocks

Project 1.3 (7001130, IRIS)

Project manager: Jan Ludvig Vinningland
Key personnel: Jan Ludvig Vinningland, Hongkyu Yoon, Sandia National Laboratories
Project duration: Januar 2015 – Mars 2016

Final Project Report

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Project number and location: 7001130, IRIS
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Project manager: Jan Ludvig Vinningland, IRIS
PhD students and postdocs: None
Other key personnel: Dr. Hongkyu Yoon, Sandia National Laboratory, Albuquerque

1. Executive summary

A total of 11 chalk pore geometries have been obtained using FIB-SEM imaging to reach a resolution of 10 nm in samples ranging from 5 – 10 μm in size. These geometries provide a detailed three-dimensional description of the solid surface and volume of real rock samples, and they are used in numerical models to investigate how solid surfaces, oil and water interacts and evolve under various conditions. The imaging and post-processing have been performed at Sandia National Laboratories, Albuquerque, USA. The permeability of the pore geometries are calculated using a numerical flow model developed at IRIS that employs more than 500 processors to efficiently compute flow properties in geometries defined by up to 500 million grid points. The pore geometries are also used in other IOR Centre projects to investigate how the pore space evolve as a result of mineral reactions caused by different flooding brines, and how oil recovery can be optimized on the pore scale by tailoring the injection brine.

2. Introduction and background

Experimental observations of improved oil recovery processes is most commonly performed on the core scale, i.e. on a 7 cm long cylinder of about 3 cm in diameter. Oil resides in tiny pores with a size that in chalk can reach down to sub-micrometer scales. To fully understand the mechanisms that drive oil recovery, we need to observe the interaction between oil, water, and the solid rock surface at this level; the pore scale level. However, direct experimental observation of evolving pore scale processes in chalk is challenging. Numerical modelling offers an alternative approach where hypothetical IOR mechanisms can be tested using models implemented with known physical and chemical laws. The numerical predictions can then be tested against experimental data. Numerical models enable us to look inside the core. However, the quality and the predictive power of the numerical models depend strongly on the quality of the digital rock samples the model is applied on. This is why a numerical investigation that seek to uncover oil recovering mechanisms has to start with the acquisition of realistic high quality pore scale geometries.

3. Results

This project has obtained 11 chalk pore geometries, i.e. digital copies of real rock samples, using electron microscopy to record images of chalk surfaces. The technique is known as FIB-SEM imaging, an acronym for Focused Ion Beam – Scanning Electron Microscope. The ion beam cuts off thin slices of the sample while the electron microscope image the exposed cutting plane.

These images, up to 700 for each sample, are then processed using a segmentation technique to discriminate between solid and void regions.After the FIB-SEM imaging, a segmentation procedure is necessary to divide each image into solid and void sections. This can be a cumbersome and challenging task since solid and void parts of an image might be represented by almost equal grayscales.

This is illustrated in Figure 2 and Figure 3 where an image from each of the 11 samples is shown together with a red segmentation line that divides solid from void. By close inspection of the red line, it is possible to find regions where the segmentation procedure seemingly has not been able to find the true location of the solid-void interface. However, it is sometimes very difficult to judge where the interface is based on one single frame. In any case, the quality of the segmentation vary between the different samples depending on the image quality.

Both the FIB-SEM imaging and the subsequent segmentation have been performed at Sandia National Laboratories and lead by Dr. Hongkyu Yoon. The segmentation was far more time consuming than first anticipated. The segmentation differentiate between solid and void regions of the image based on the grayscale color values using the watershed algorithm. This is a semi-automated procedure which require significant input from the user to yield a satisfactory result, in particular when solid and void regions appear in almost similar gray scales.

Finally, a three-dimensional geometry is constructed from the segmented images to yield a detailed representation of the solid surface and volume in the sample. To reduce noise, a sequence of binary erosion and dilation operations is performed on the segmented images. Three-dimensional representations of the pore space of all the 11 samples are shown in Figure 4 and Figure 5.

Table 1: A list of all the sample geometries with porosity and calculated permeability

Sample	Porosity	Permeability [mD]	Size [μm]	Resolution
Kansas 1	0.19	$8 \cdot 10^{-5}$	$9.0 \times 6.5 \times 7.0$	$894 \times 652 \times 696$
Kansas 2	0.28	2.2	$9.7 \times 6.7 \times 7.0$	$971 \times 670 \times 696$
Liege 1	0.32	0.40	$9.8 \times 6.5 \times 7.0$	$976 \times 646 \times 696$
Liege 2	0.34	0.67	$9.9 \times 6.5 \times 5.5$	$989 \times 650 \times 547$
Flooded Liege 1	0.076	$5 \cdot 10^{-4}$	$9.3 \times 6.8 \times 7.5$	$933 \times 675 \times 746$
Flooded Liege 2	0.29	0.38	$9.0 \times 6.1 \times 7.6$	$896 \times 606 \times 761$
Flooded Liege 3	0.073	$8 \cdot 10^{-4}$	$9.3 \times 7.1 \times 7.0$	$932 \times 712 \times 696$
Mons 1	0.42	1.5	$9.9 \times 6.8 \times 5.0$	$986 \times 681 \times 497$
Mons 2	0.31	0.58	$9.2 \times 8.2 \times 7.0$	$918 \times 821 \times 696$
Stevns-Klint 1	0.45	1.1	$8.3 \times 5.3 \times 5.5$	$833 \times 526 \times 550$
Stevns-Klint 2	0.28	0.25	$9.5 \times 6.9 \times 7.0$	$952 \times 689 \times 696$

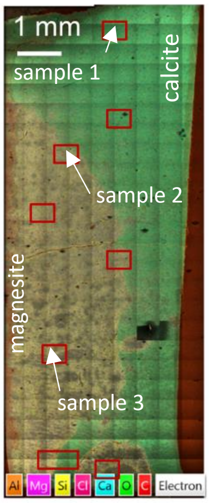

Figure 1: Map of the flooded Liege sample where a magnesite dominated region in yellow meets a calcite dominated region in green at a sharp interface. The locations of the pore geometries obtained from this core sample subset is indicated as red squares. Sample 1 represents the unaltered calcite dominated part of the core, sample 2 is obtained at the interface between the two regions, while sample 3 represents the altered magnesite dominated region.

Table 1 lists the pore geometries obtained together with calculated properties. Three samples yield very low permeability values due to low porosity and low pore connectivity in the flow direction. The permeability values are calculated for flow from right to left in Figure 4 and Figure 5. It is evident that the low permeability found in three samples (Kansas 1, flooded Liege 1 and 3) are connected to the fragmented and poorly connected pore space.

The flooded Liege samples are obtained from a core exposed to high stresses and temperatures during the $MgCl_2$ flooding which has caused considerable mechanical and chemical compaction of the core. This effect is also observed in two of the three flooded Liege samples where both porosity and permeability is very low. Note, however, that the flooded Liege sample 2, taken from the magnesite-calcite interface zone (see Figure 1), yields porosity and permeability values comparable to the values calculated for the pristine Liege samples.

4. Conclusions

Through a collaboration with Sandia National Laboratories, we have obtained 11 high-quality digital chalk pore geometries from four pristine chalk types and one flooded chalk. The permeability of the samples have been calculated using a parallelized flow model developed at IRIS capable of handling large pore geometries (on the order of 10^8 data points) using distributed computation on high-performance clusters (e.g. abel.uio.no). The pore samples demonstrate a large variation in flow properties, and some of the samples display permeability values that agree well with values observed in core scale experiments. However, for other samples, the calculated permeability is well below experimentally observed values due to low porosity and poor connectivity. This indicates that the size of certain types of pore samples need to increase beyond the 5-10 μm values used in this project, particularly for low porosity and poorly connected samples.

5. Future work

The plan is to write a journal paper together Dr. Hongkyu at Sandia which discuss the question of how large pore samples need to be to yield a good representation of core scale properties. In other words, what is the representative elementary volume for chalk of different origin?

6. Dissemination

An invited presentation titled *"Can we measure core scale properties in pore scale models?"* was given at the IOR NORWAY 2016 conference in Stavanger.

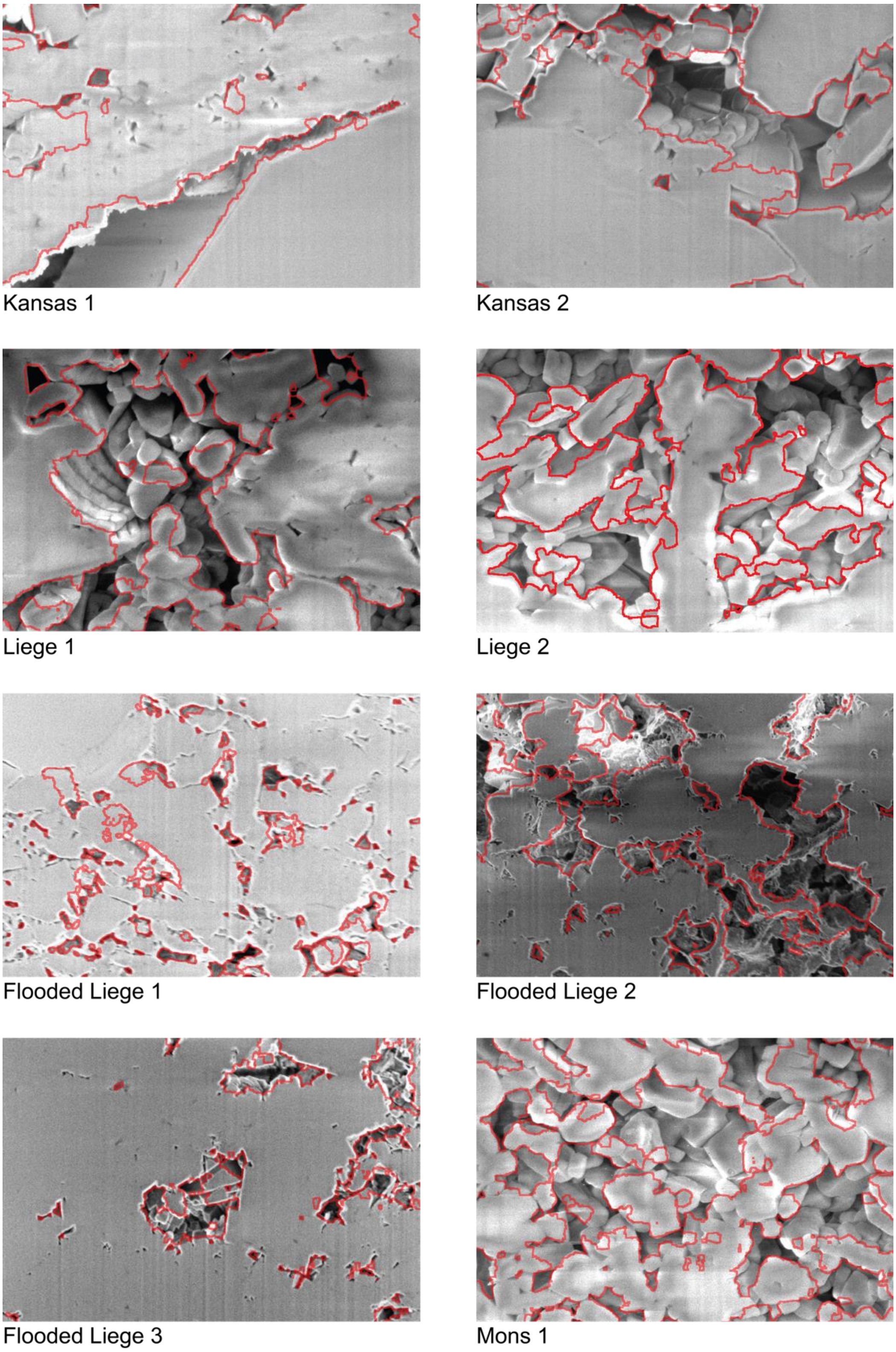

Figure 2 Examples of FIB-SEM images for eight different chalk samples with a red line indicating the interface separating solid and void parts. The solid-void interface is calculated in a segmentation procedure, but the correct location of the interface is not always identified due to poor contrast between solid and void regions of the image.

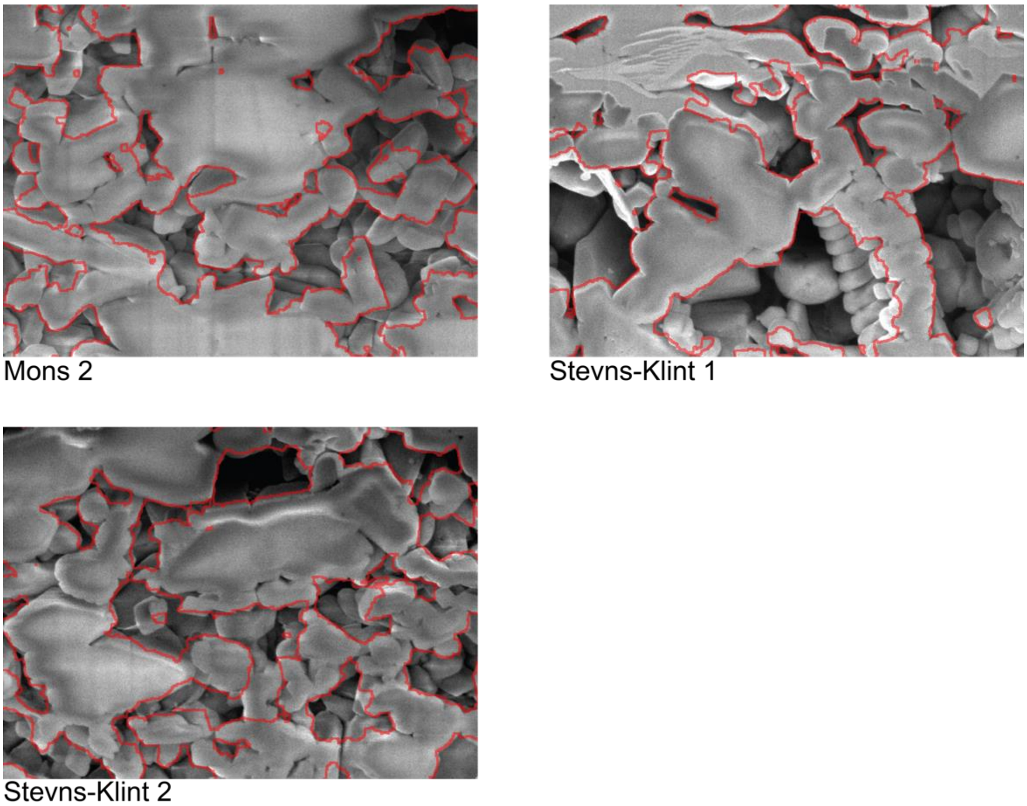

Figure 3 A continuation of Figure 2 showing FIB-SEM images of the remaining three chalk samples where the red line represents the solid-void interface obtained during the image segmentation.

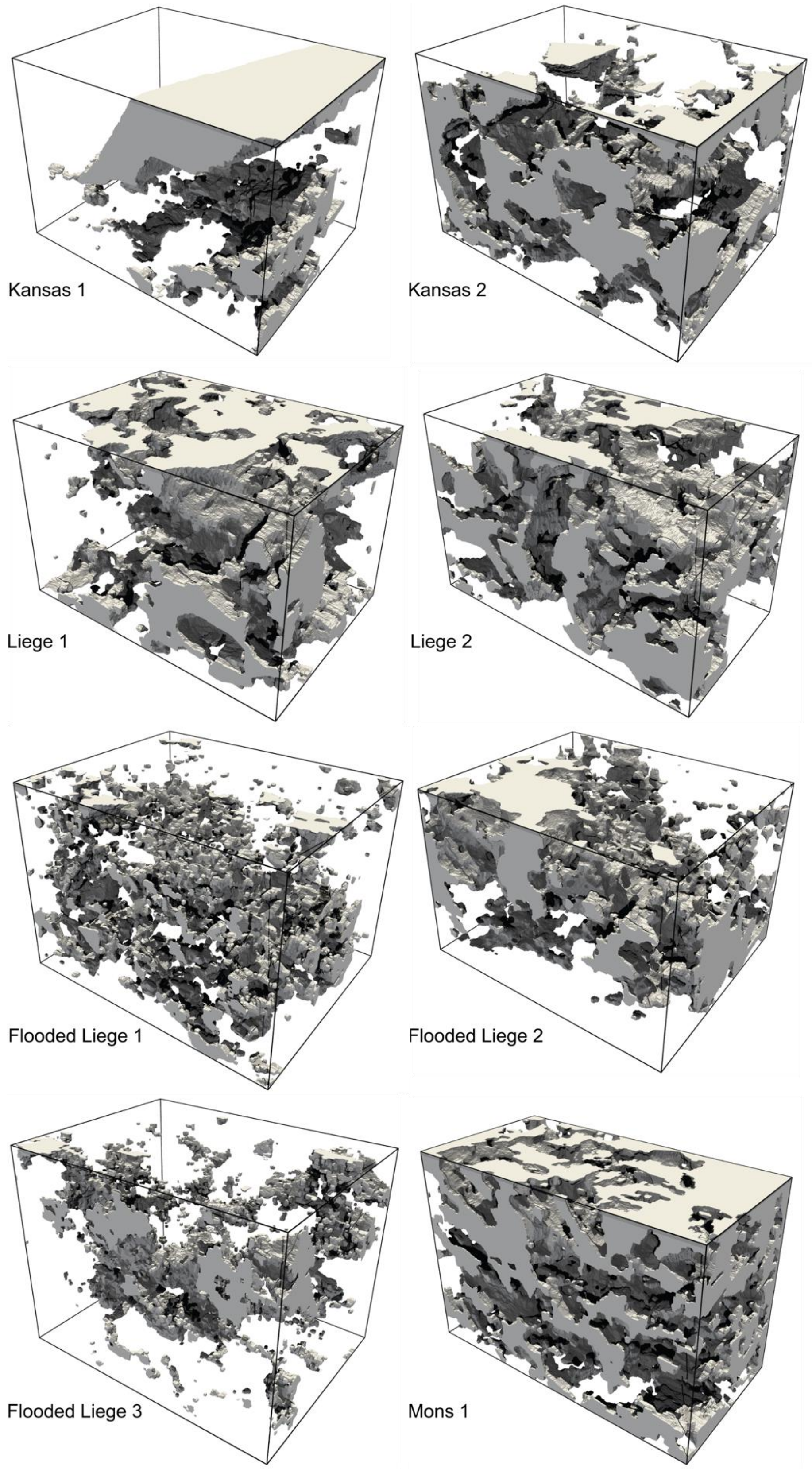

Figure 4: Three-dimensional representations of the pore space of eight chalk samples. Porosity, permeability (flow from right to left), and size of the samples are listed in Table 1. A FIB-SEM image from each of the samples is shown in Figure 2.

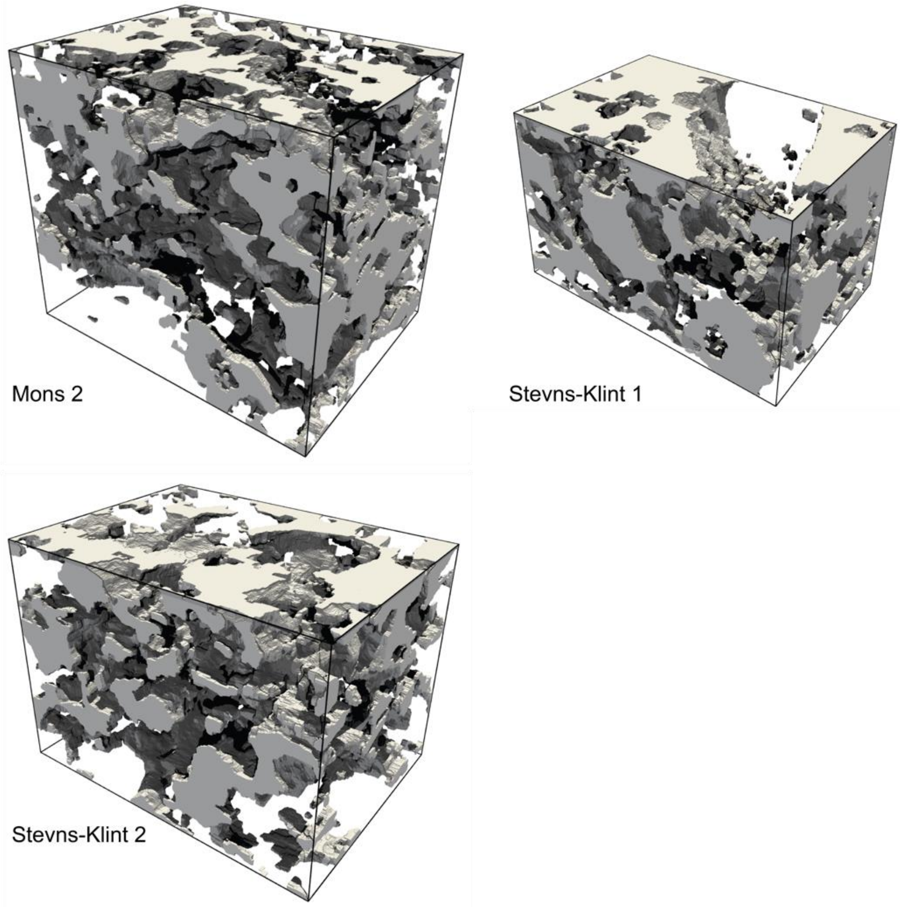

Figure 5: Continuation of Figure 4 showing three-dimensional representations of the final three pore geometries. The permeability values in Table 1 is calculated for flow in the right-left direction.