Australian National University

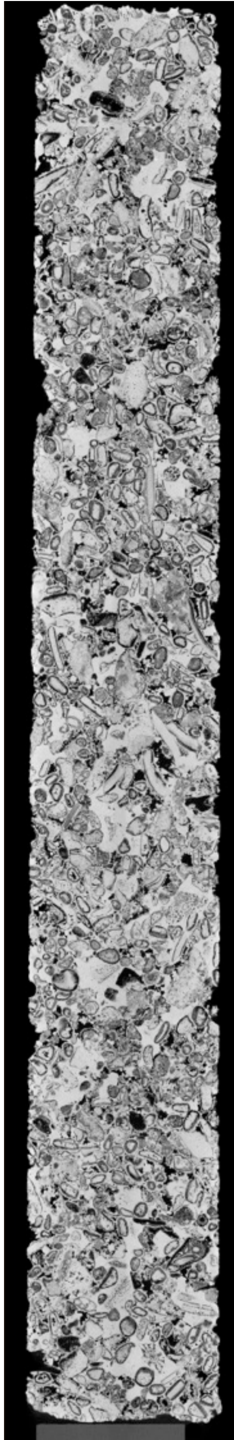
Cross-scale 3D characterisation of complex and heterogeneous geomaterials with X-ray micro-CT

Adrian Sheppard[1], Shane Latham[1], Andrew Kingston[1], Glenn Myers[1], Thomas Li[1], Mahsa Paziresh[1], Pieter Botha, Andrew Fogden[1,2], Tim Sawkins[1], Ron Cruikshank[1], Mohammad Saadatfar[1], Ryan Armstrong[3], Christoph Arns[3] and Tim Senden[1]

[1]Department of Applied Mathematics, Research School of Physics and Engineering, Australian National University

[2]FEI Australia

[3]School of Petroleum Engineering, University of New South Wales, Sydney, Australia

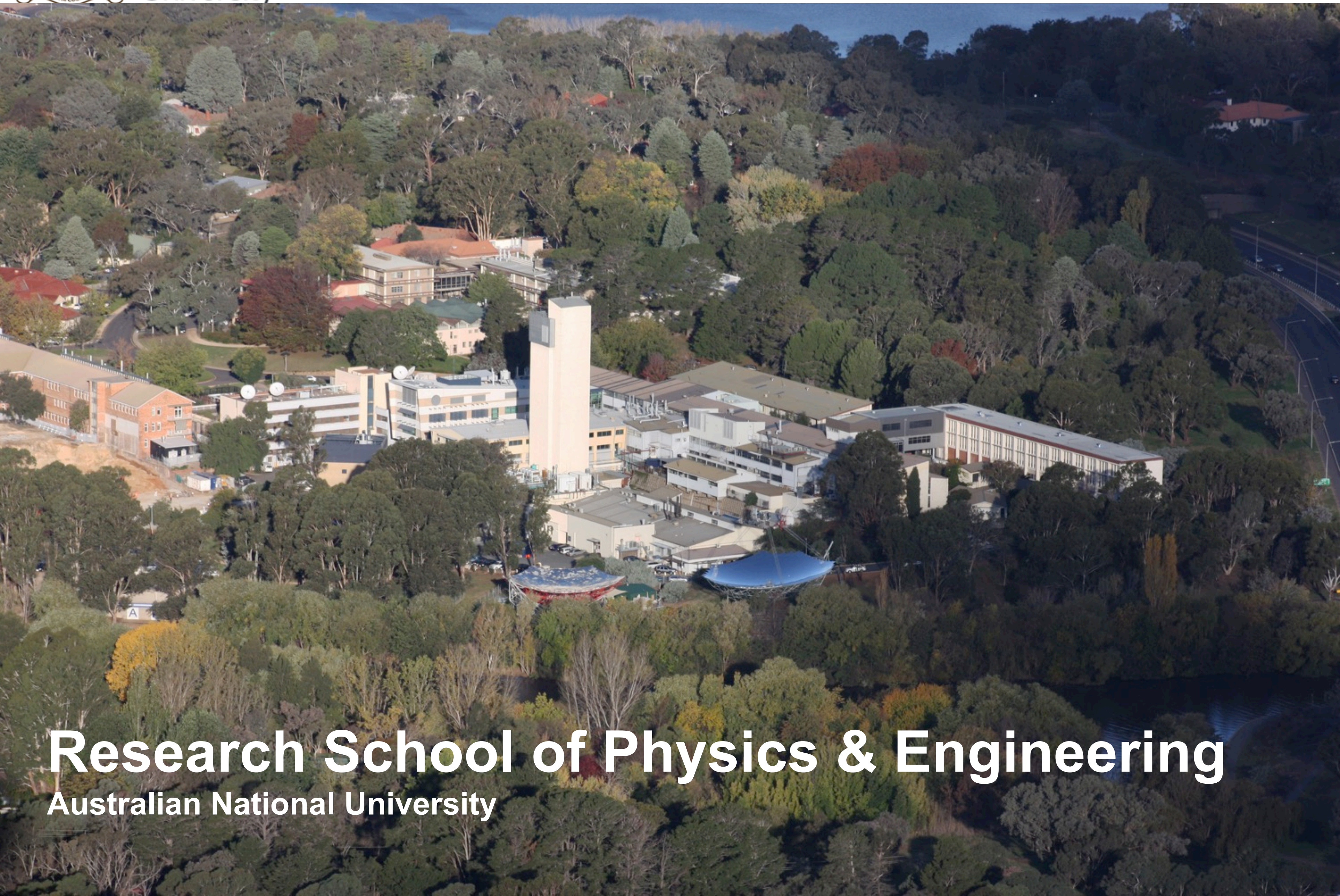


Australian National University

Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - Correlating SEM-EDX mineral mapping with x-ray uCT
  - Imaging diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

Australian National University



Research School of Physics & Engineering

Australian National University

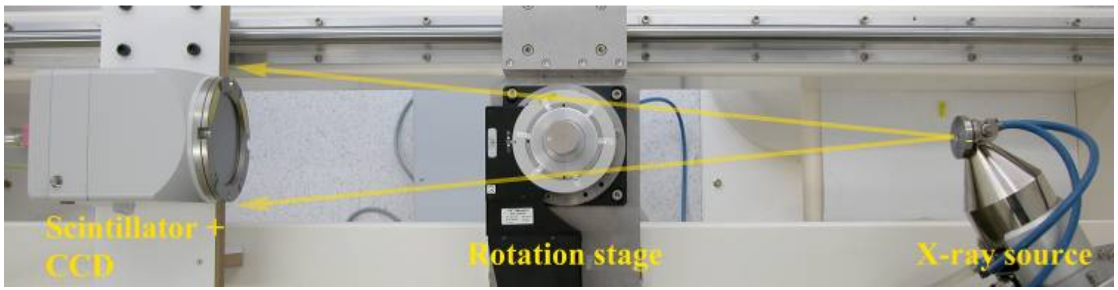
Australian National University

Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - Correlating SEM-EDX mineral mapping with x-ray uCT
  - Imaging diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

Australian National University

Instrument development at ANU



2001

- 3µm voxels,<60mm FOV
- CCD detector
- circular scanning

2014:

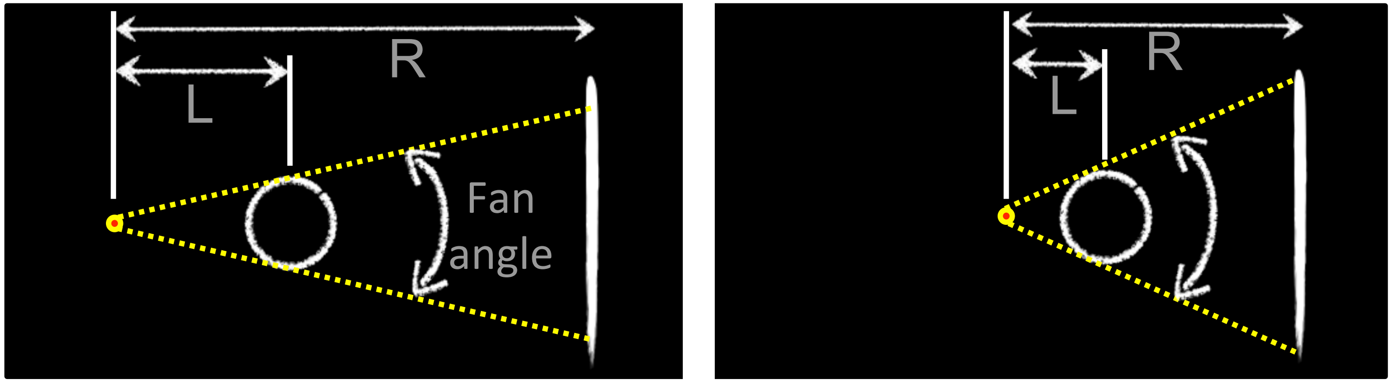
- 1 µm / 2–40mm
- flat panel detector
- helical scanning
- licensed to FEI

2015: ‘nano’ CT:
300 nm / 0.7mm

2017: whole core µCT
50 µm / 100 mm

Helical-scanning cone-beam micro-CT – why?

- Image noise in tomography is entirely due to finite photon numbers
- X-ray sources emit in all forward directions, can increase photon flux simply by moving sample and detector closer to the source

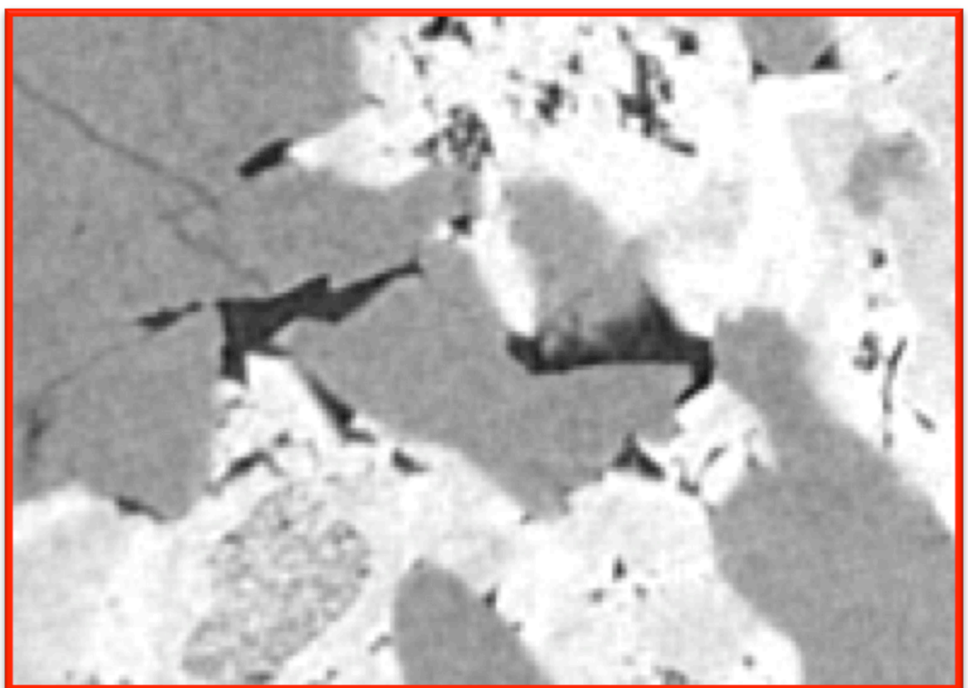


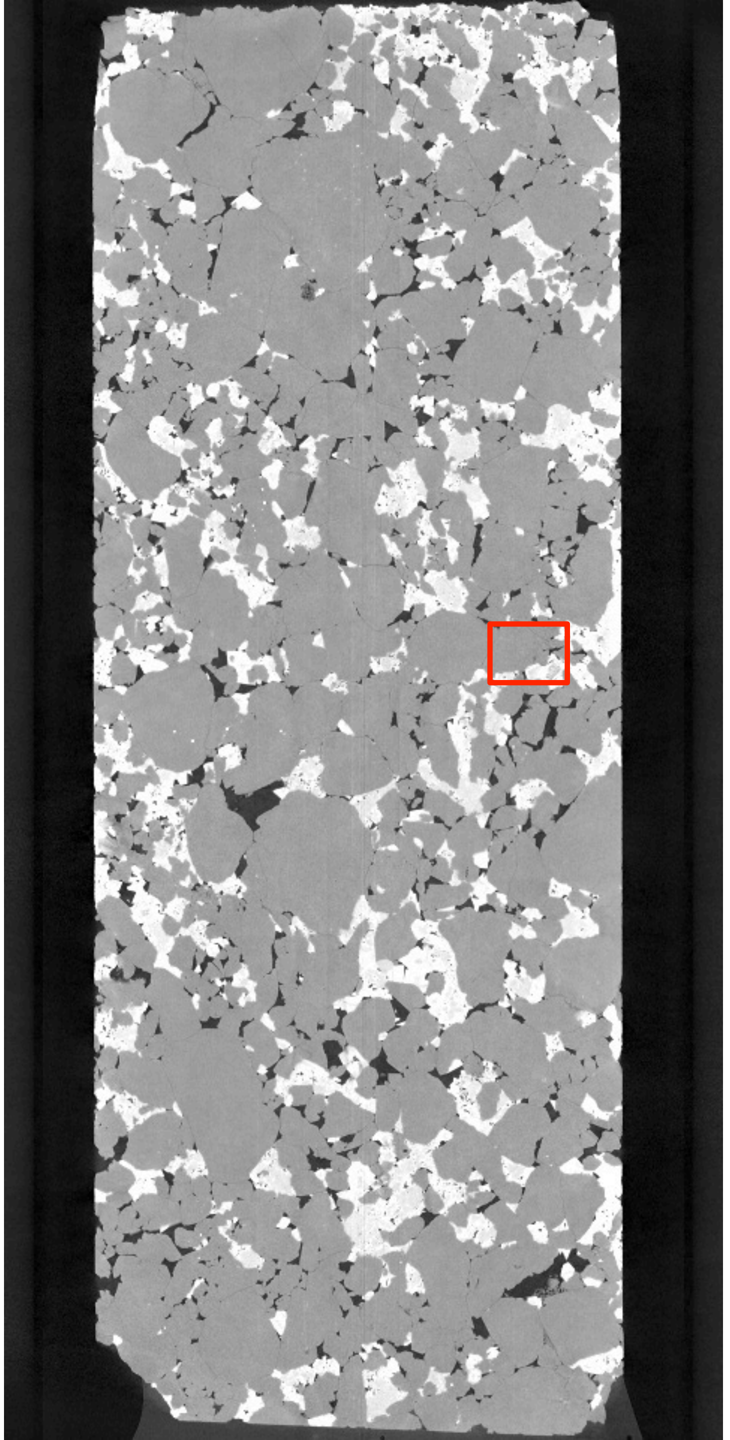
- Circular scanning trajectory does not provide sufficient data for high cone-angle acquisition
- Helical scanning data is “complete”, allows exact reconstruction techniques such as FBP method of Katsevich

Australian National University

Helical cone-beam micro-CT

- cone angles up to 60°
- “Autofocus” techniques critical for micron scale
- Order-of-magnitude improvement in acquisition times, for no loss of SNR
- Images up to 18000 x 3000 x 3000 (so far)





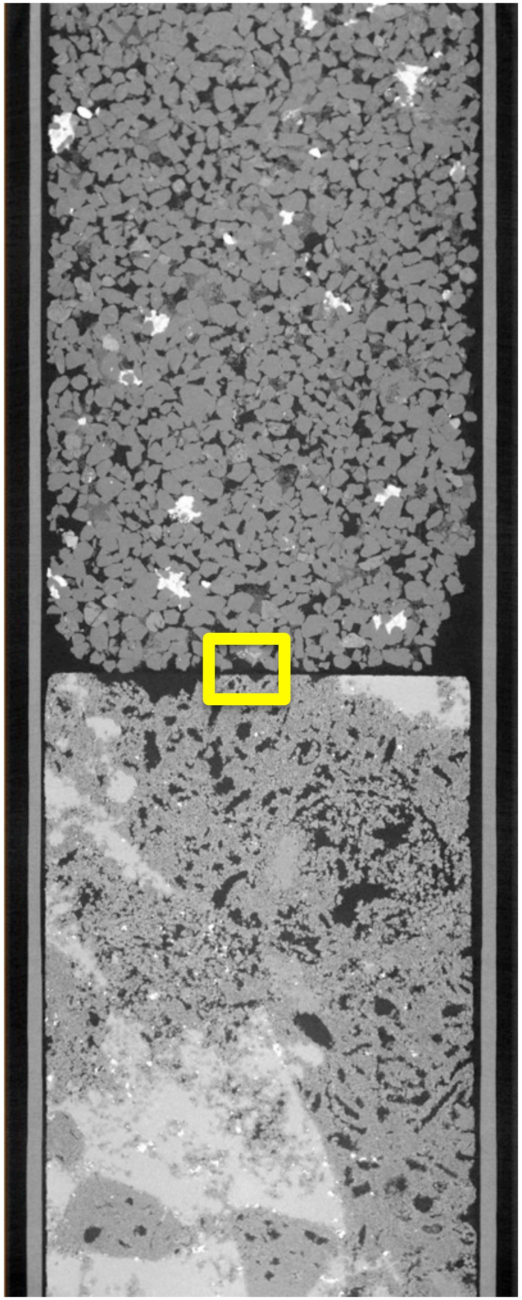
Large-scale iterative reconstruction

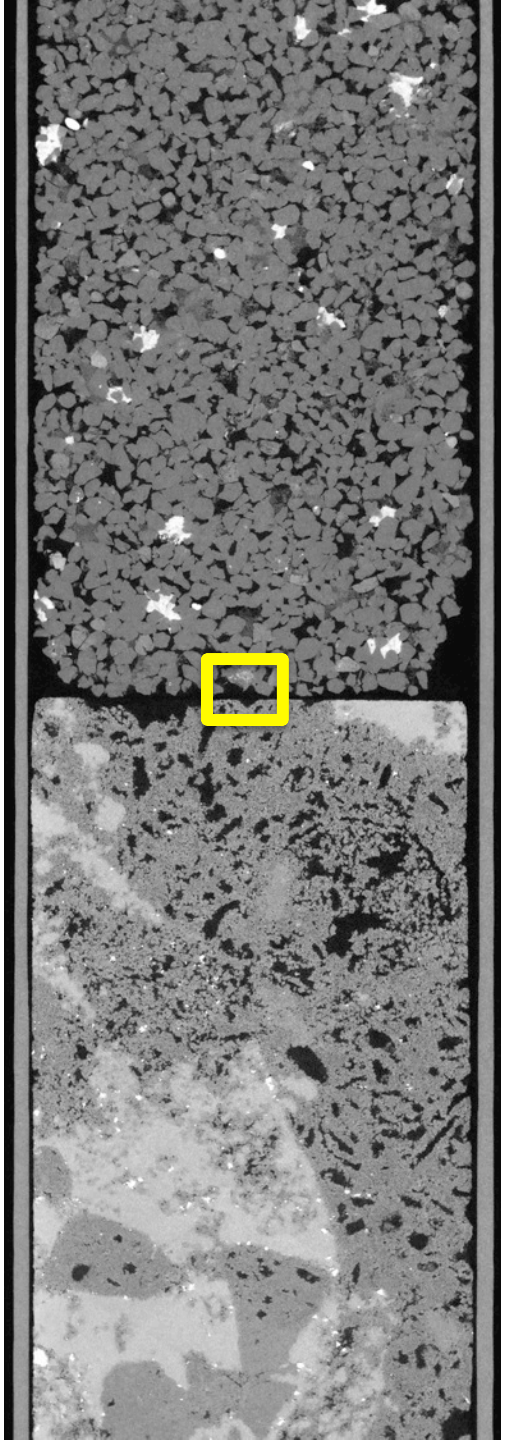
Iterative reconstruction (*reconstruction-by-optimisation)* is needed for advanced tomography.

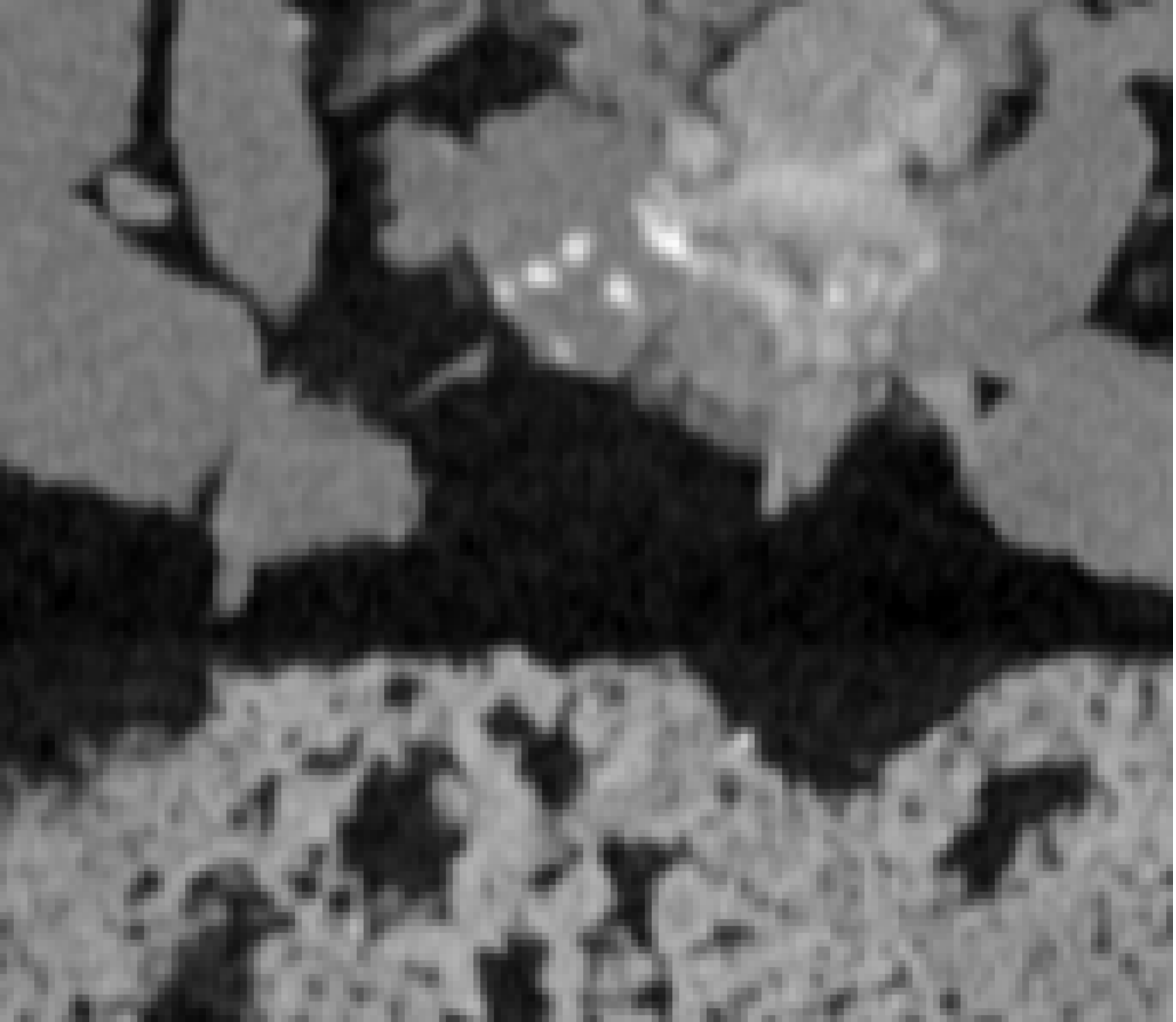
Problem: too computationally demanding for big data

Solution: Multi-resolution iterative reconstruction; converges in two multi-grid iterations

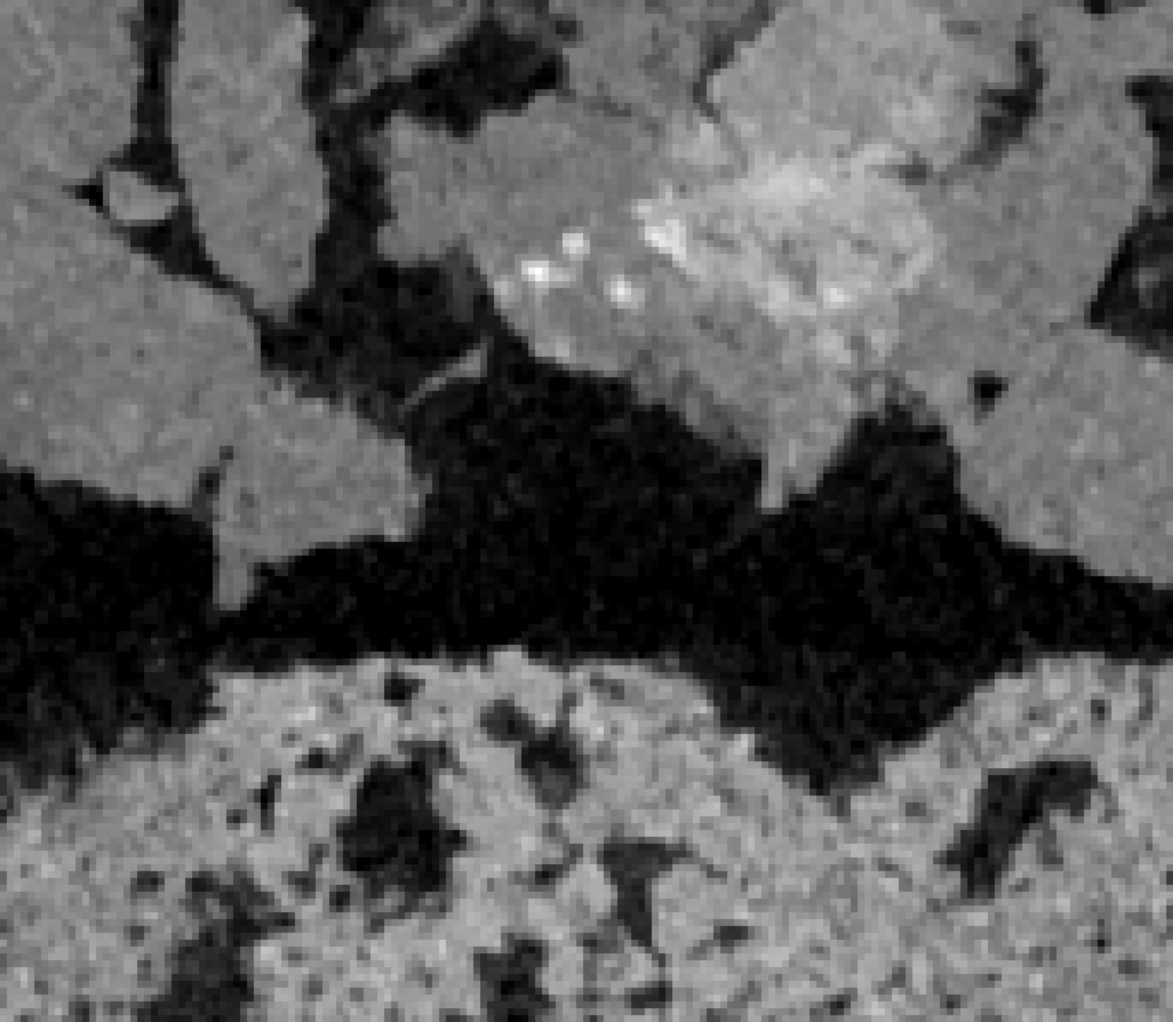
Demonstrated on 40 Gvoxel images.



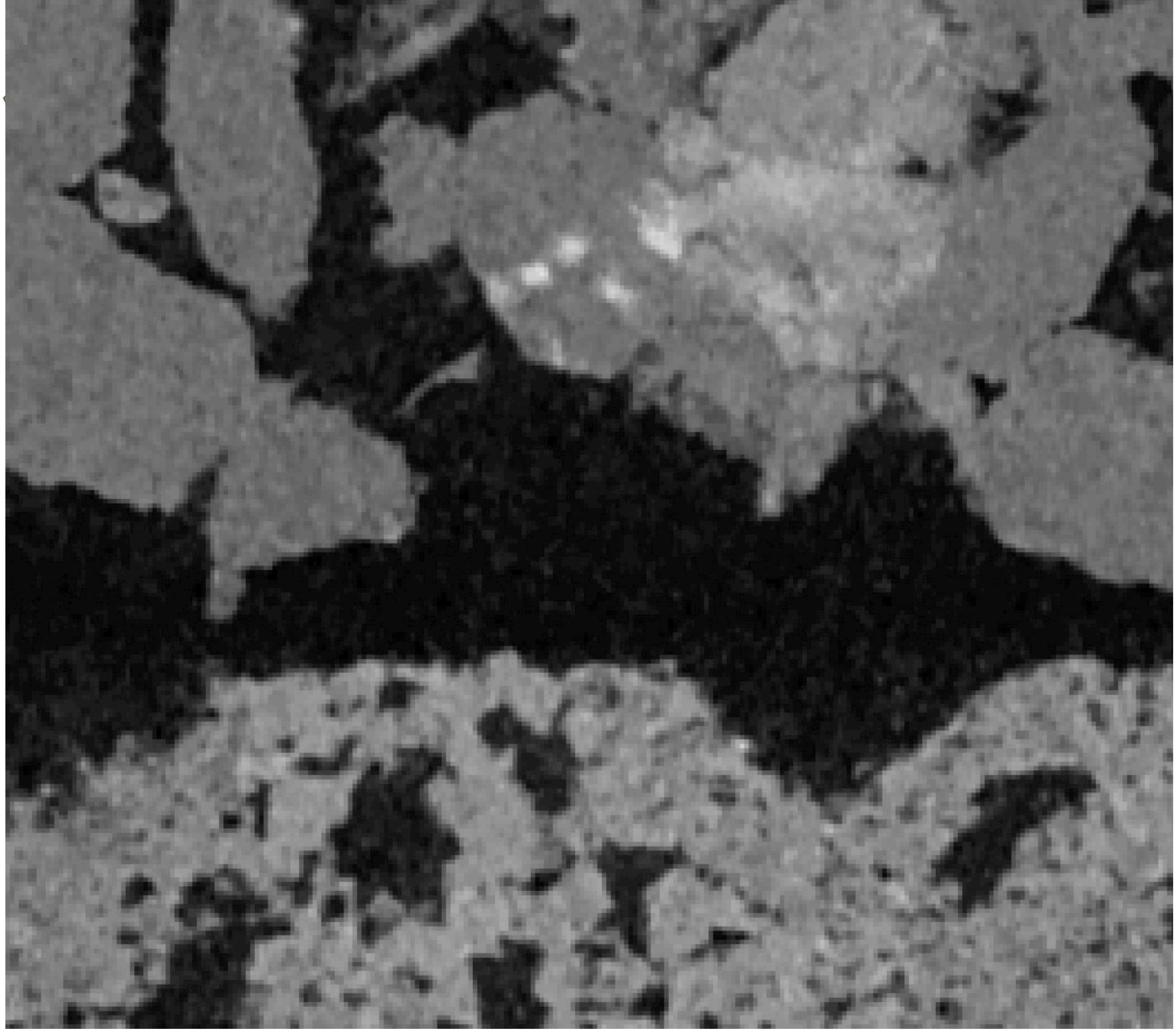




FBP

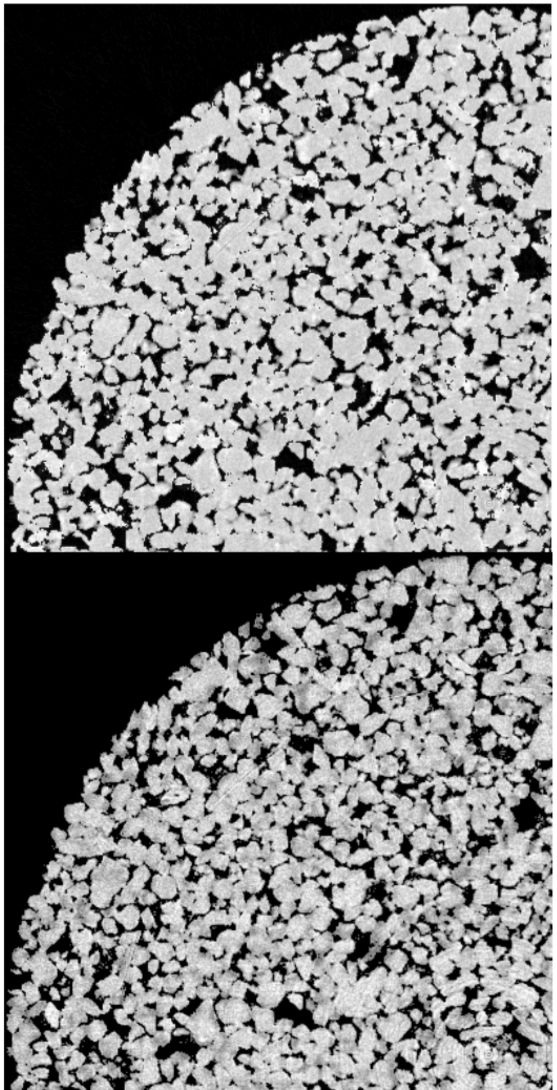


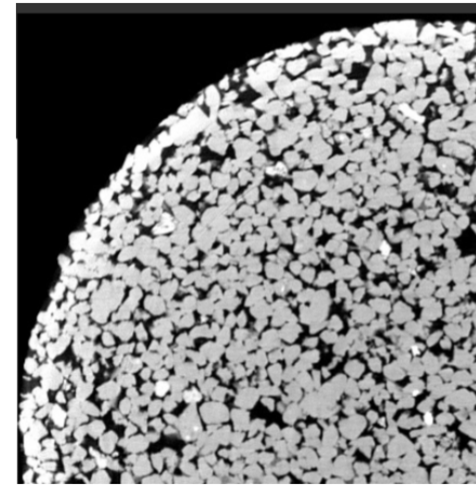
MG
Iterative

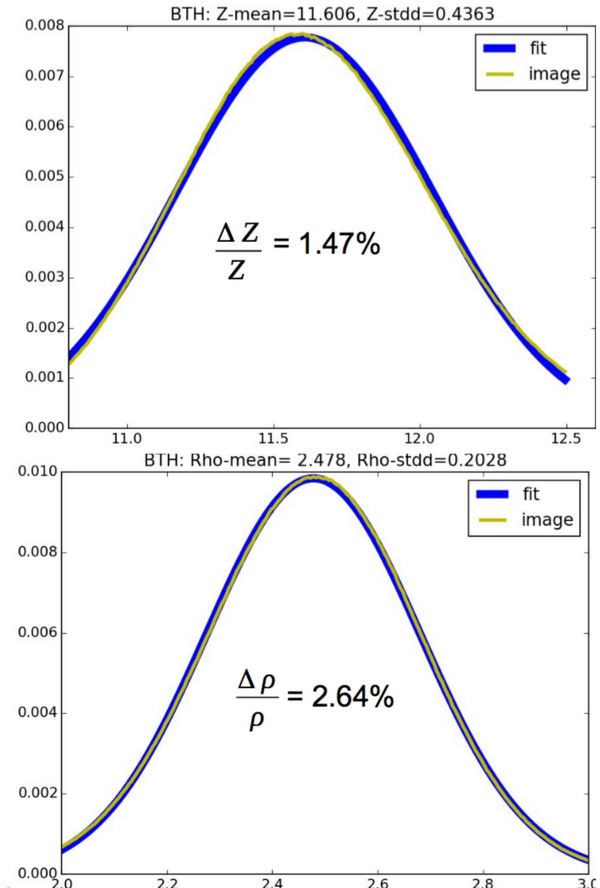


MG
Iterative
1.5x higher
resolution

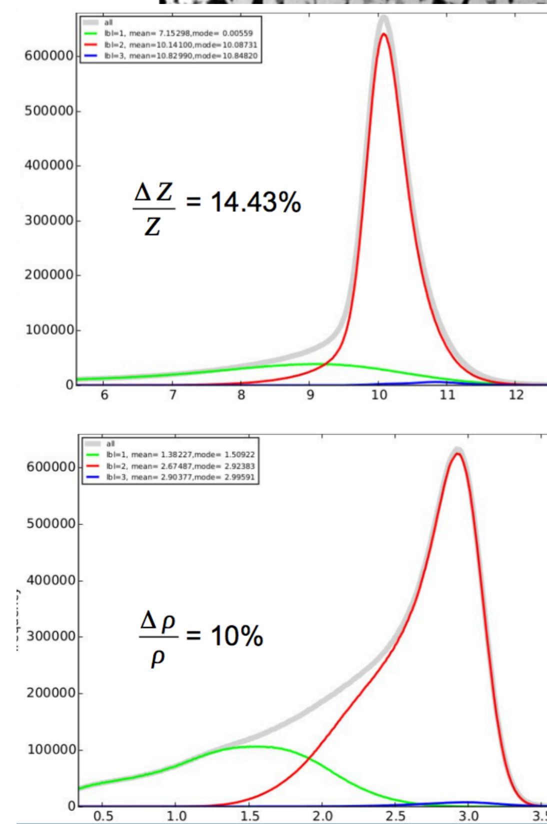
Density and Atomic Number
From dual energy imaging







Alvarez-Makowski



Siddiqui-Khames

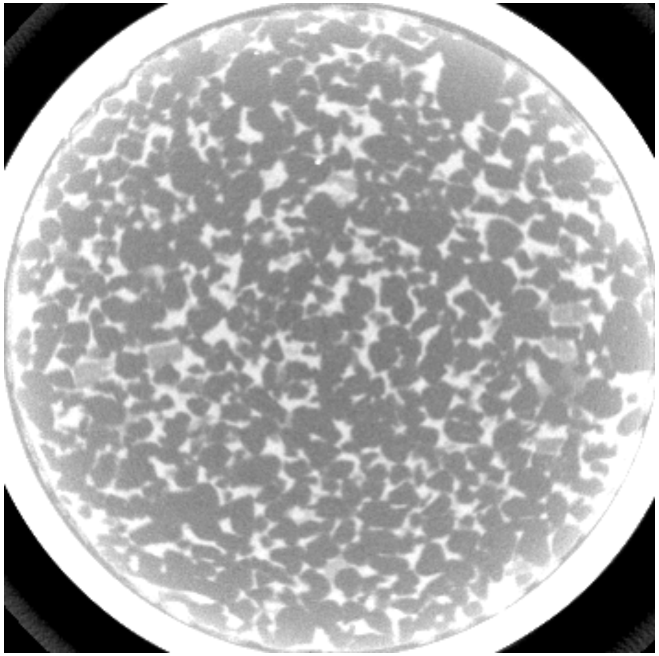
Australian National University

Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - correlating SEM-EDX mineral mapping with x-ray uCT
  - diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

Dynamic Tomography

- MPEG compression greatly reduces movie file sizes: the information required to encode the *changes* from one moment to the next is much less than that required to encode each frame in isolation
- Similarly, when doing 4D tomography to capture dynamic processes, one should need far fewer projections to reconstruct just the changes between successive frames.
- Two-phase immiscible fluid flow is a good candidate for this, since it is geometrically constrained
- Can incorporate these constraints into iterative reconstruction techniques

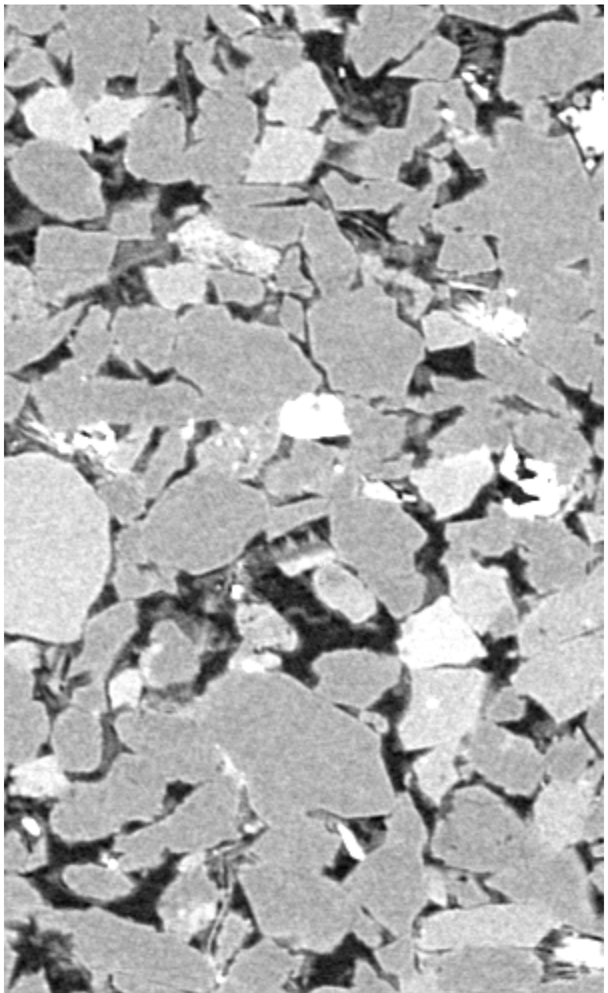


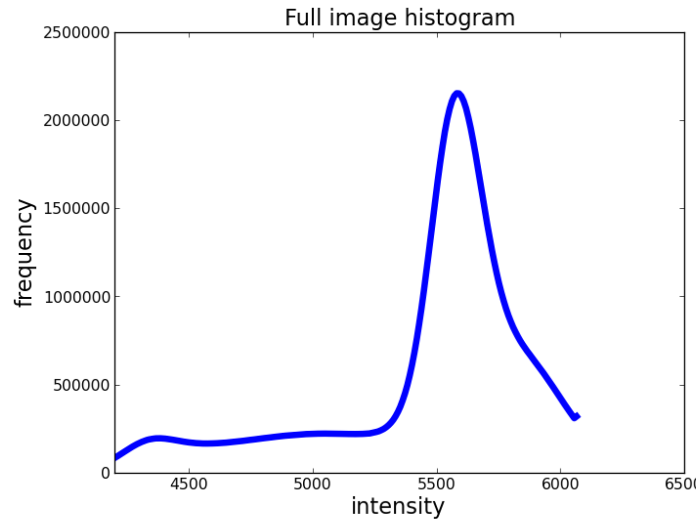
Myers et al Med Phys 2011

Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - Correlating SEM-EDX mineral mapping with x-ray uCT
  - Imaging diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

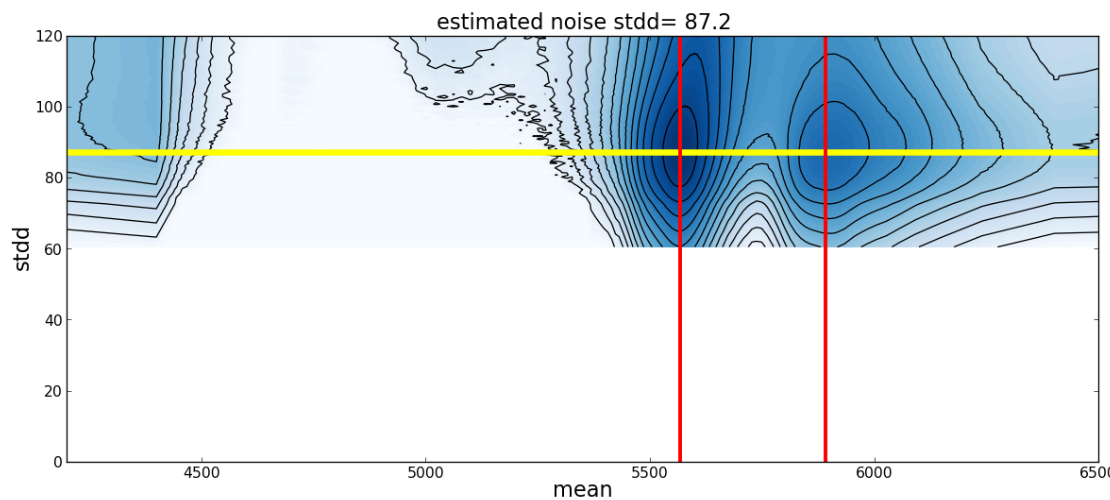
Bilateral Filter: Estimating Noise





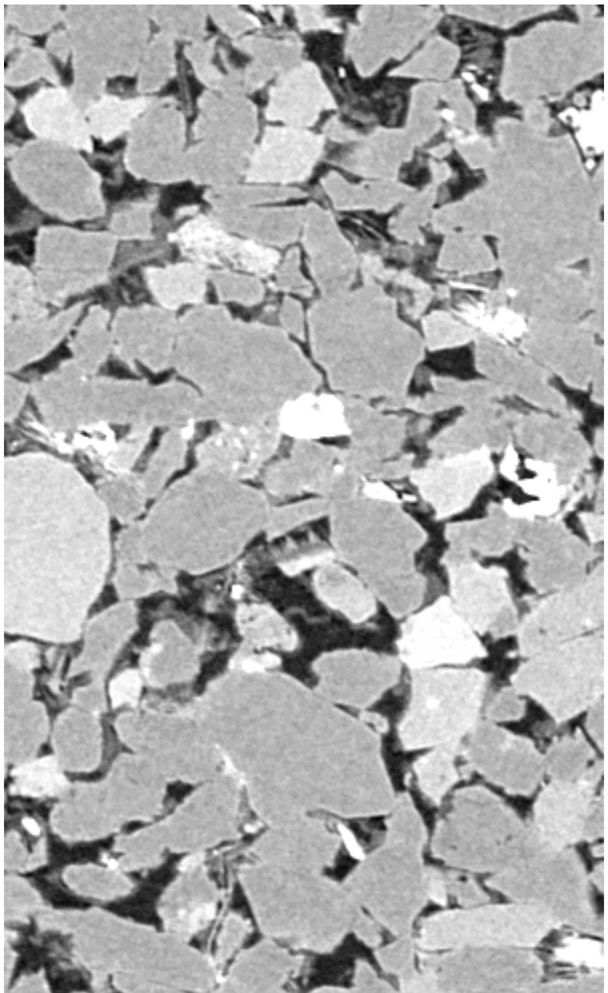
Original image

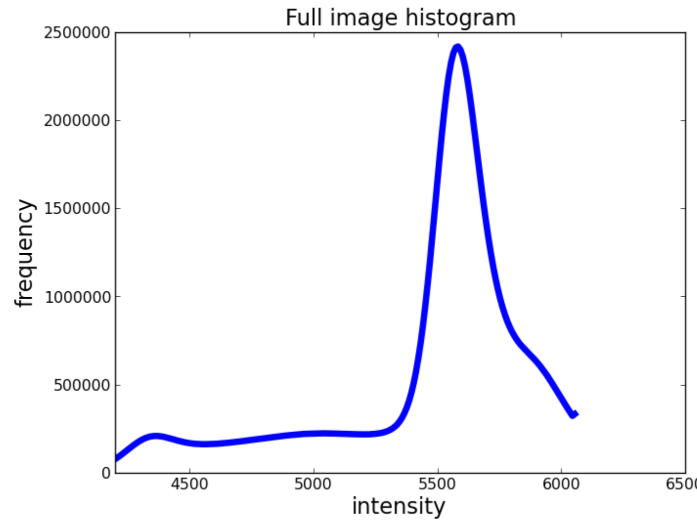
noise = 87.2



Australian National University

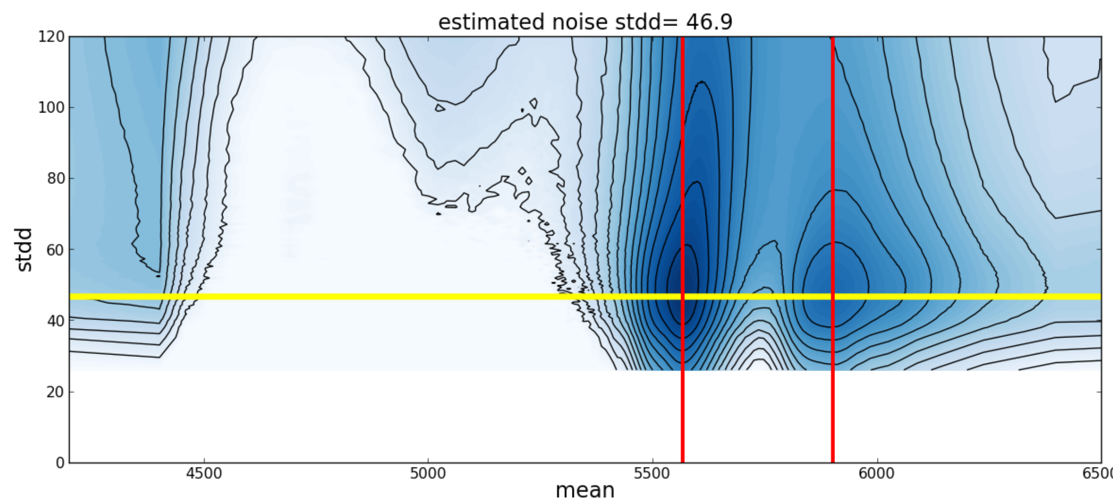
Bilateral Filtering: using estimated noise



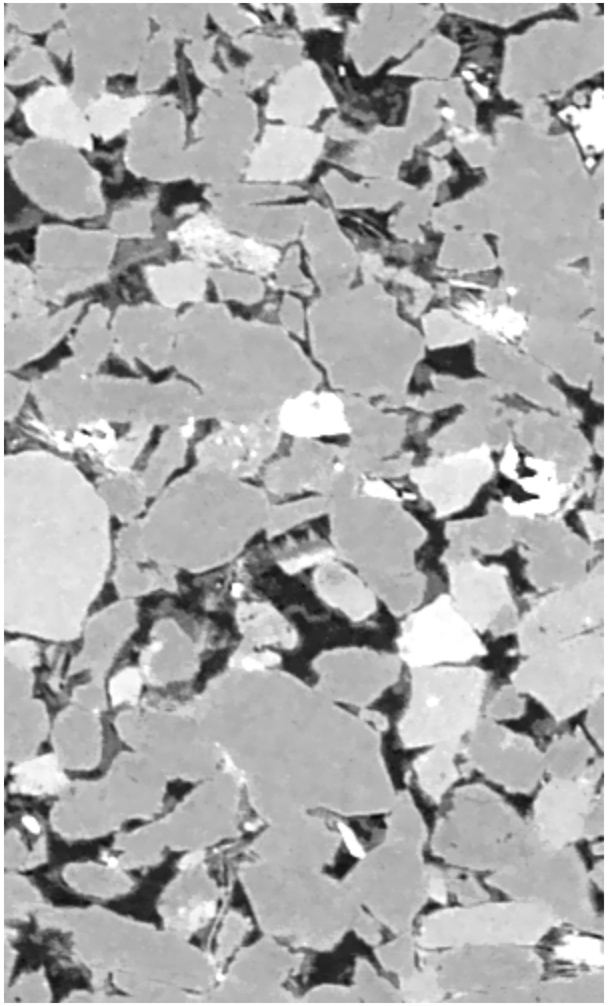


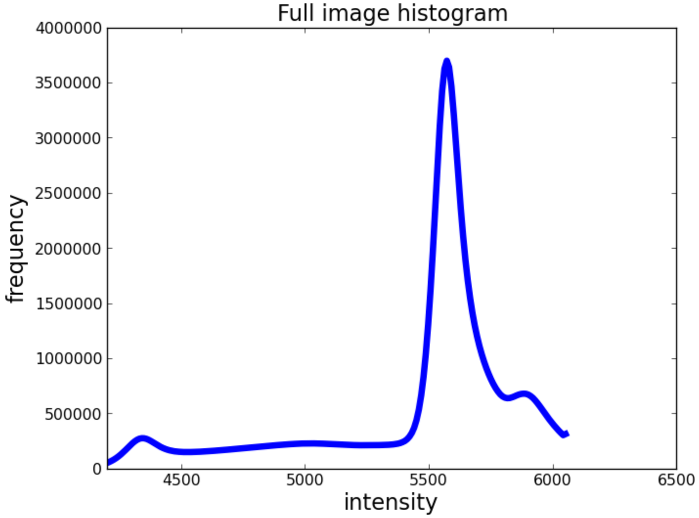
Iteration 1

noise = 46.9



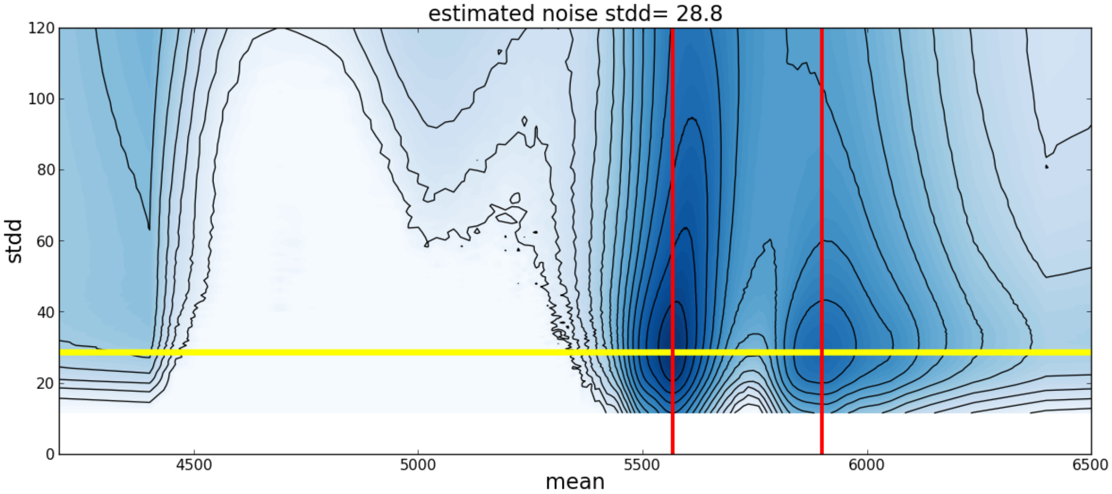
Bilateral Filtering using estimated noise



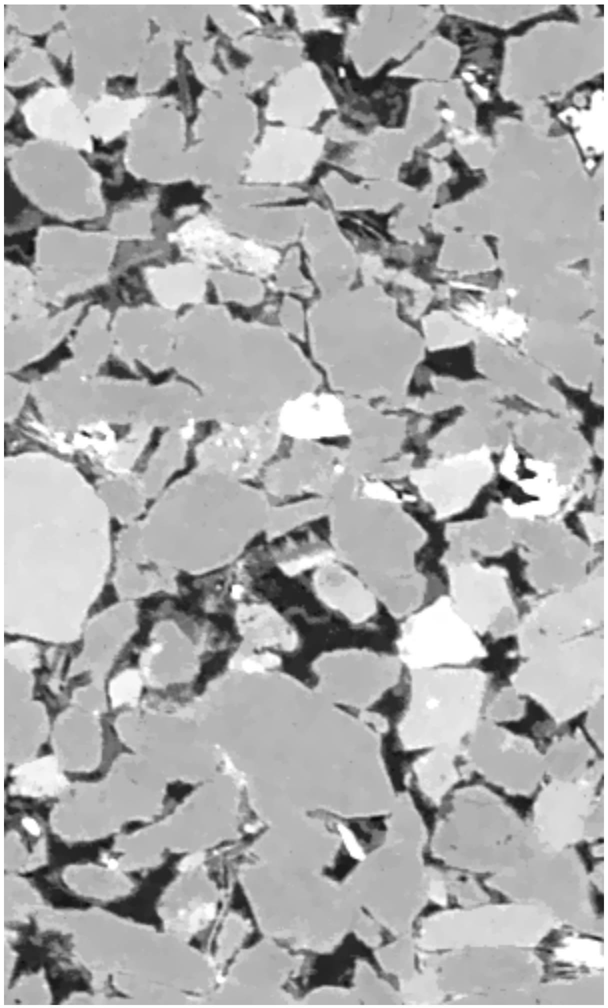


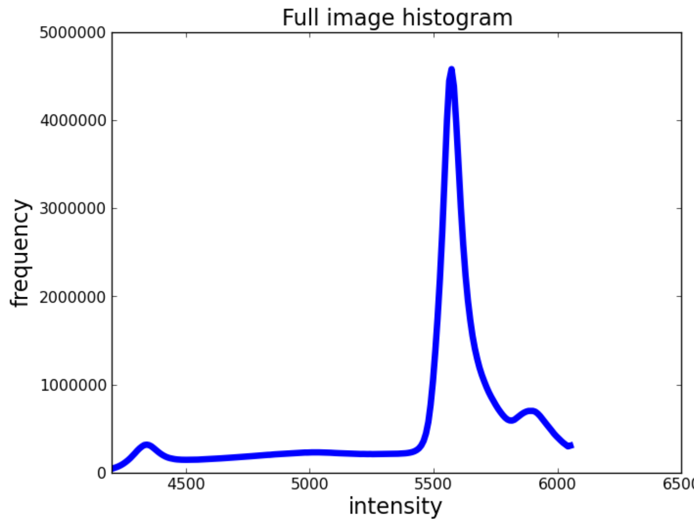
Iteration 2

noise = 28.8



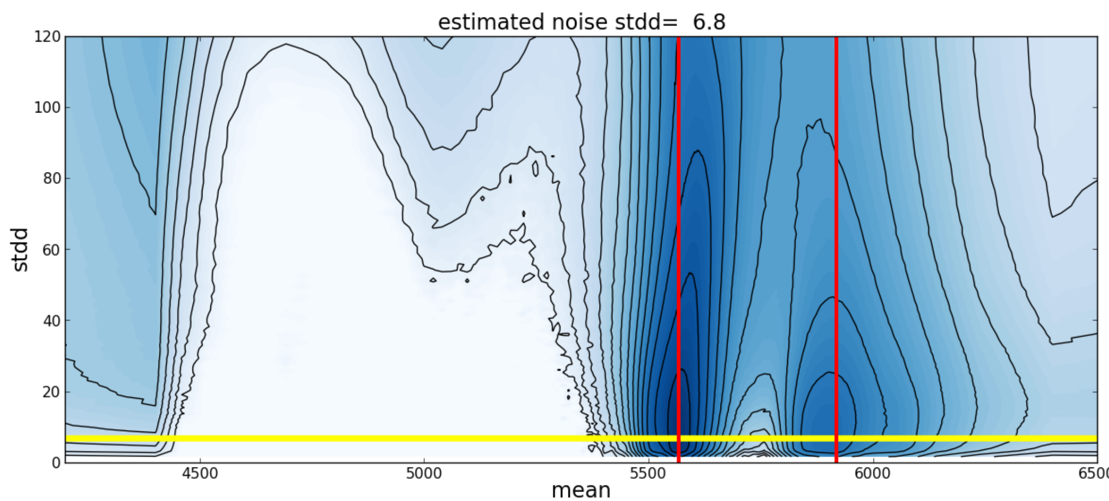
Bilateral Filtering using estimated noise



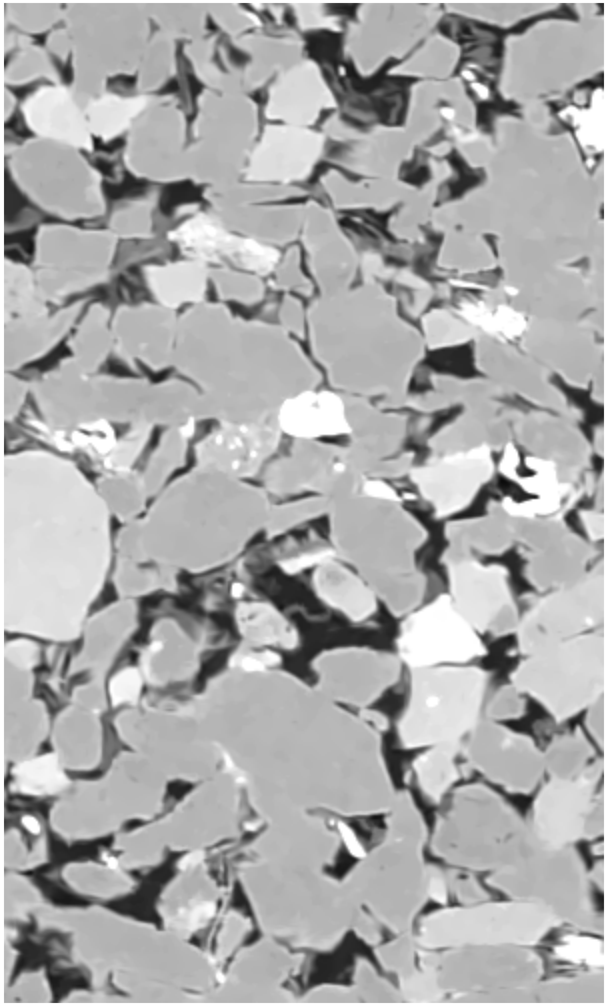


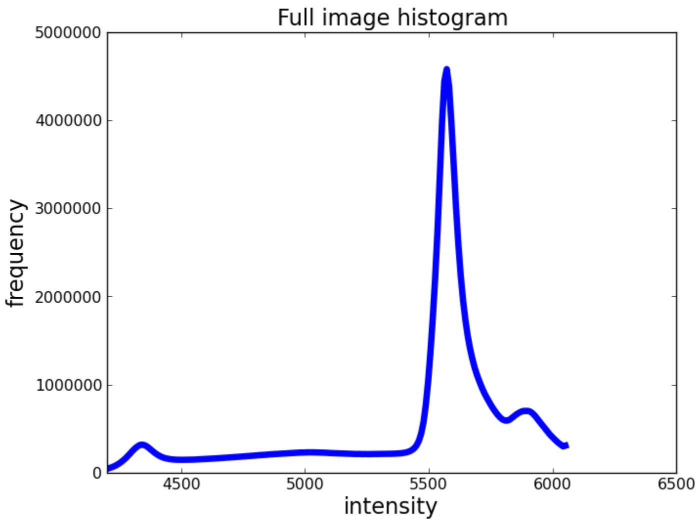
Iteration 8

noise = 8.8



Bilateral Filtering + Anisotropic Diffusion





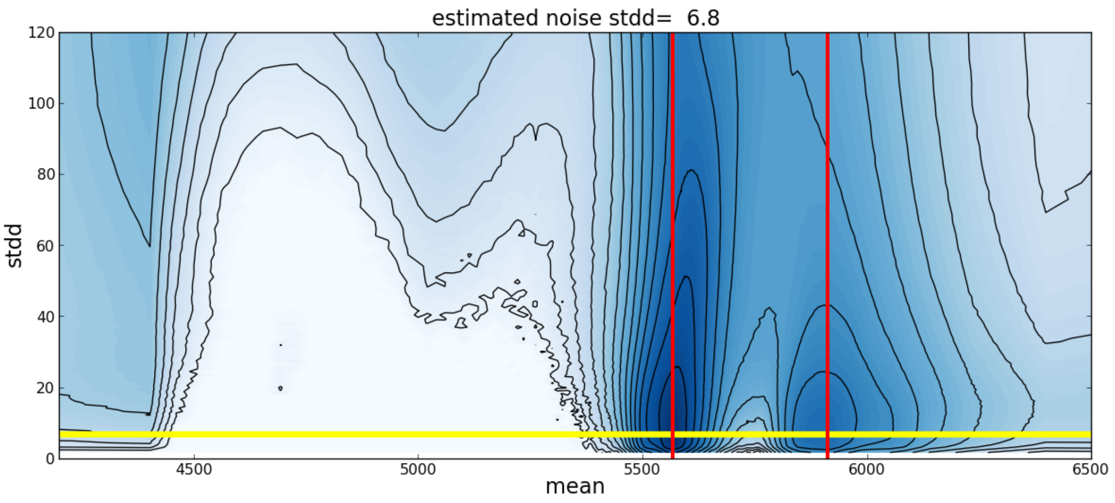
Iteration 8

+

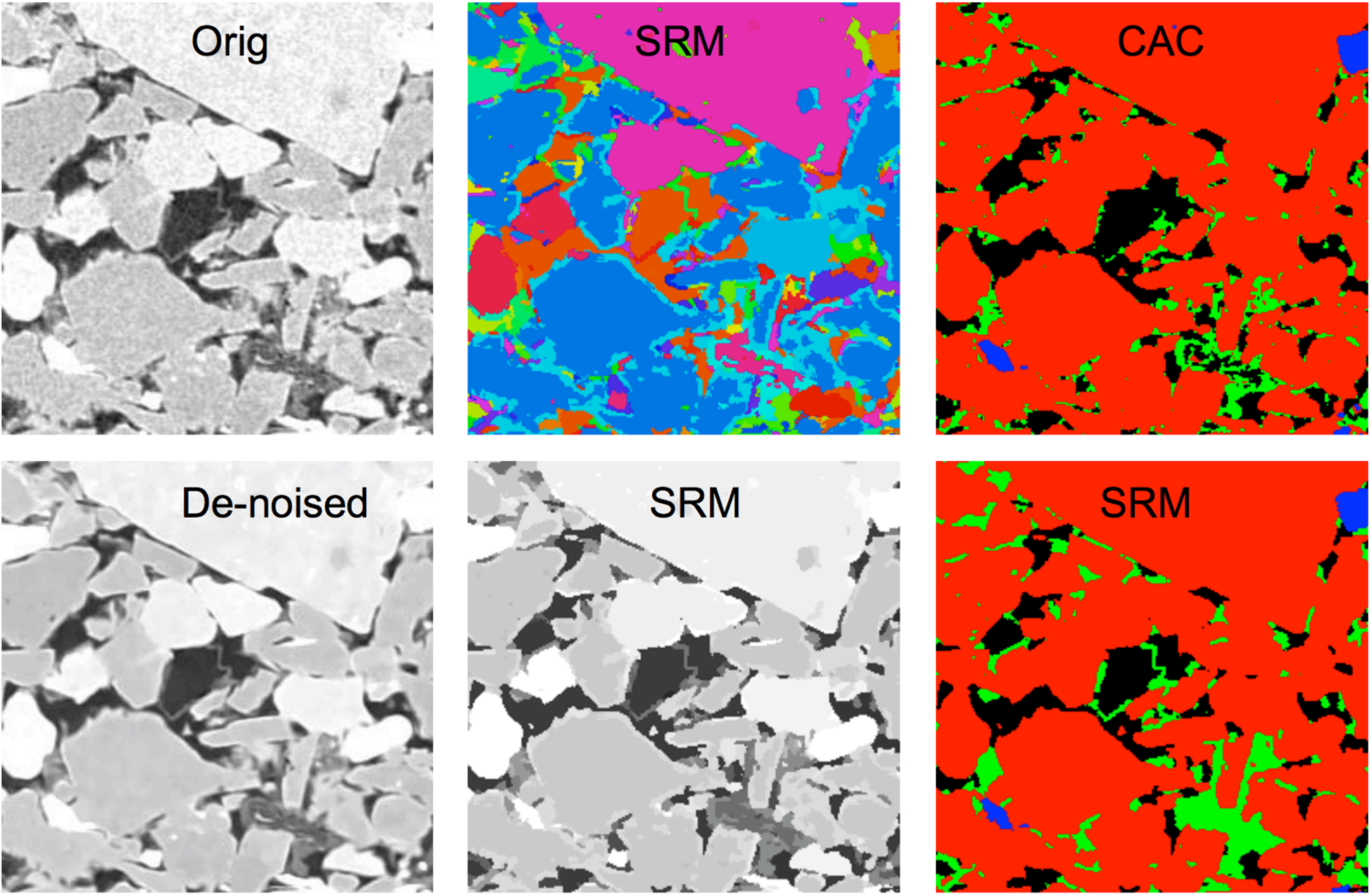
Anisotropic

Diffusion

noise = 6.8



Statistical region merging versus manual (CAC) segmentation



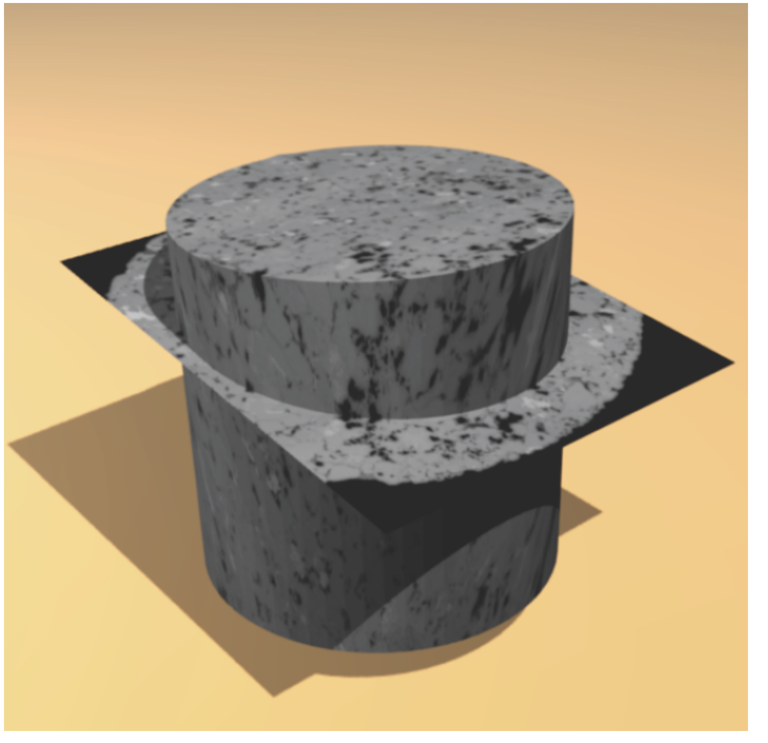
Australian National University

Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - correlating SEM-EDX mineral mapping with x-ray uCT
  - diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

Image registration

- scalable, metric-based implementation
- 3D-3D:
  - Align 3D image to another, similar, 3D image
- 2D-3D:
  - after tomography, physically cut sample and make 2D image of surface within the same volume
- Image registration plays a role in most imaging studies at ANU.



Latham et al SCA2008-35

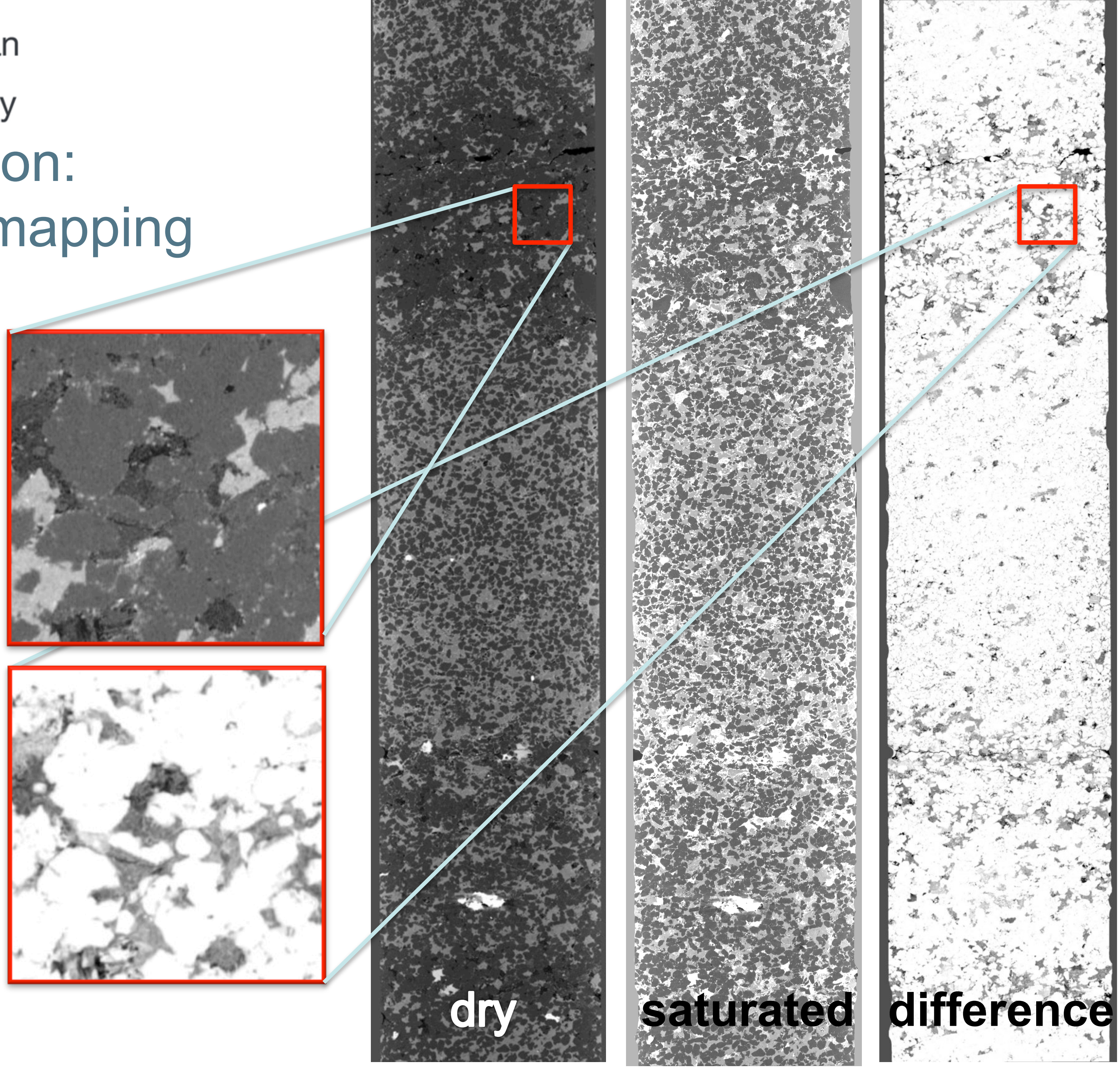
Australian National University

Registration: Porosity mapping

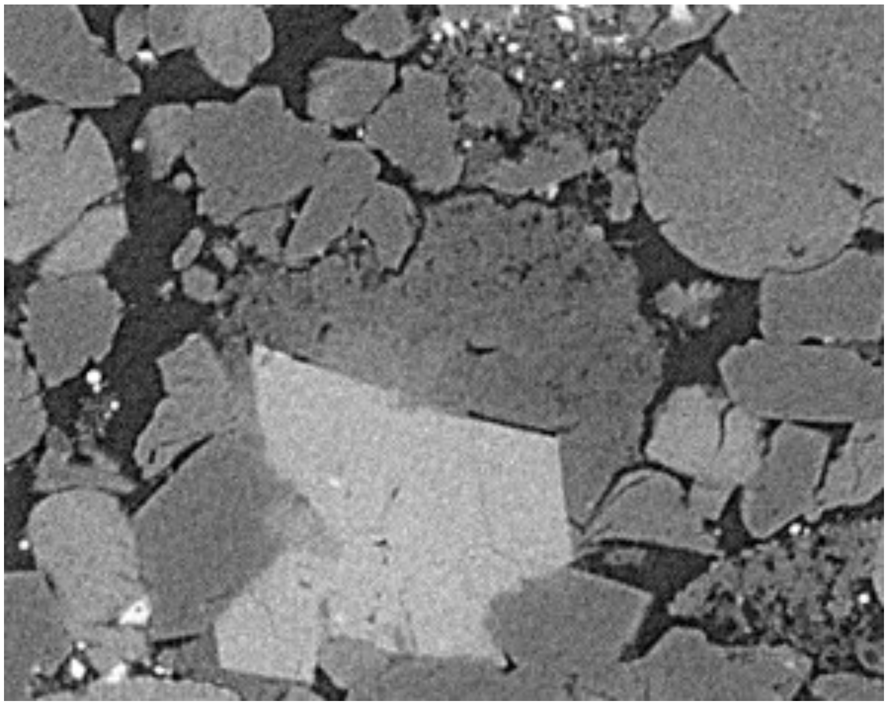
Heterogeneous tight sand 36x8mm

Imaged at 7200×1600^2 5μm voxels

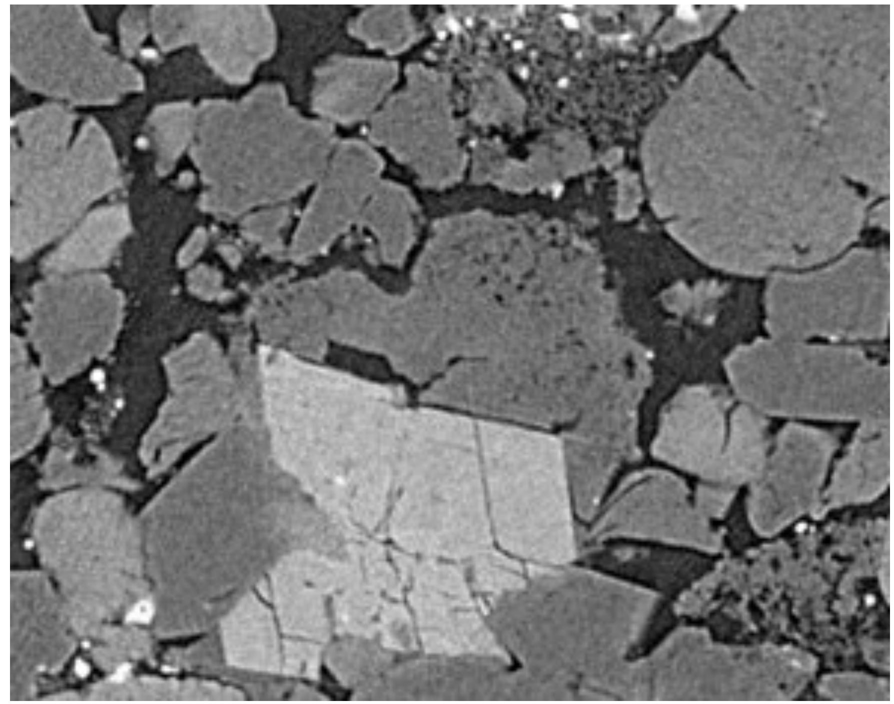
Difference between saturated and dry image yields porosity map



Imaging of CO_2 dissolution



before



after

Barrow Island rock sample before and after treatment with carbonic acid for 329 hours under 1 MPa pCO_2 at 15-20°C. Field of view 0.8 x 0.7mm

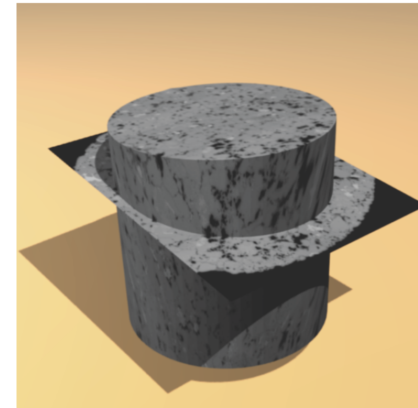
Australian National University

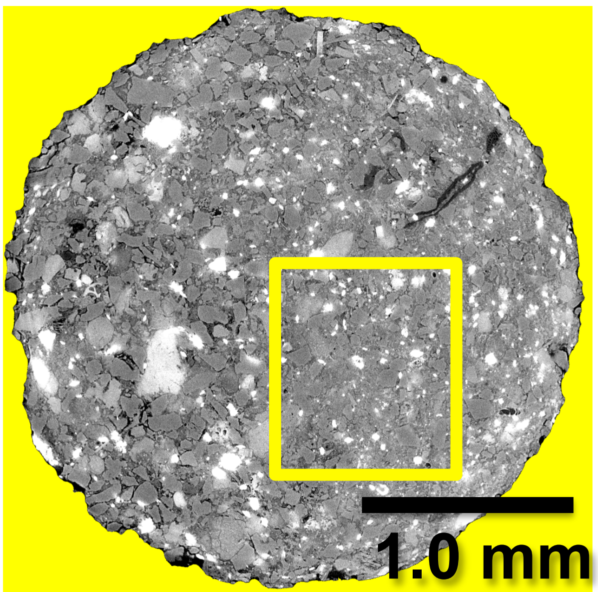
Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - Correlating SEM-EDX mineral mapping with x-ray uCT
  - Imaging diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

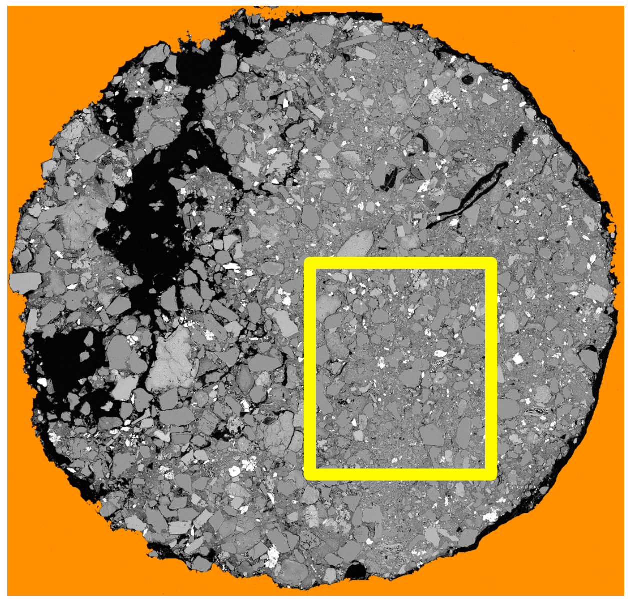
Australian National University

2D-3D Registration:
X-ray MCT to SEM-EDX

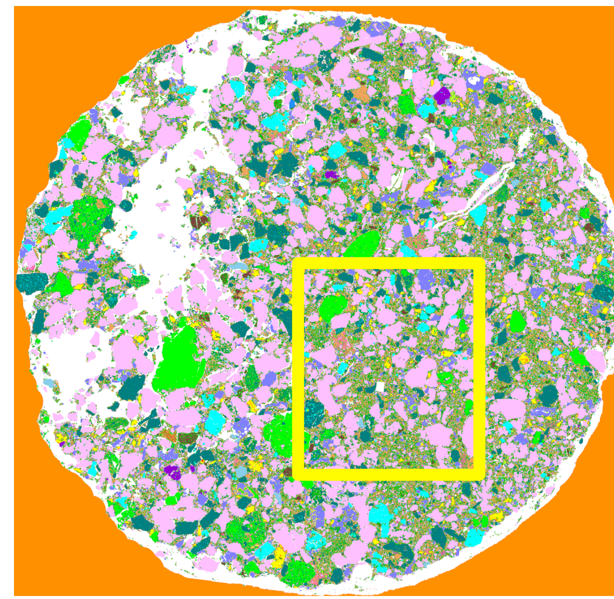




X-ray microCT



SEM

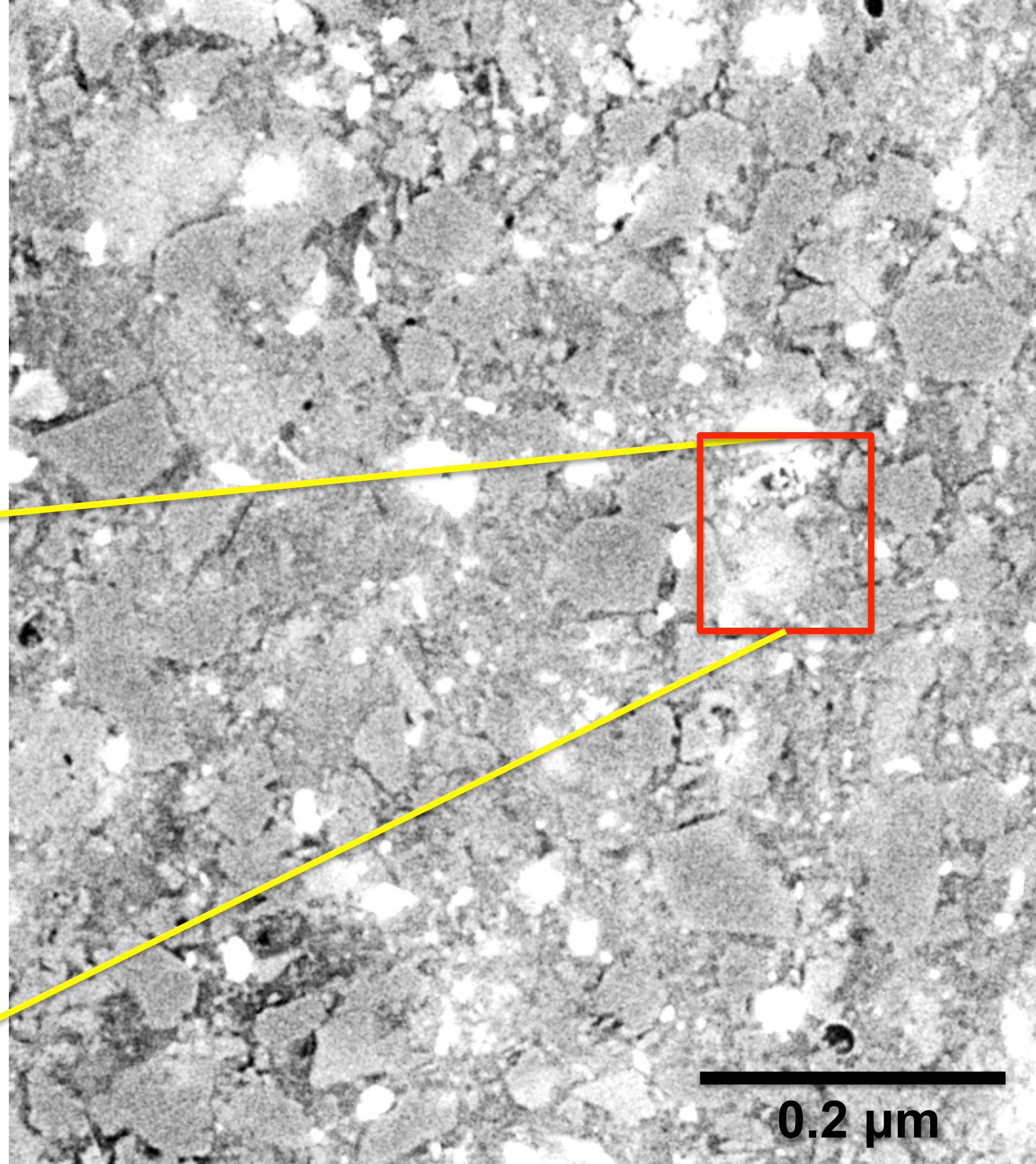


SEM-EDX (QEM)

Australian National University

X-ray microCT

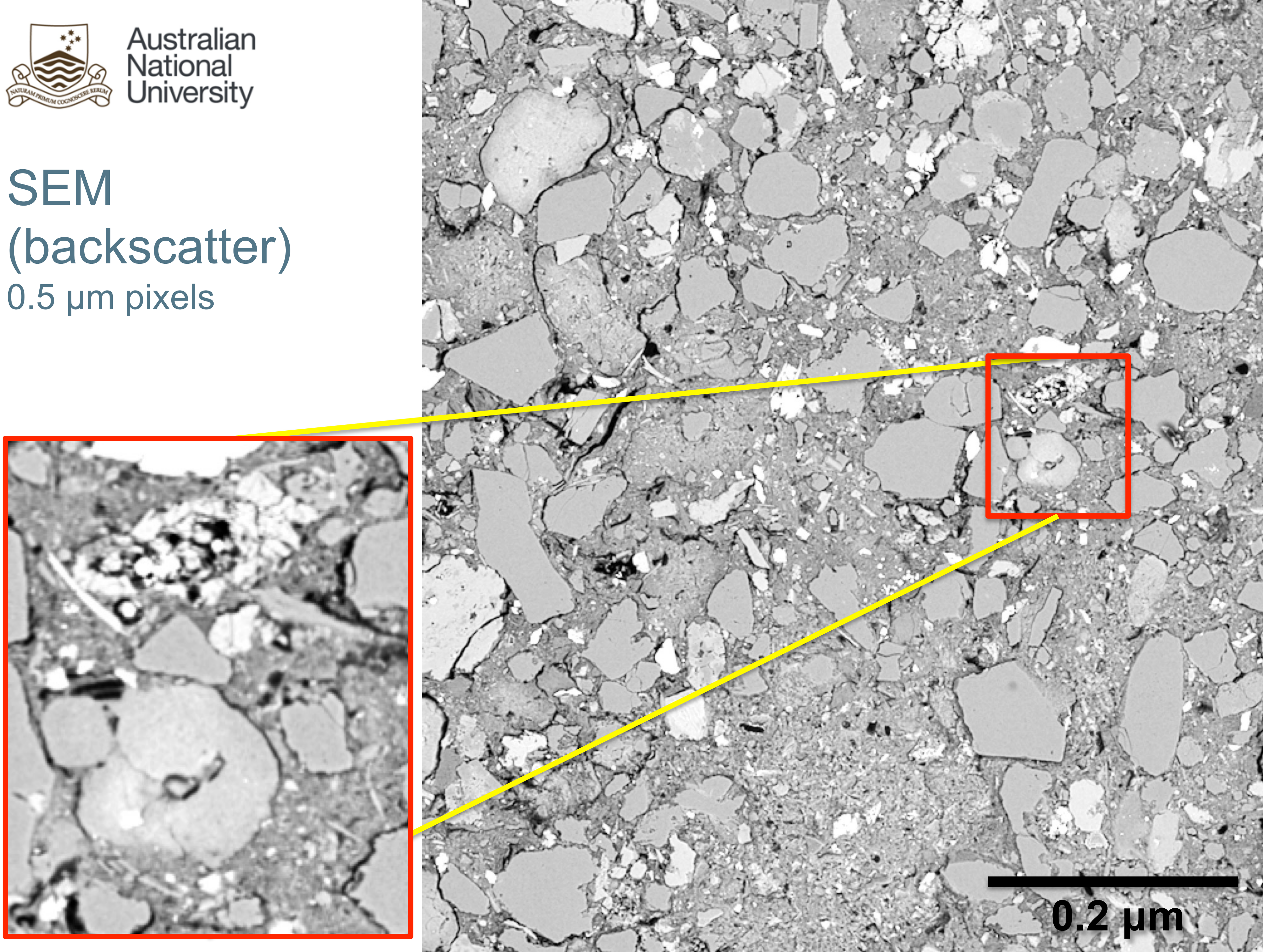
2.0 µm voxels



Australian National University

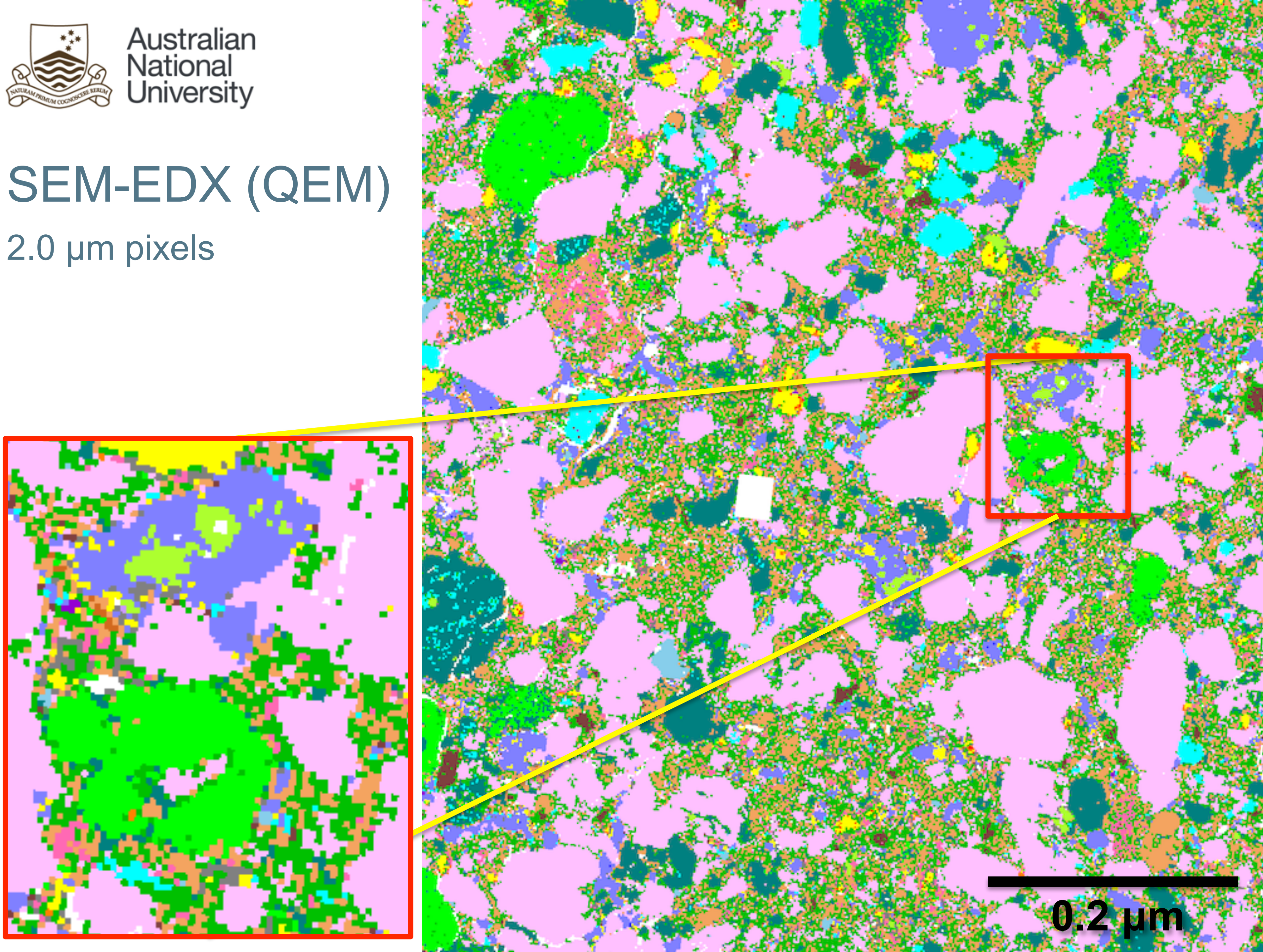
SEM (backscatter)

0.5 μm pixels



SEM-EDX (QEM)

2.0 µm pixels



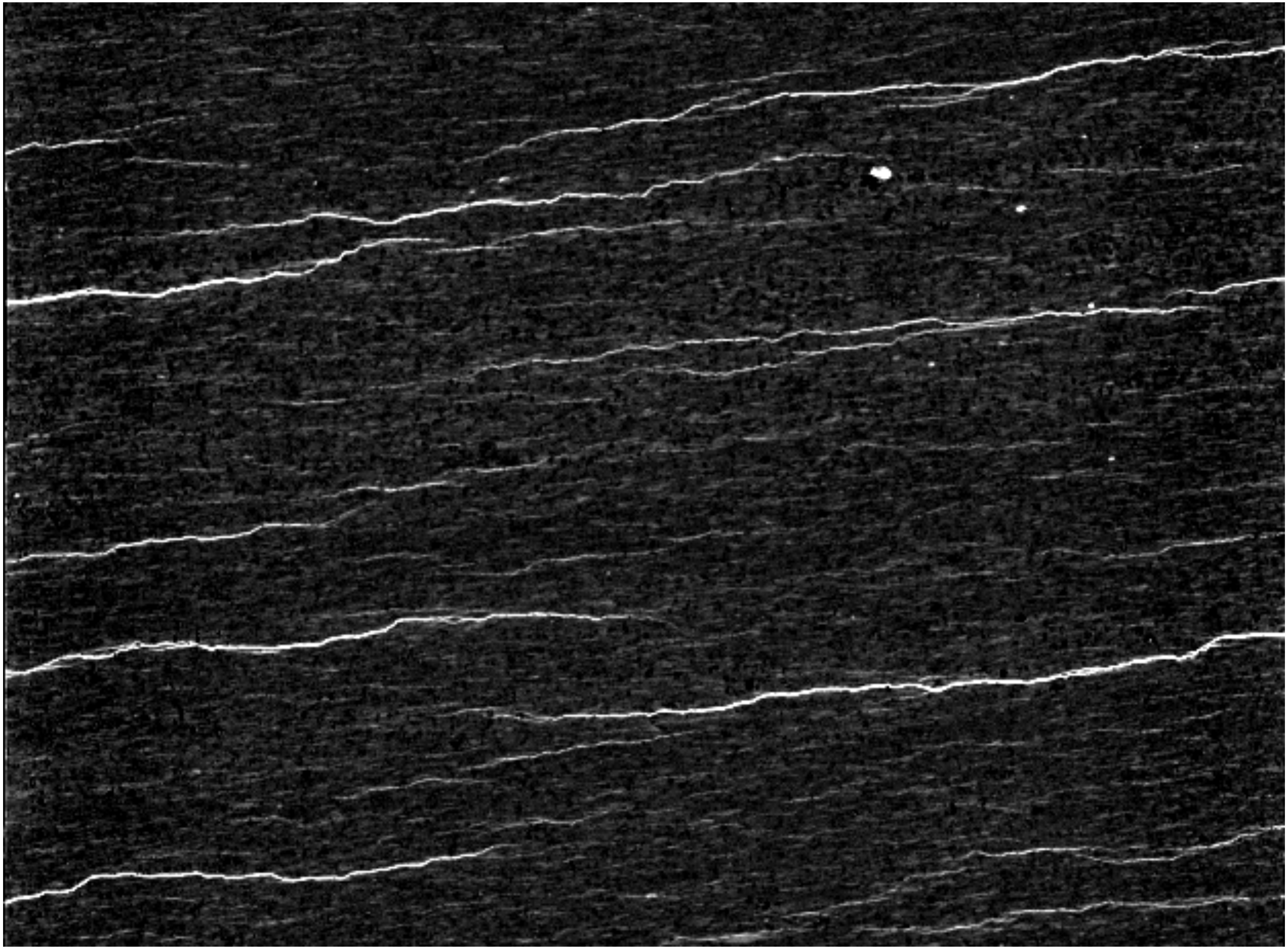
Outline

- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - Correlating SEM-EDX mineral mapping with x-ray uCT
  - Imaging diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

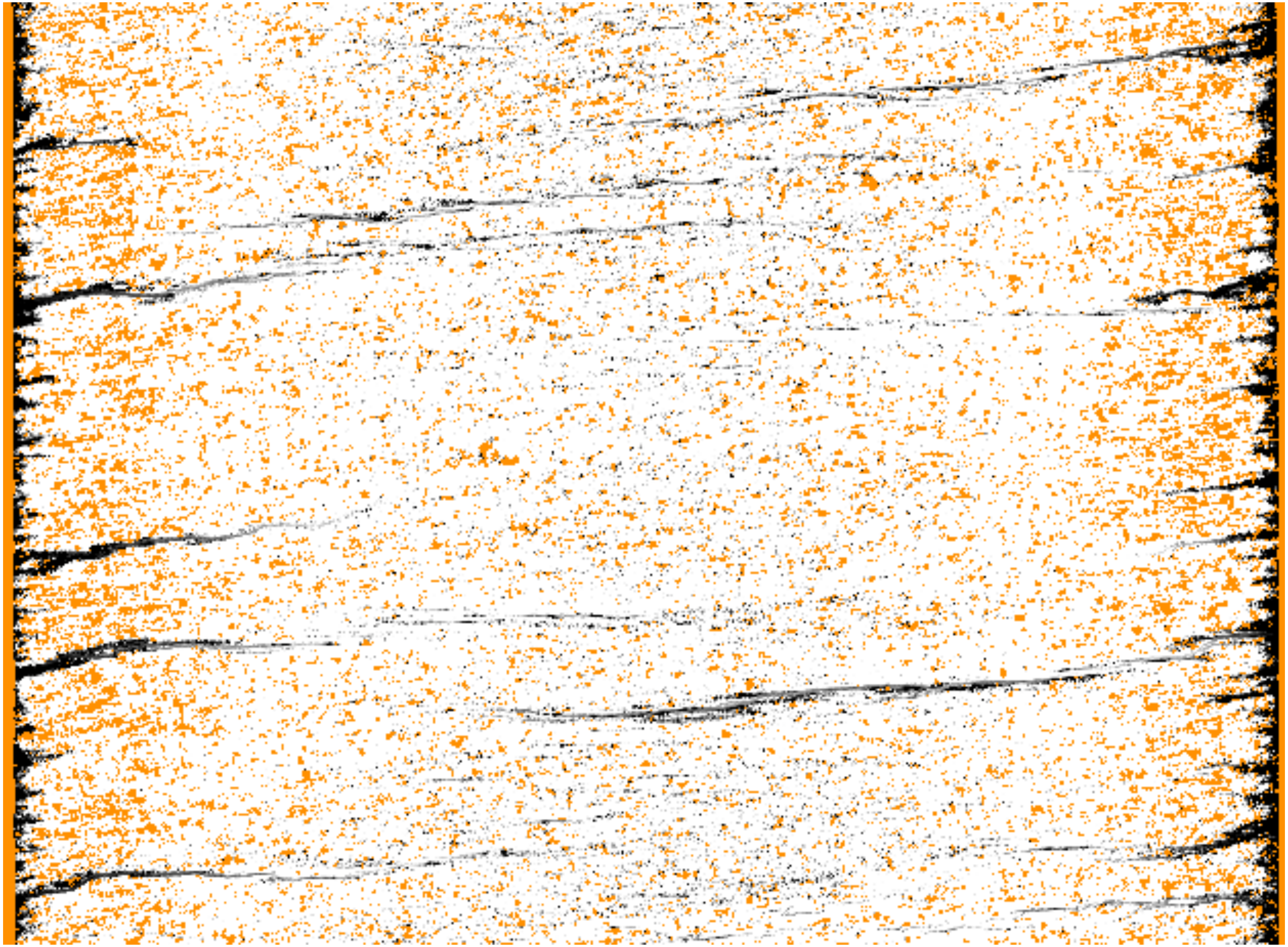
Studies of diffusion in shale

- CH_2I_2 saturated sample immersed in toluene inside micro-CT
- sequence of 80 tomograms acquired while CH_2I_2 diffuses out and toluene diffuses in
- goal is to compute spatial diffusivity map, which should be closely correlated to permeability
- need concentration and mass of CH_2I_2 in each voxel
- 3 samples studied at three different resolutions (3 mm, 8 mm and 12 mm)

12mm Shale (porosity map)

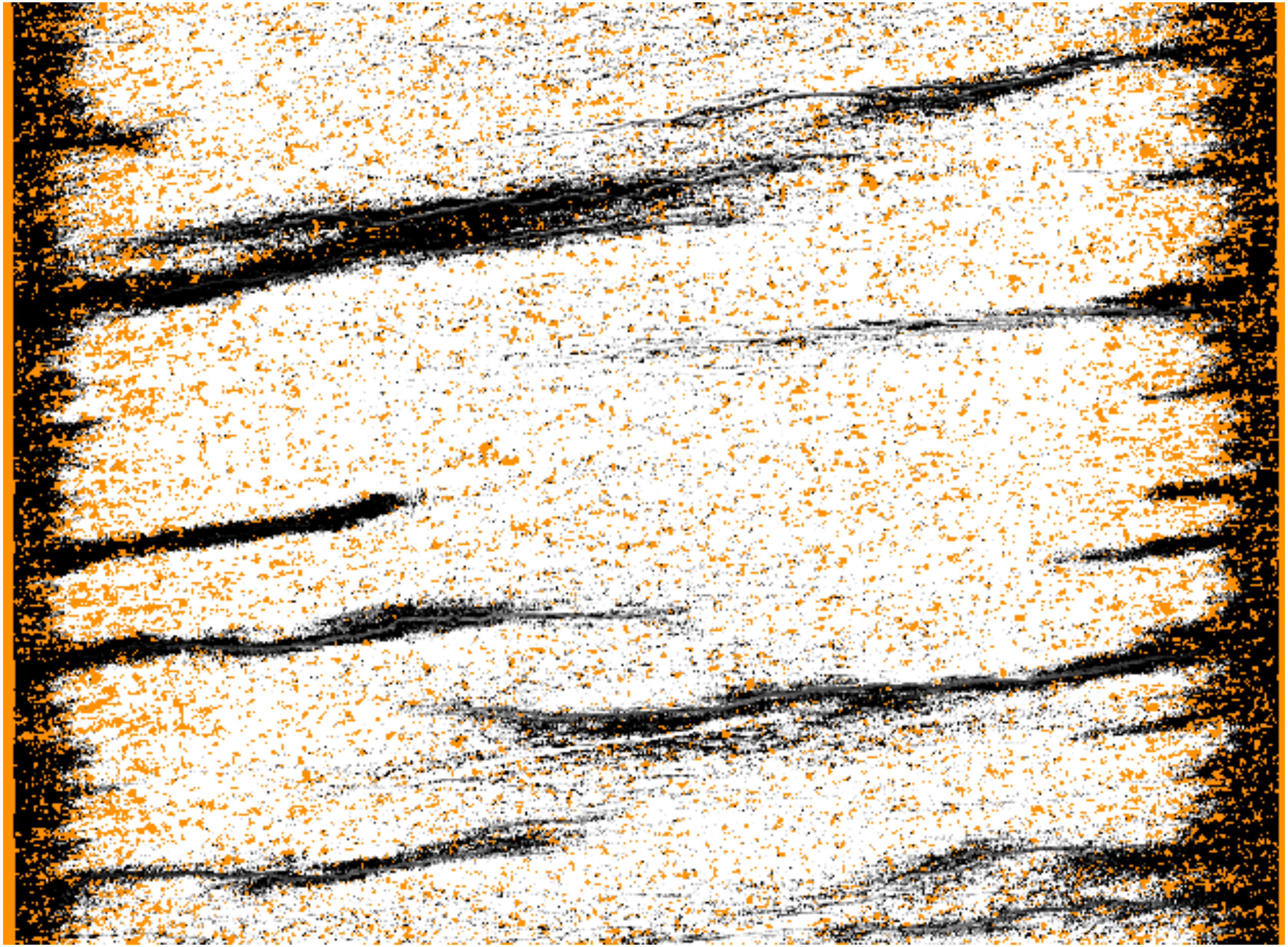


1st frame, map of conc(CH_2I_2)

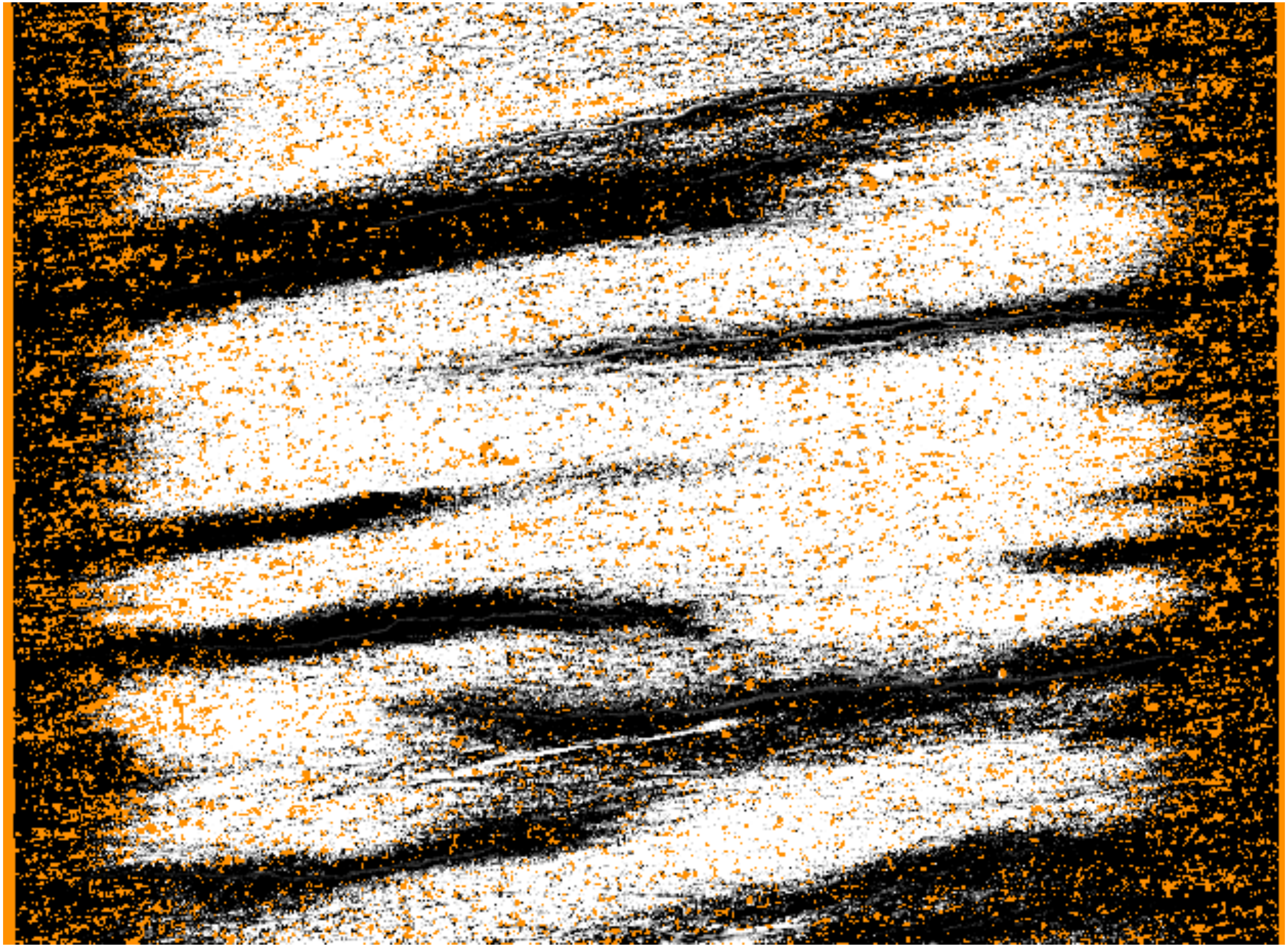


Australian National University

15th frame after tol. immersion

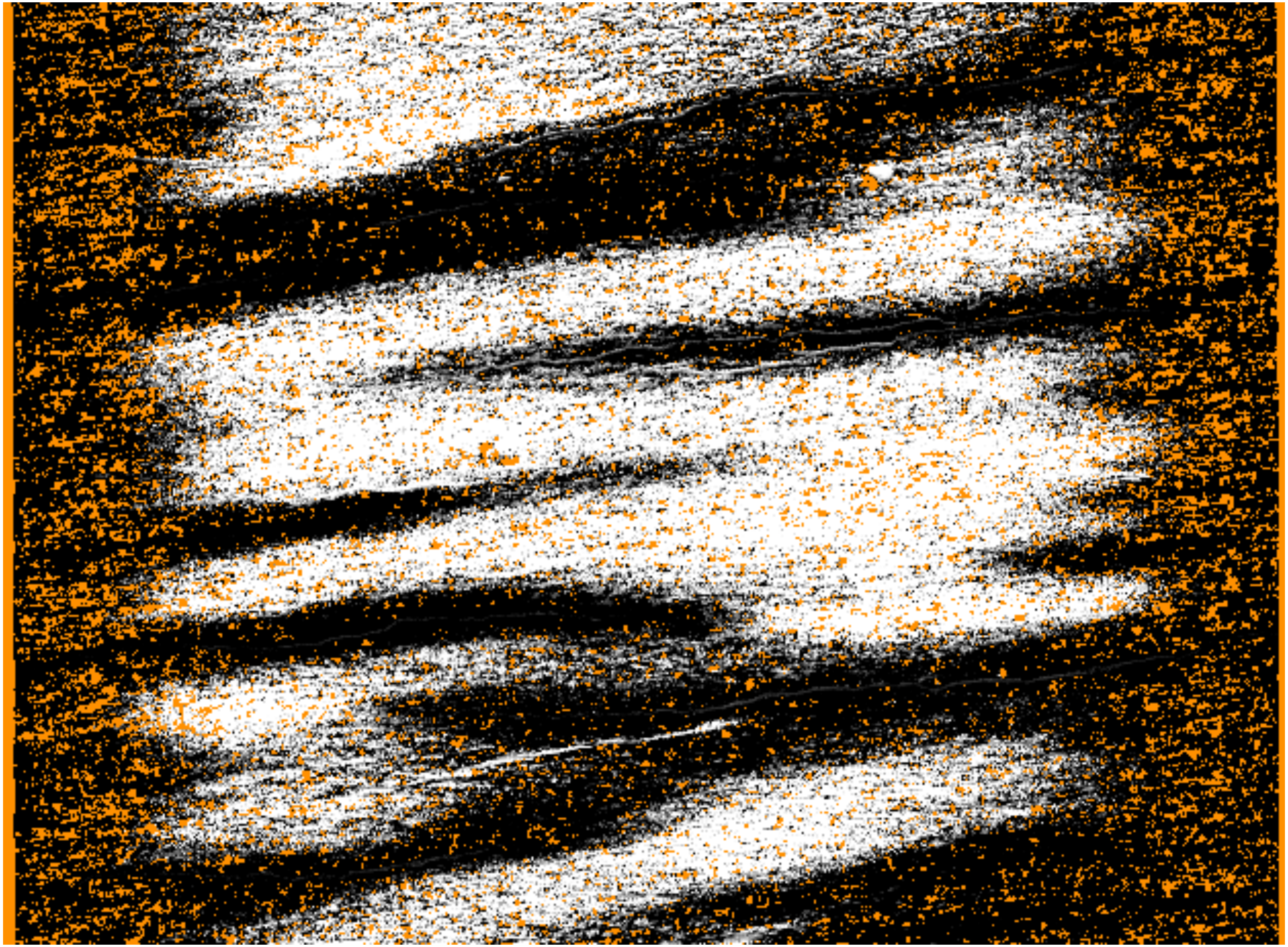


48^{th} frame after tol. immersion



Australian National University

80^{th} frame after tol. immersion

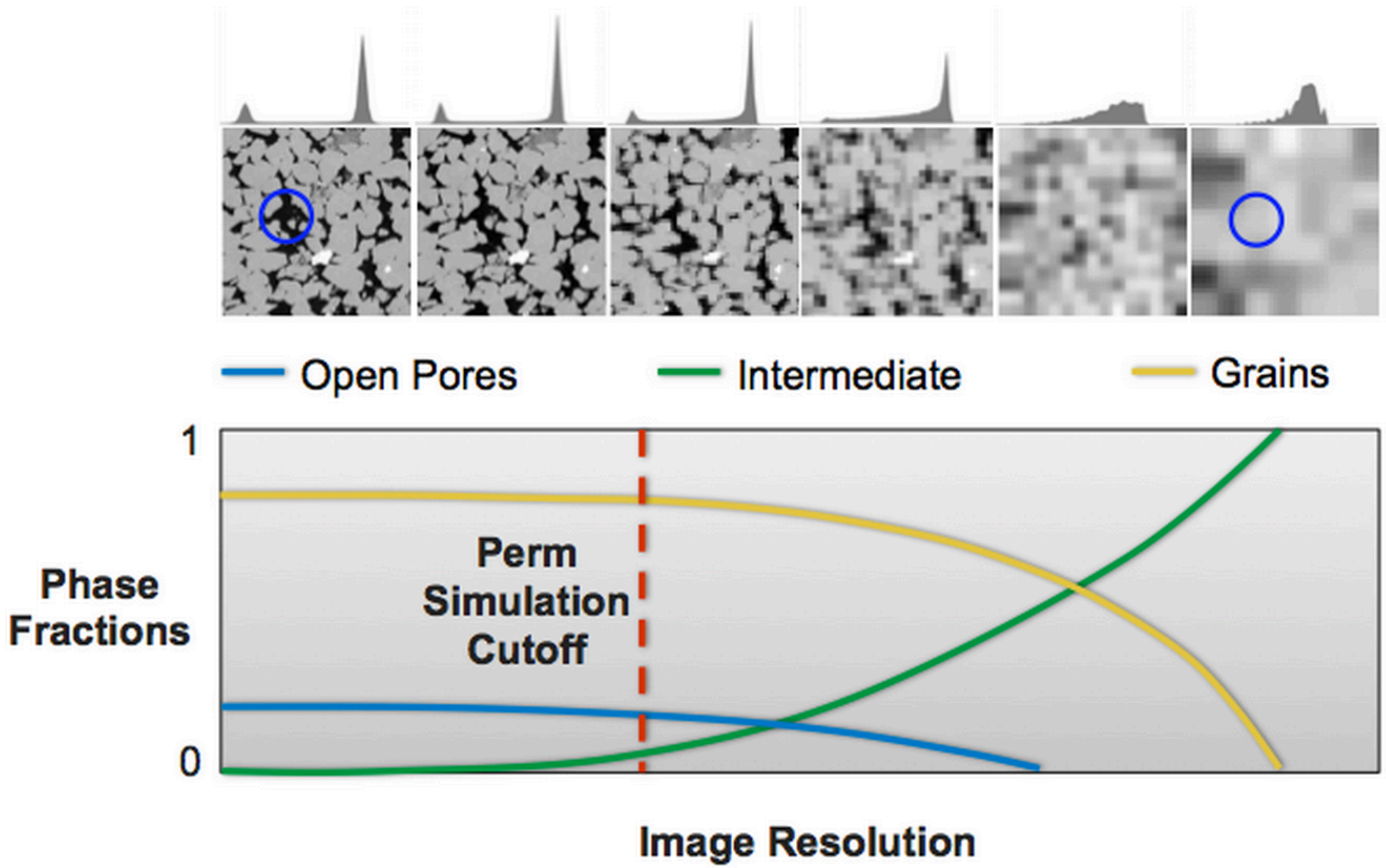


Australian National University

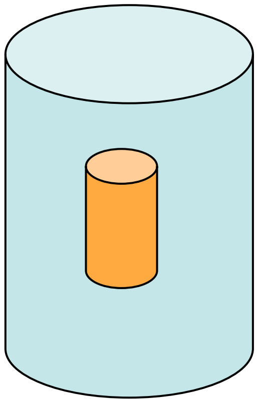
Outline

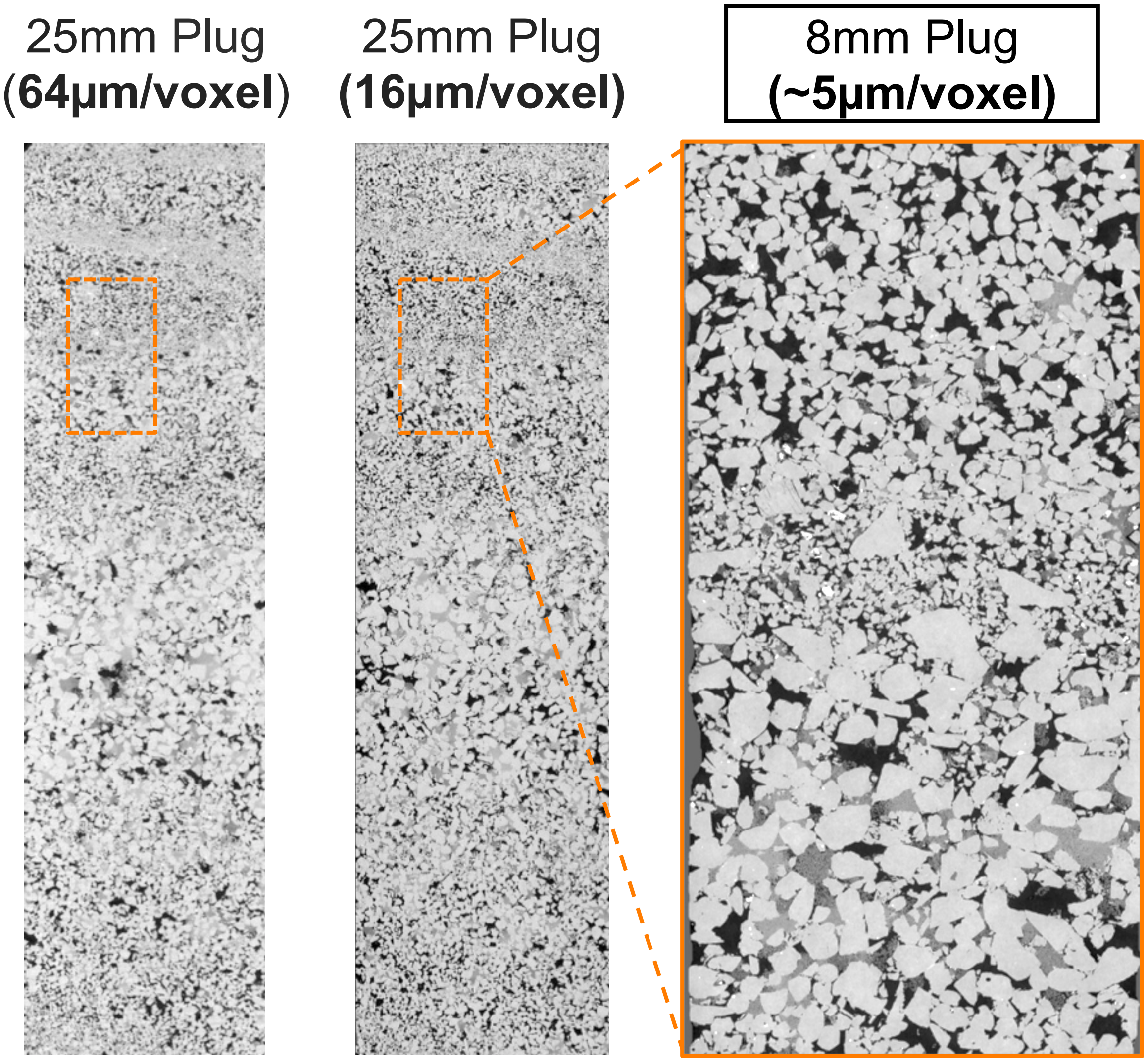
- **Imaging techniques**
  - Improving quality: new scanning and reconstruction techniques
  - Dynamic tomography
- **Image analysis**
  - Towards automated segmentation
  - Image registration
- **Application examples**
  - correlating SEM-EDX mineral mapping with x-ray uCT
  - diffusion in shale
  - Iodine labelling of sub-resolution surface area
  - Cross-scale mapping of permeability in heterogeneous sandstones

Effect of diminishing resolution



Cross-scale imaging and registration



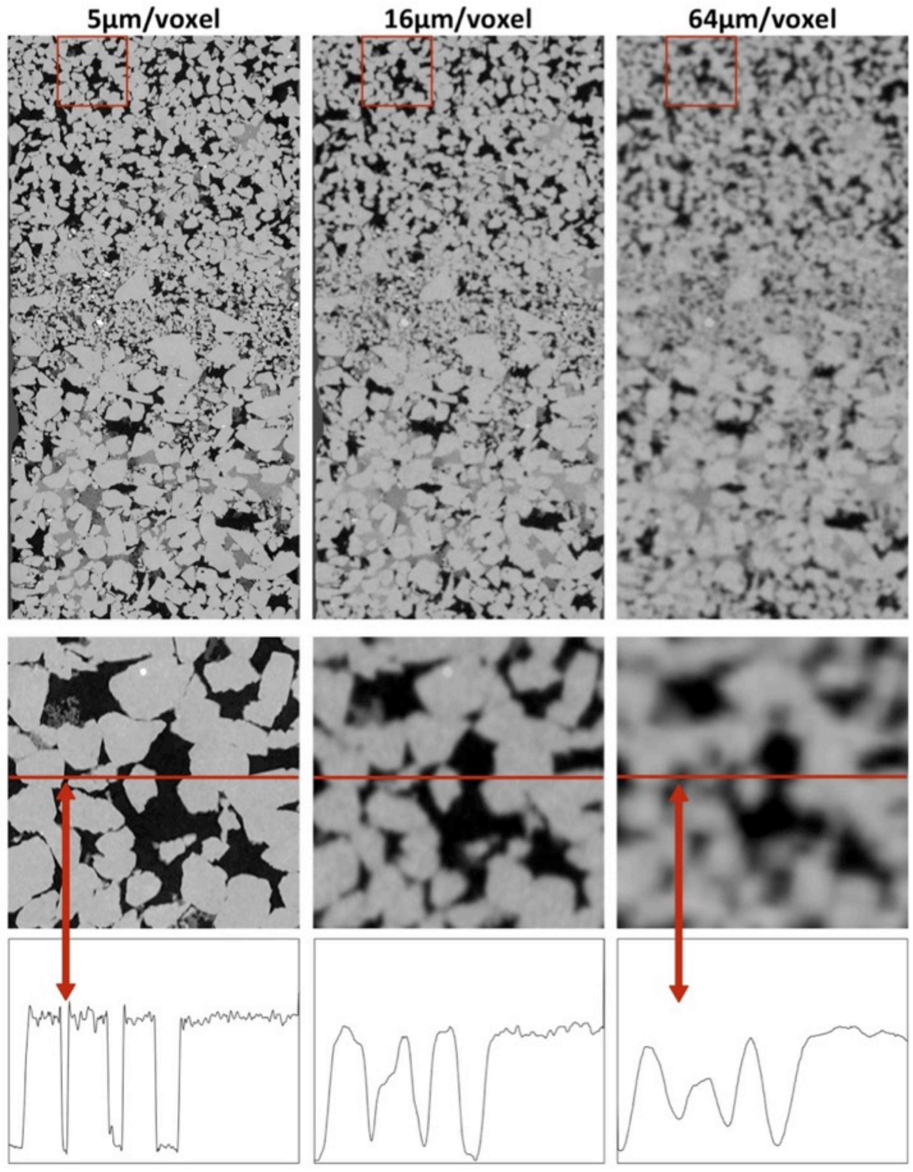


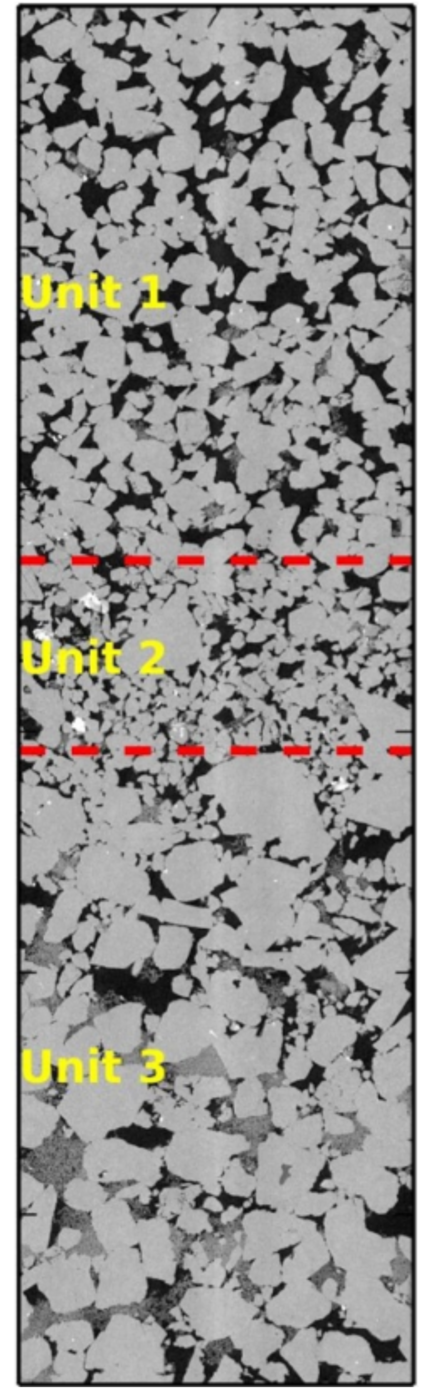
Precipice sandstone

Imaged at 5, 16 and 64 μm

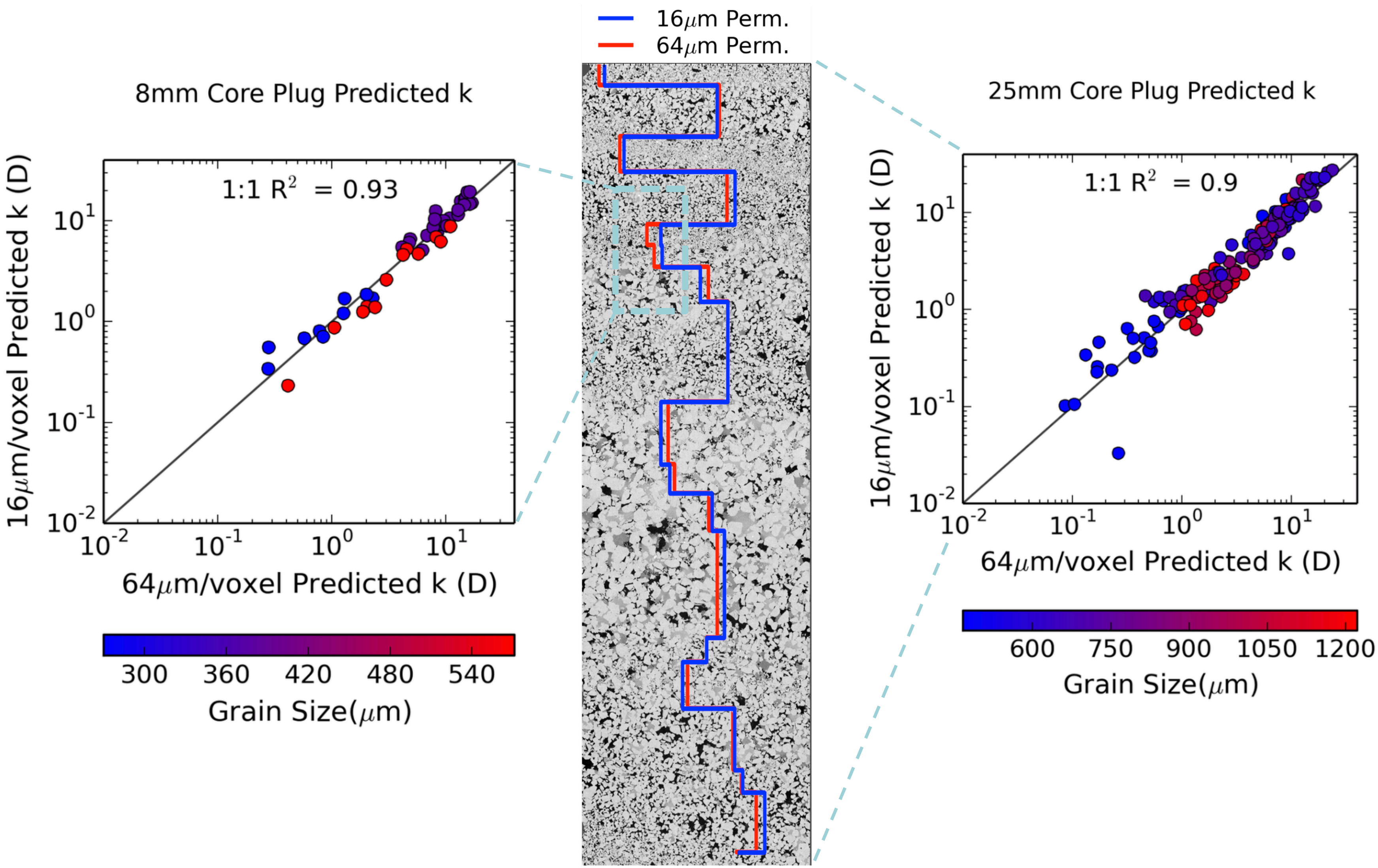
25 mm plug, 8mm subplug

'Unitised' according to porosity, grain and pore size



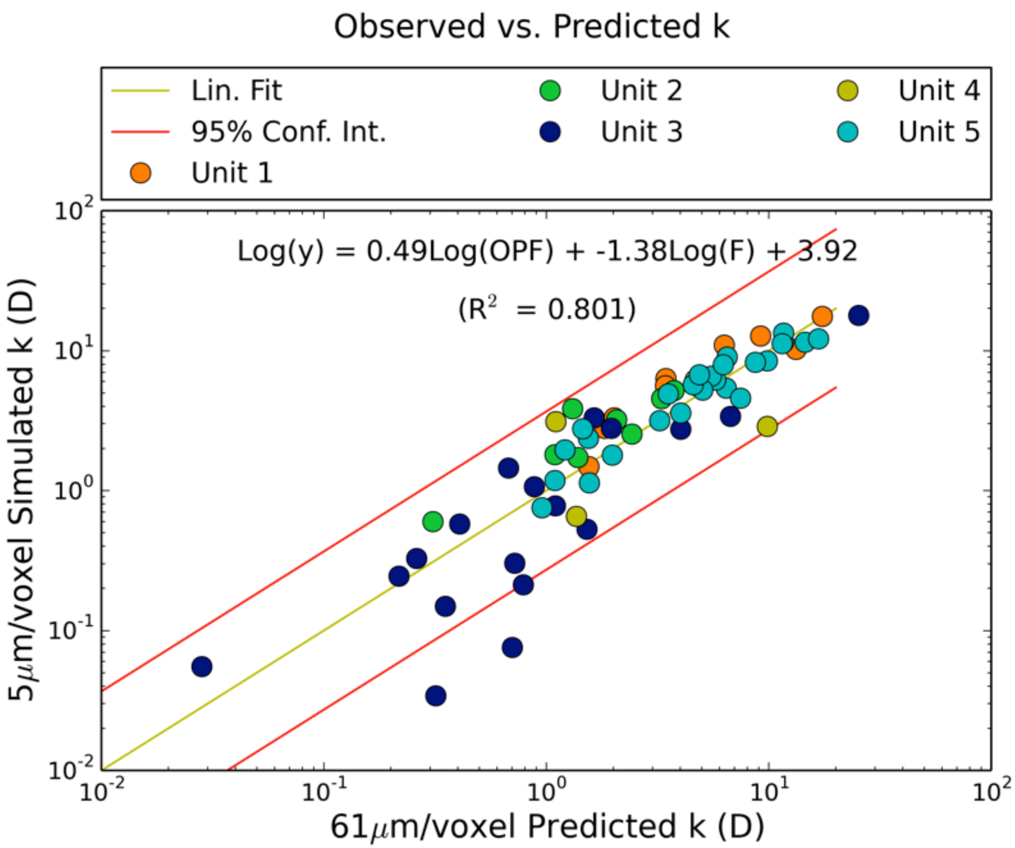


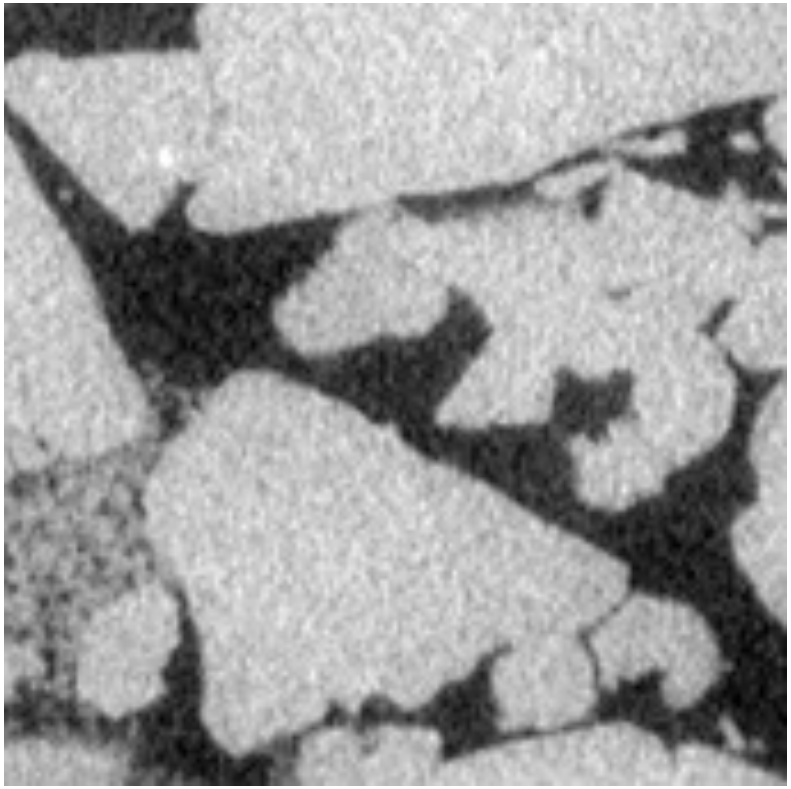
Prediction Results



Australian National University

Data Considerations

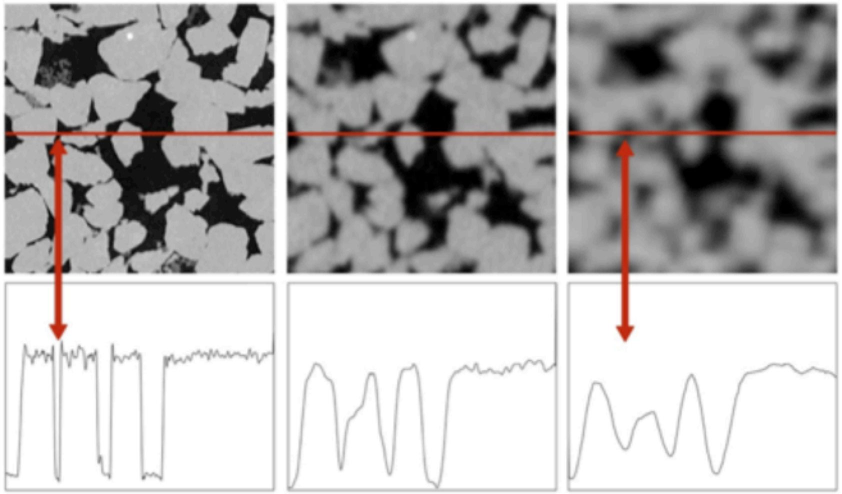




Australian National University

Conclusions from cross-resolution study

- There is a range of resolution in which the sharp edges are lost, but in which the grayscale data still contains useful geometric information



- For this sandstone one can make worthwhile estimates of permeability from images at 1/10th of the resolution needed for Navier-Stokes solvers.
- Future work:
  - capillary pressure and other two-phase properties
  - carbonates

Australian National University

Conclusions - the future?

- Quantitative X-ray tomography is possible and could hold the key for industrial applications
  - dual energy imaging and iterative reconstruction are key elements
- Unsupervised segmentation is another critical element – but what are its limits?
  - need methods that quantify their accuracy
- Multi-scale and multi-modal imaging crucial for heterogeneous media
  - need robust, fast image registration
  - often have “training” volumes, so machine learning may play a role

Australian National University

Acknowledgements

- Australian Research Council
- Members of the ANU-UNSW Digicore Research Consortium
- Australian National Low Emissions Coal (ANLEC) R&D Program
- Australian National Computing Infrastructure (NCI)

Thank you!