ENERGY GeoHackathon
Society of Petroleum Engineers

SPE International
SPE Europe Region

2022 SPE EUROPE ENERGY GEOHACKATHON

5. The Geothermal Hackathon – introducing the dataset and workflow (including Scanning Electron Microscopy and Image analysis)

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#DatafyingEnergy

ENERGY GeO Hackathon
Society of Petroleum Engineers

Italian Section | London Section | Netherlands Section | Romanian Section | Copenhagen Section | Geothermal Technical Section

NYNKE KEULEN

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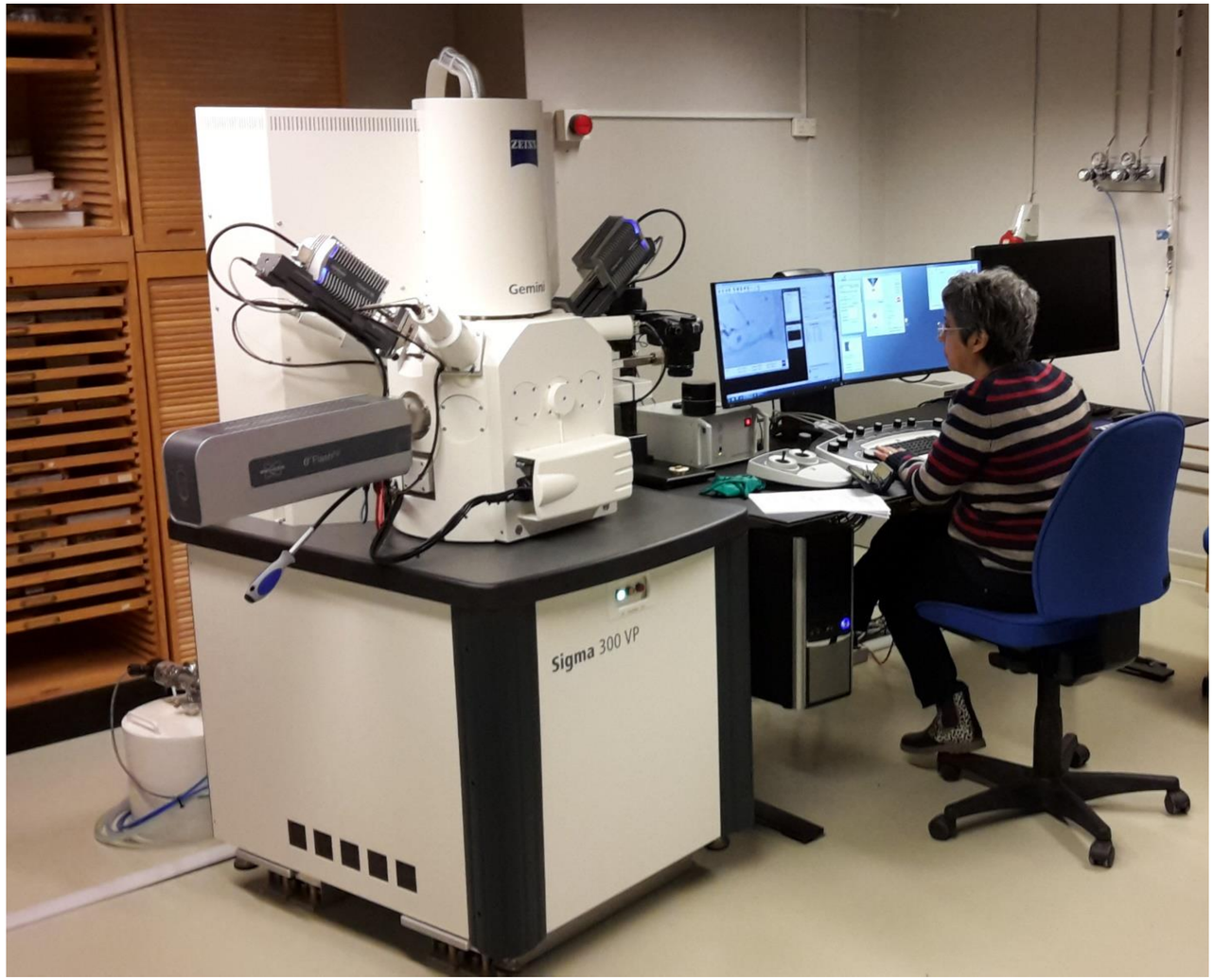
Outline

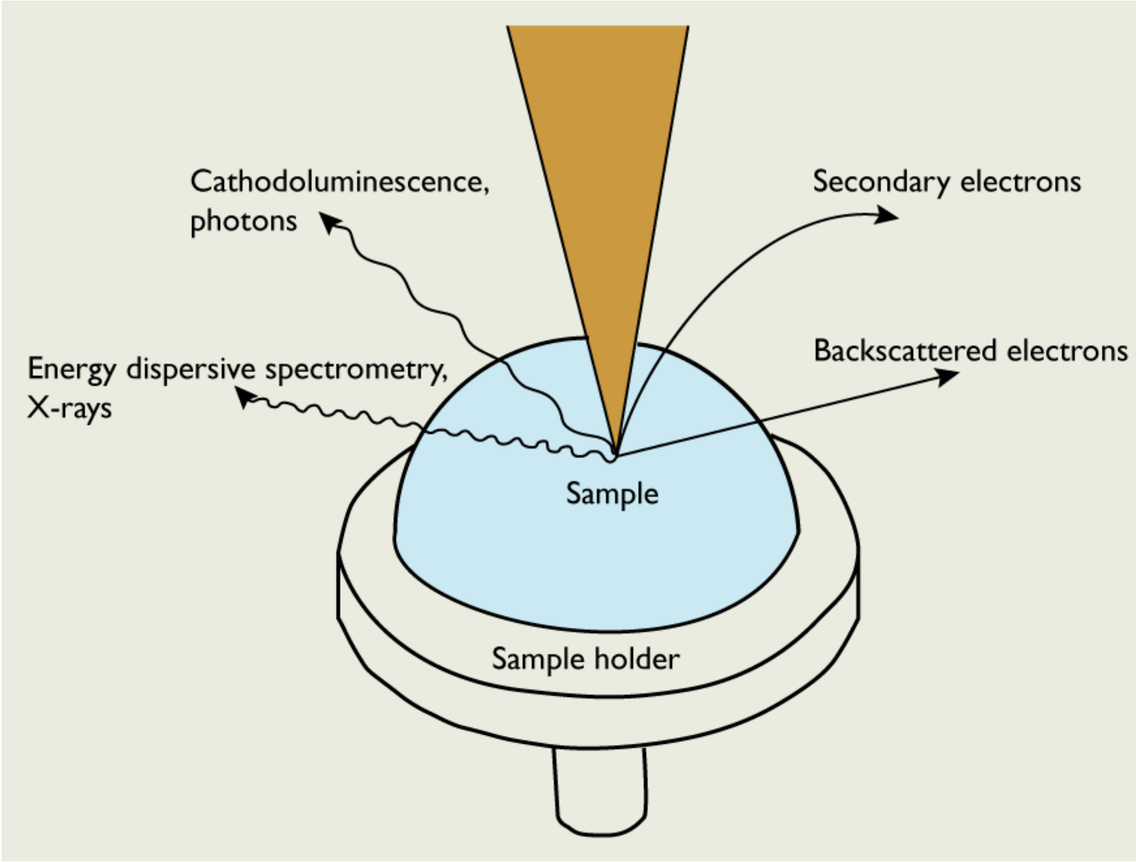
- Scanning Electron Microscopy (SEM) techniques and images
- Introduction to the Hackathon Challenge
- Practical information on the dataset

Scanning Electron Microscope



Scanning Electron Microscope = SEM

Scanning electron microscopy signals

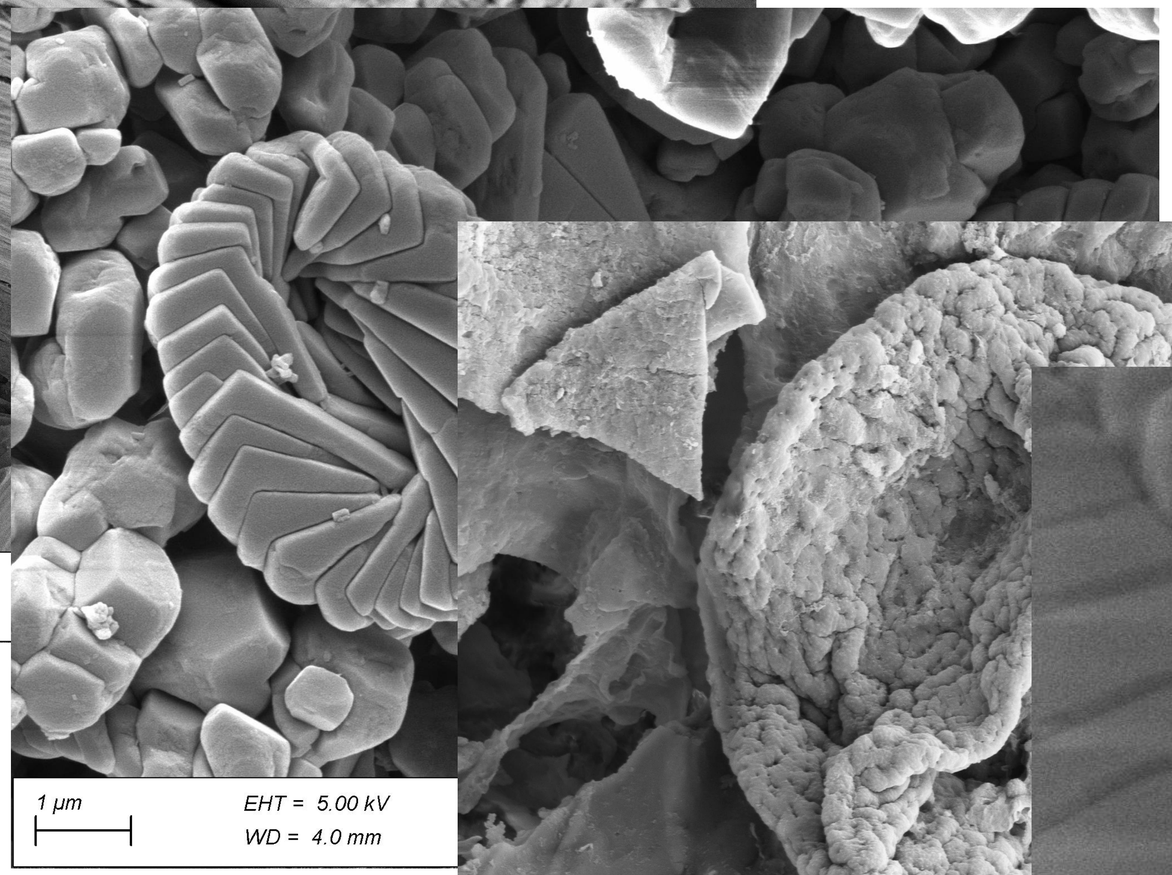


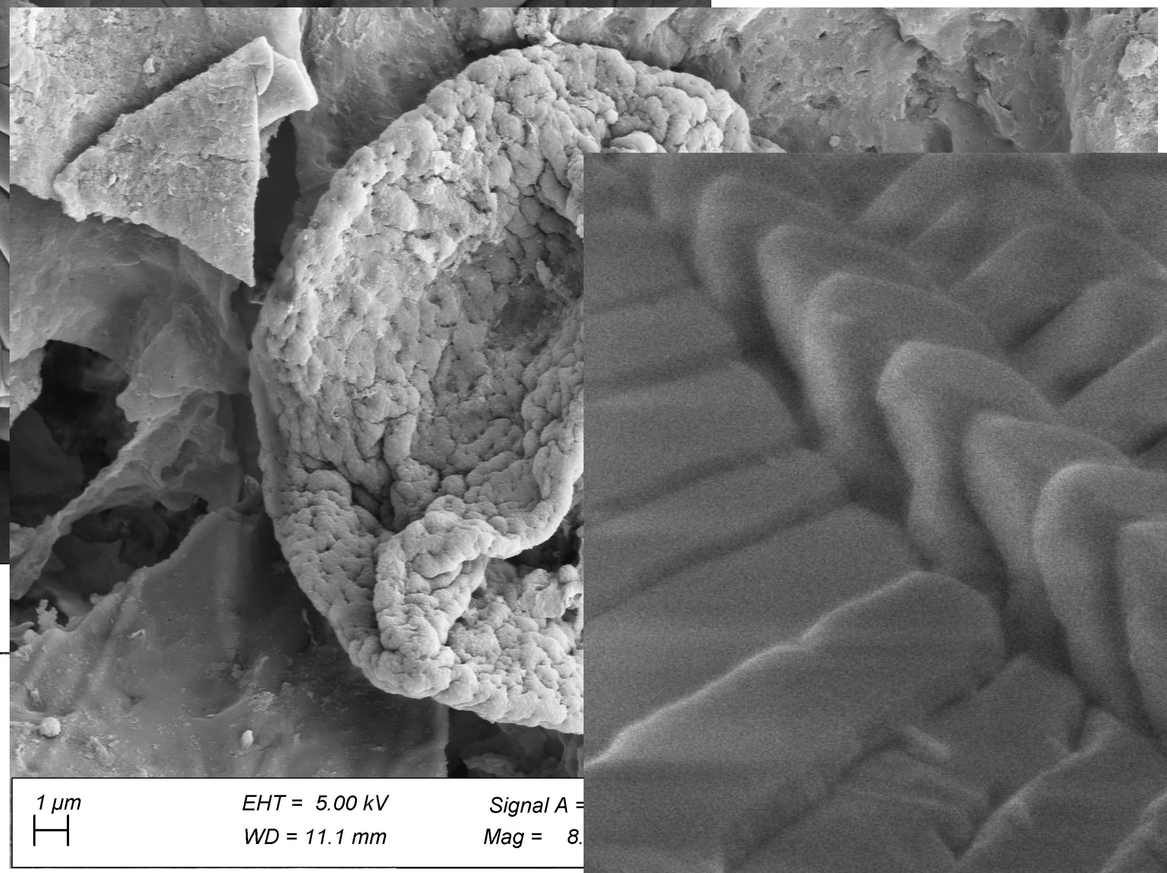
SEM signals:

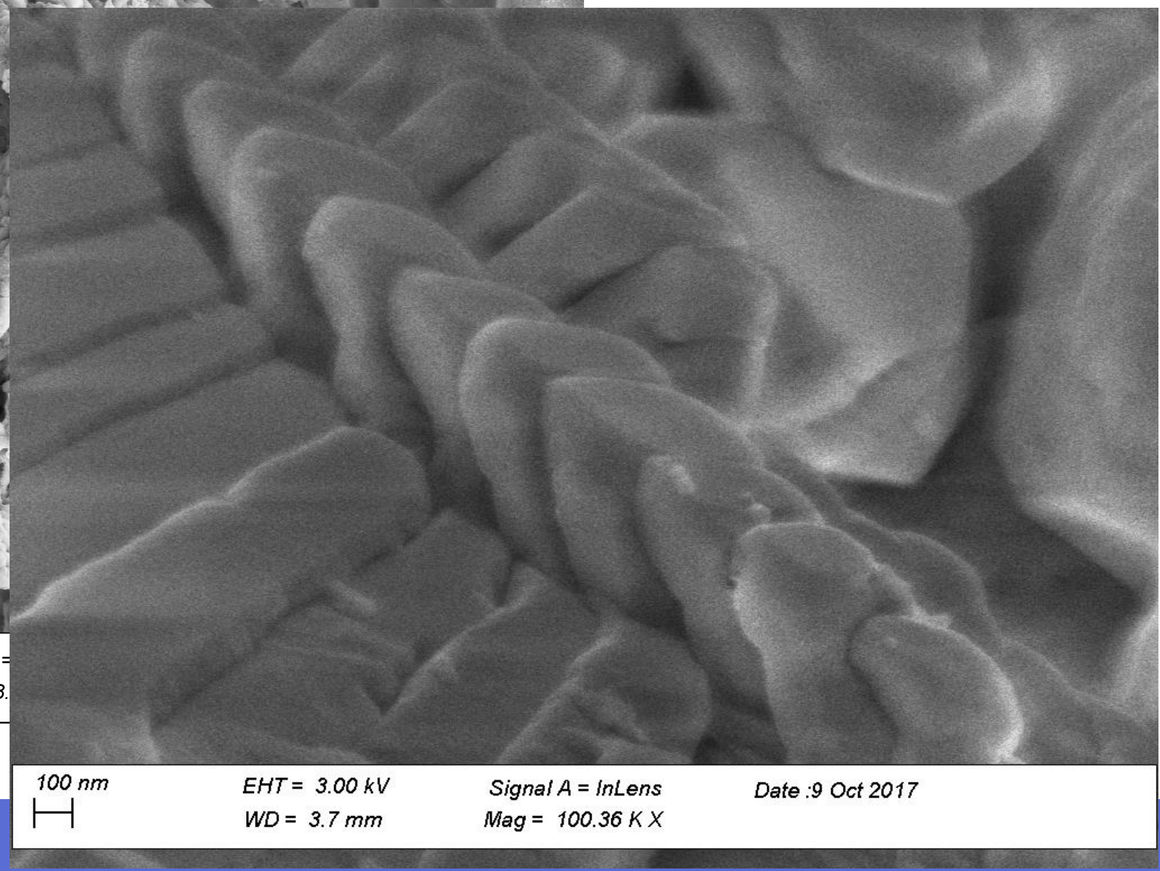
- Secondary electrons: topography imaging
- Backscattered electrons (BSE): material contrast imaging
- Forward scattered electrons: crystallographic information
- Photons: Cathodoluminescence (CL) -> growth information
- X-rays: chemistry

Imaging – topography

Secondary electrons

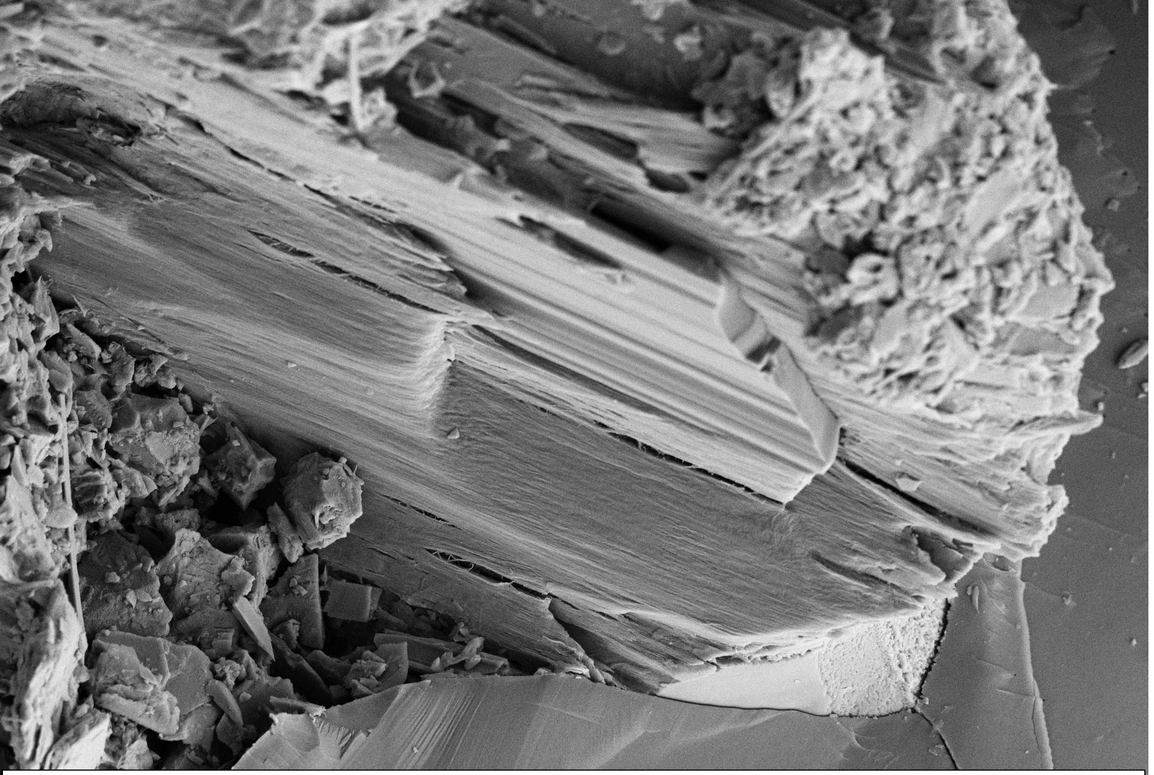


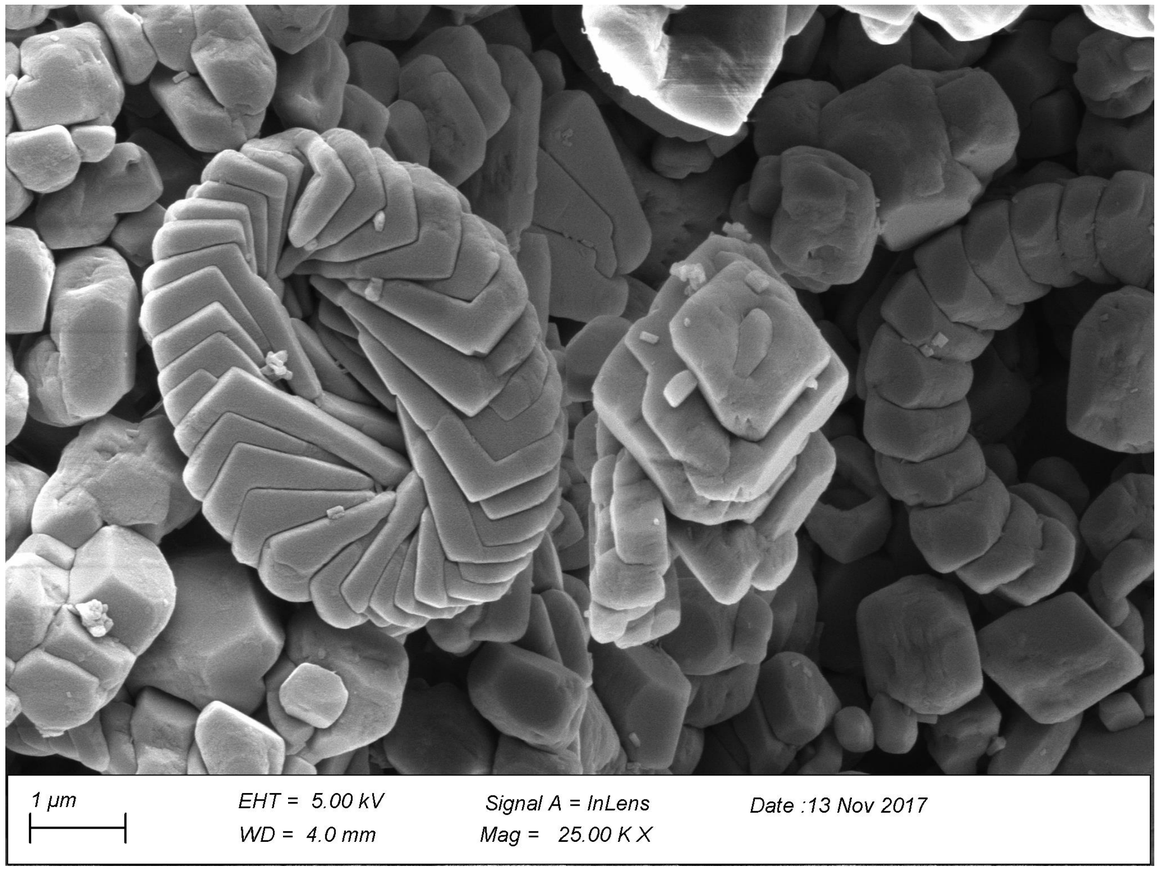




Imaging – topography

Secondary electrons



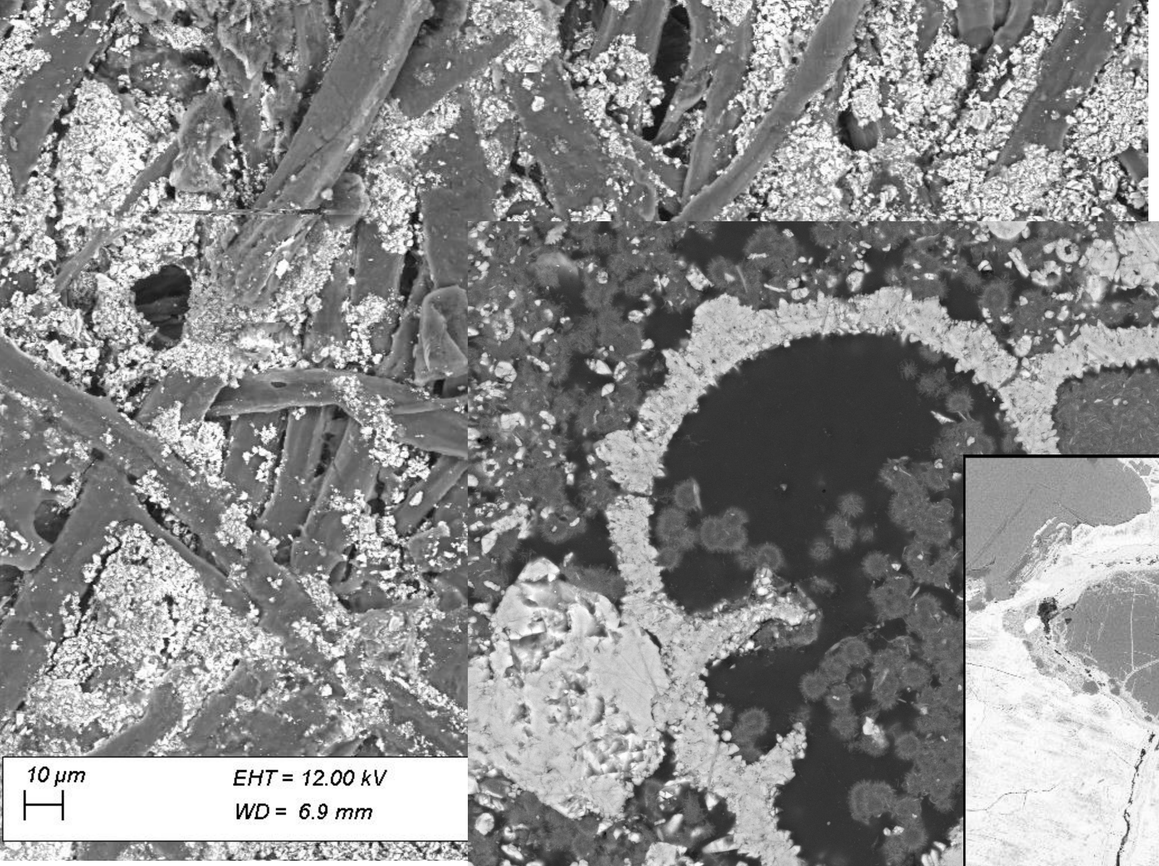


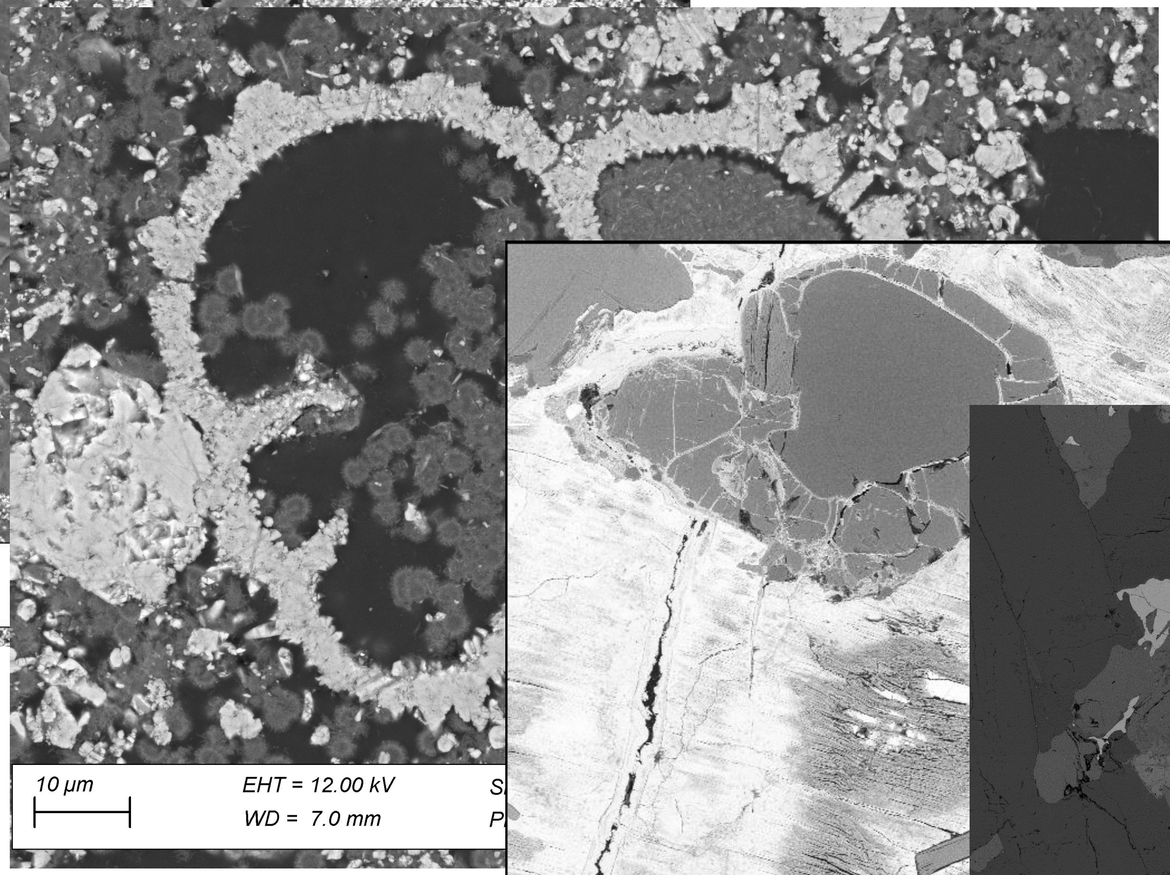
*For 3D-images of fossils, minerals, porosity, overgrowths
*structure, topography, relief

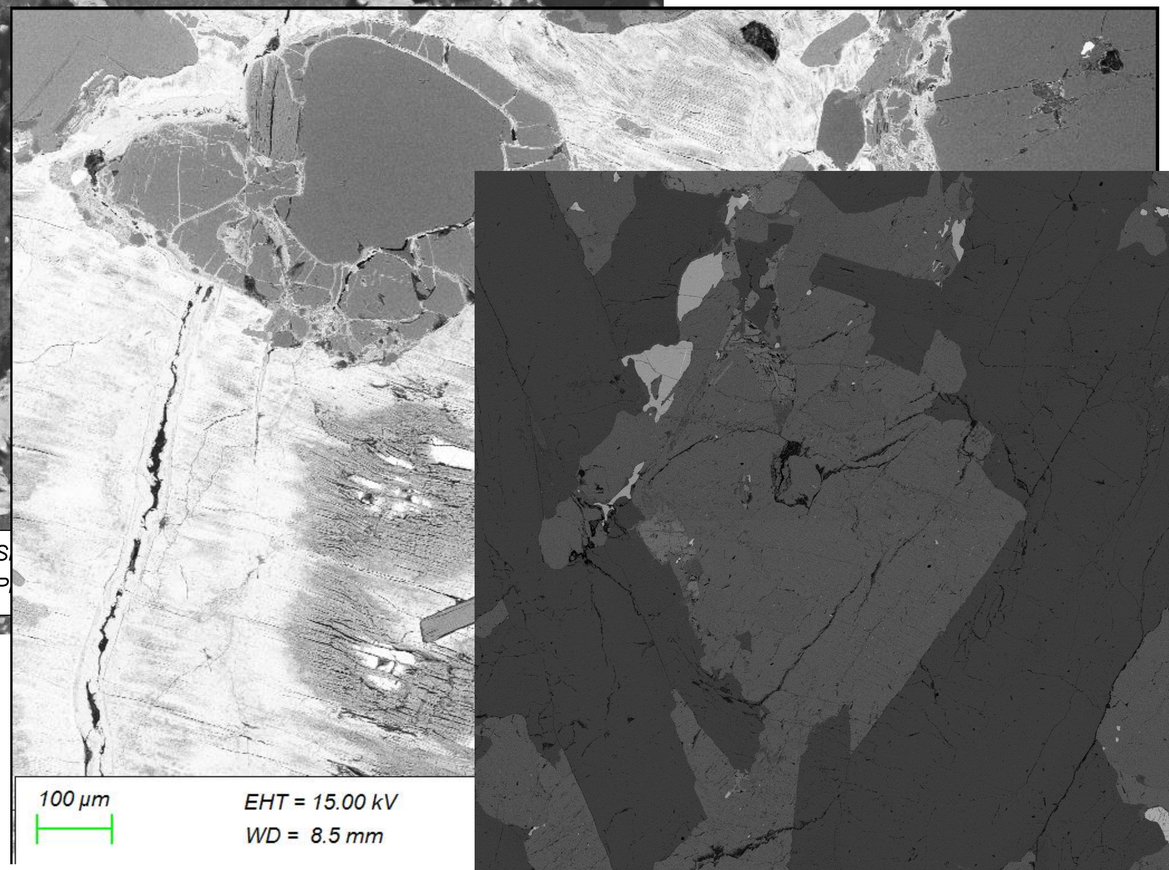
Imaging – material

Back-scattered electrons

BSE



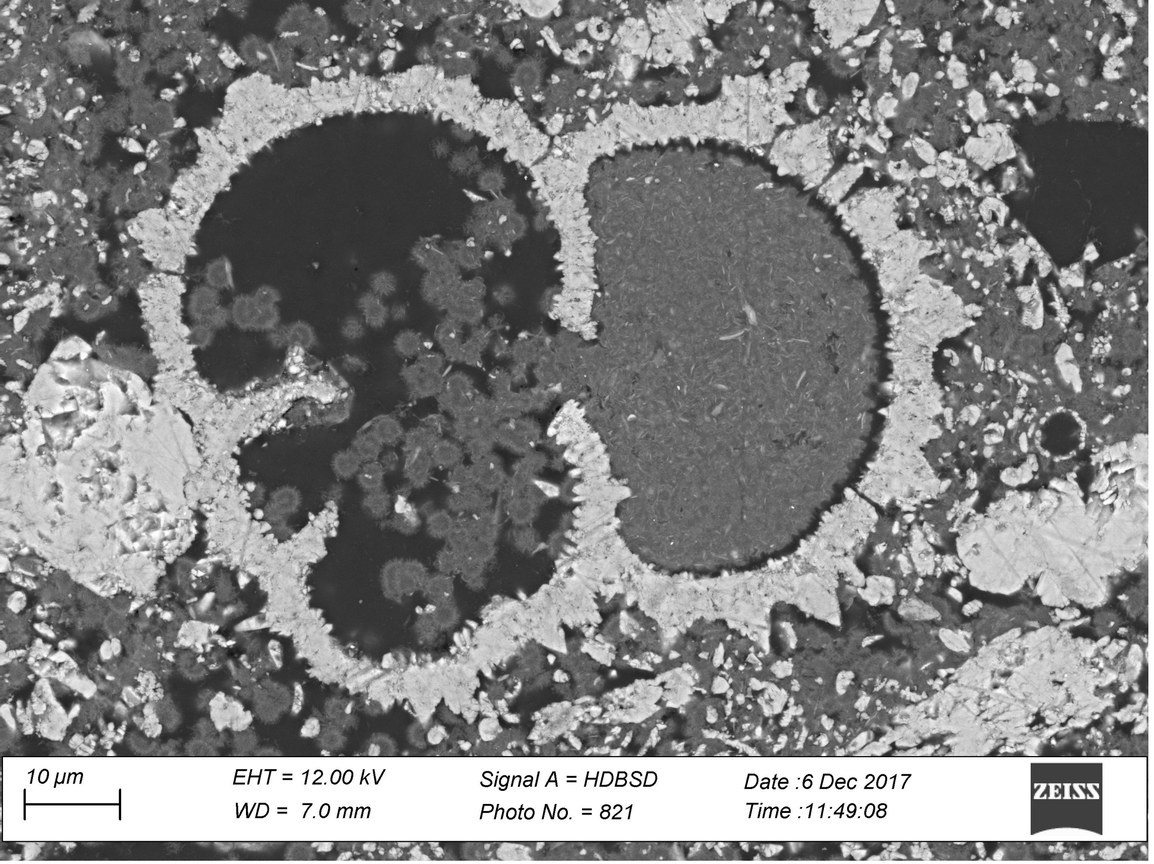




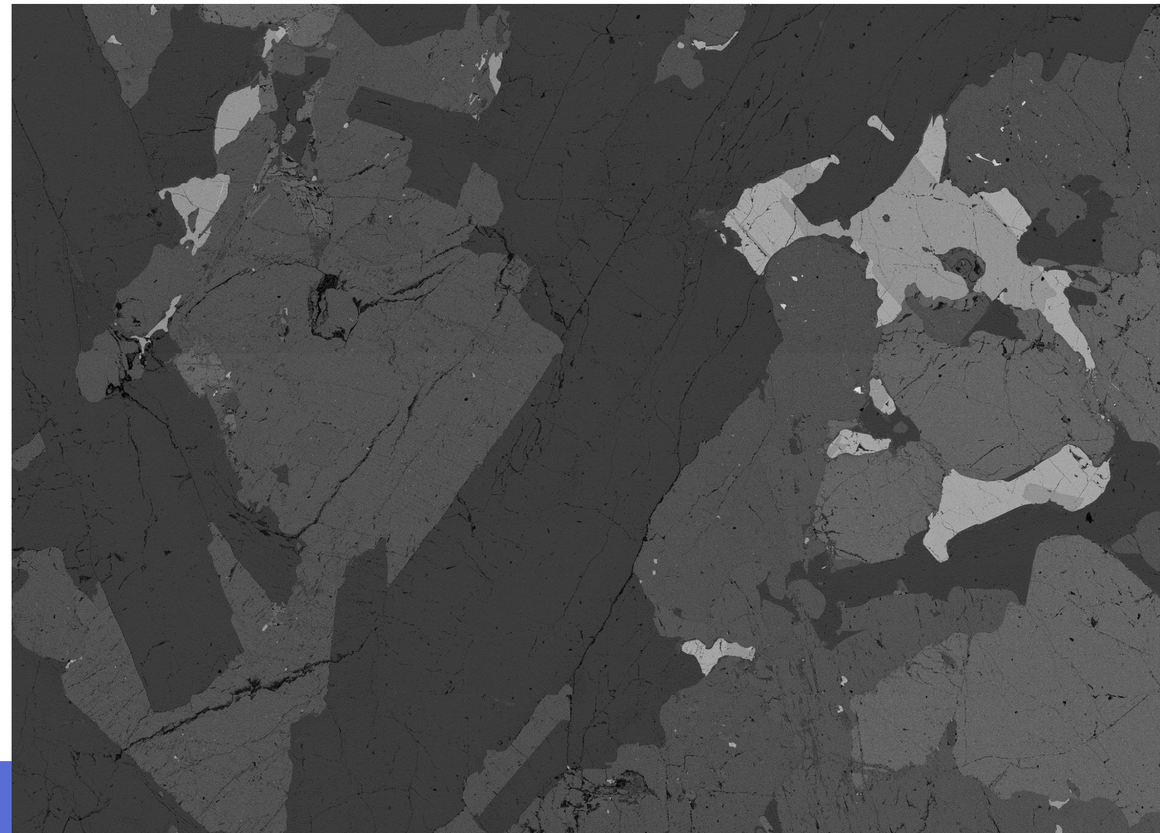
Imaging – material

Back-scattered electrons

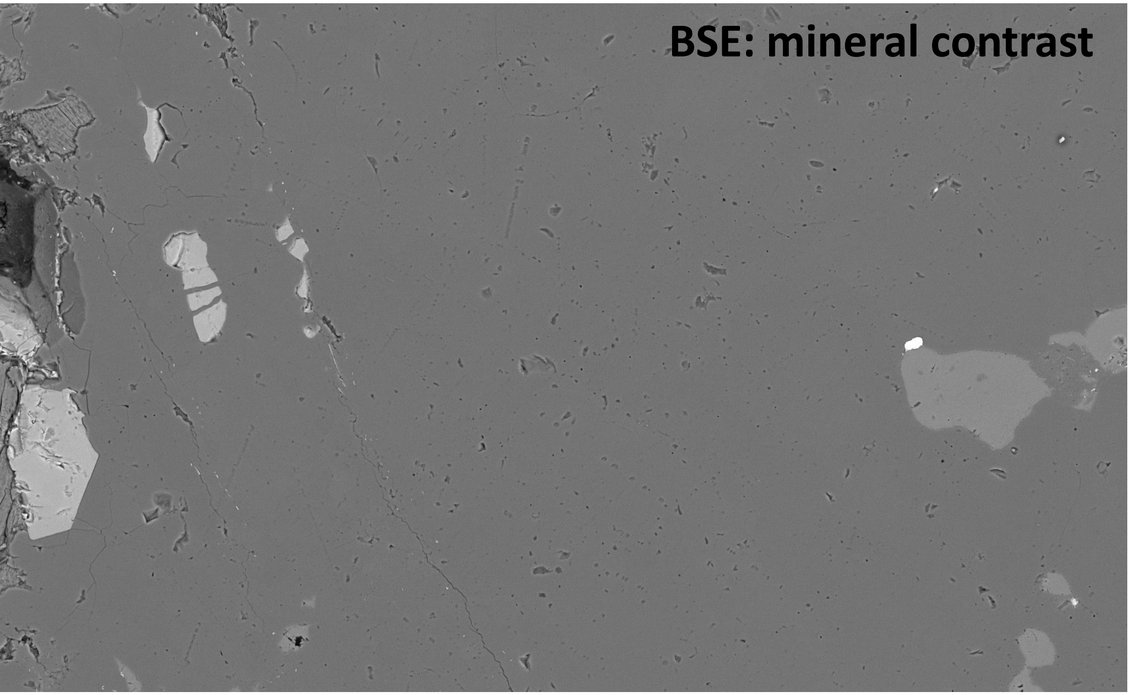
BSE

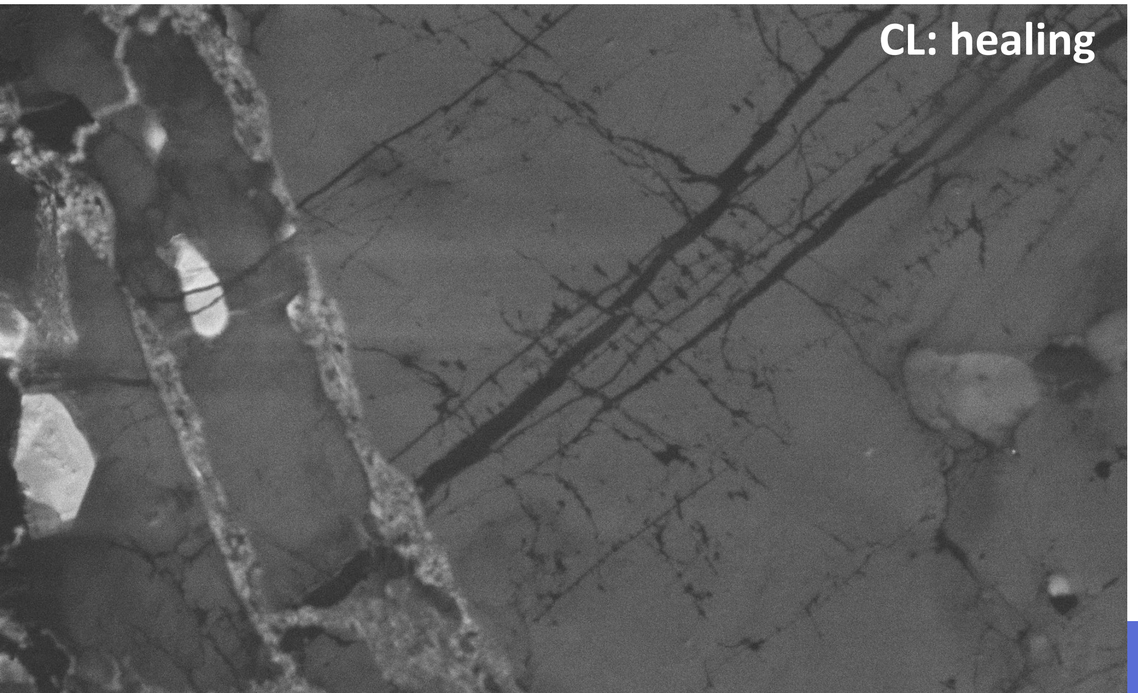


*For polished sections with material contrast
*Surface image based on composition and density

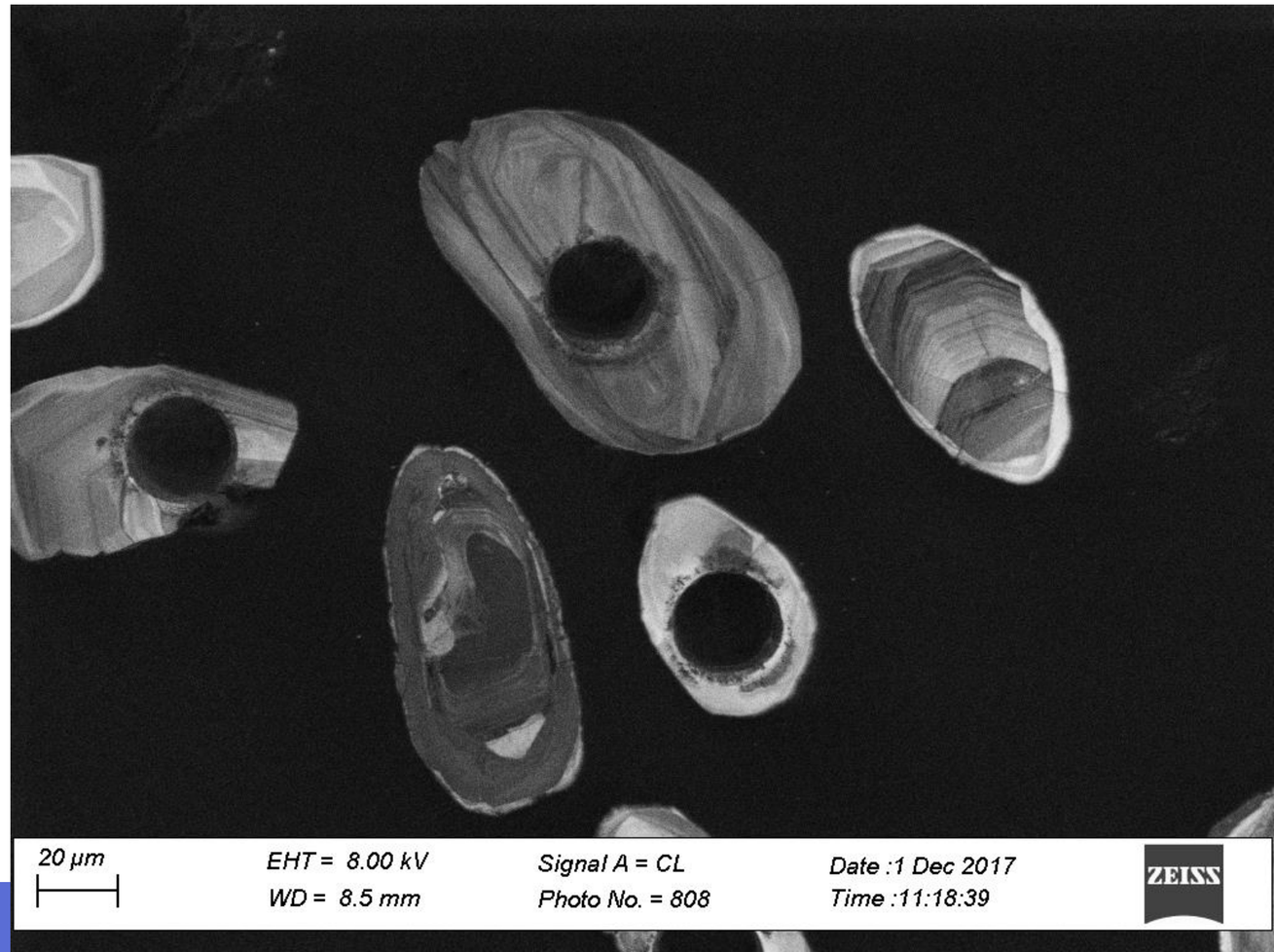


Cathodoluminescence





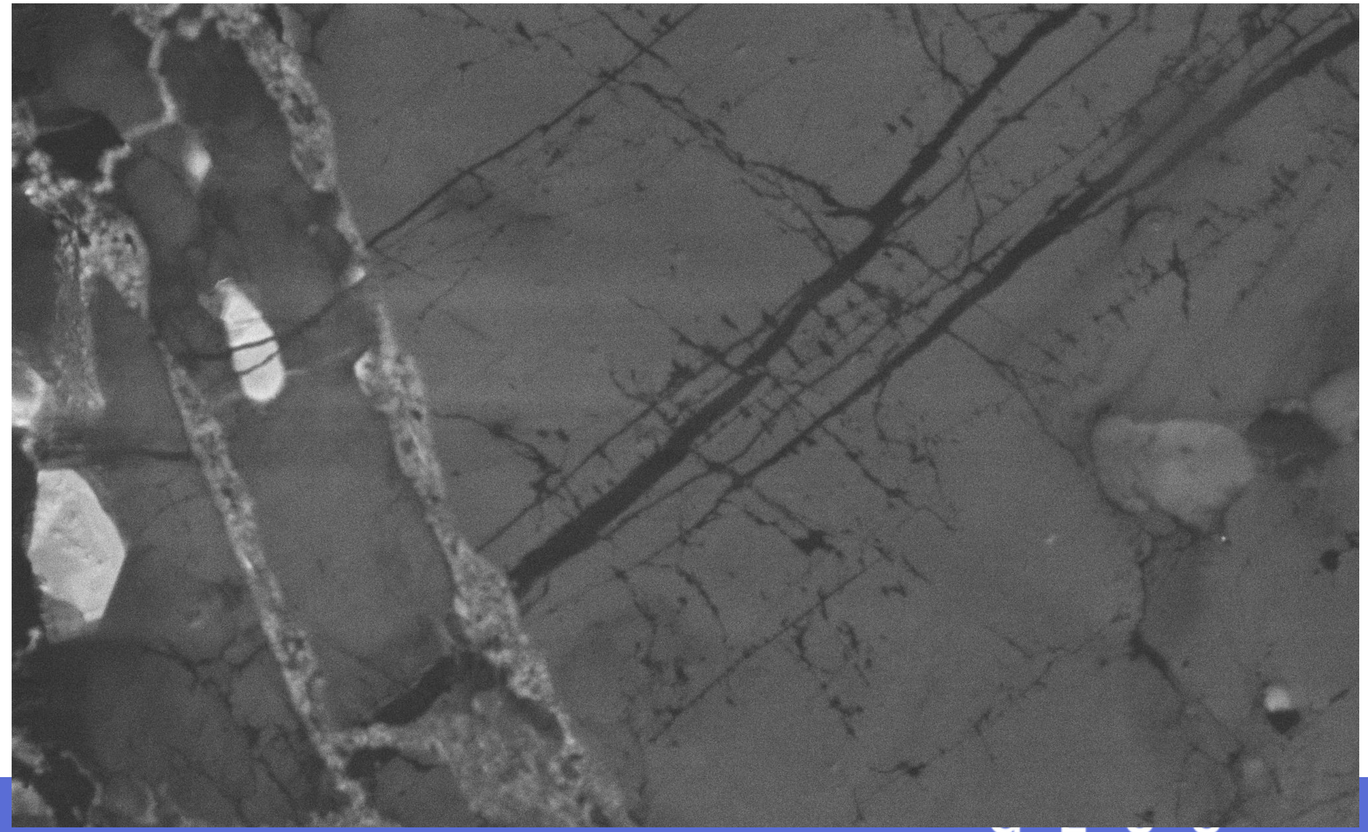
CL



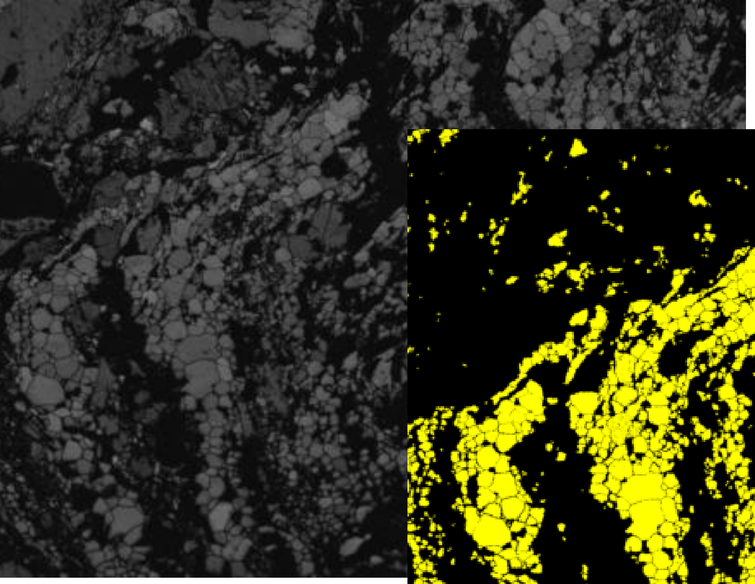
Cathodoluminescence

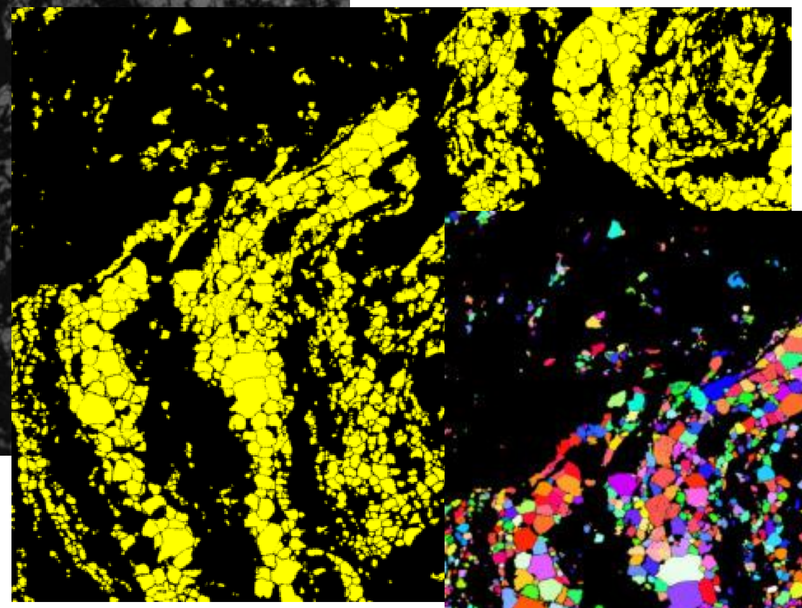
CL

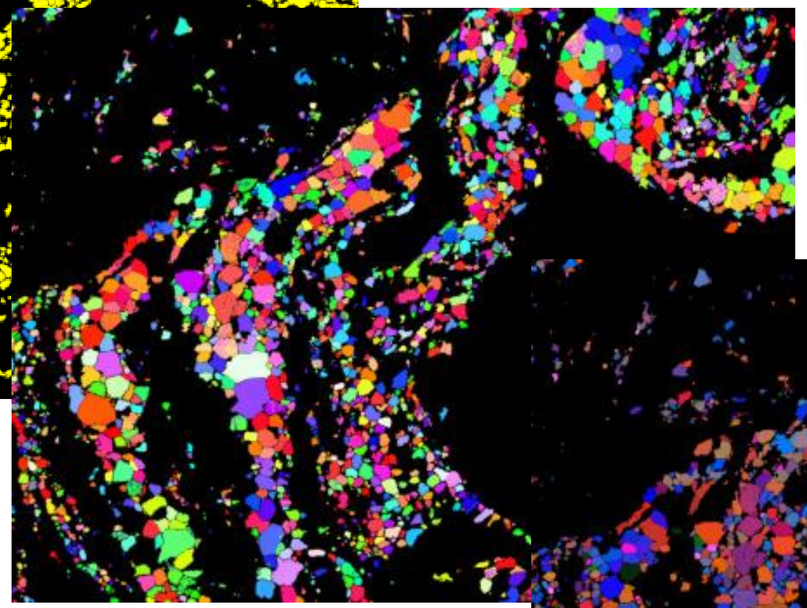
*Zircons, fault zones, different growth events, (ore formation, metamorphism, diagenesis)
*shows variations in trace elements/temperature during crystallisation

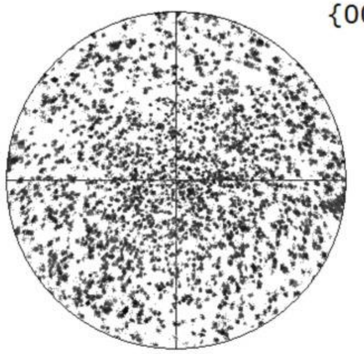


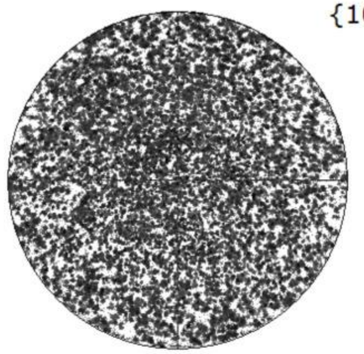
Crystallography

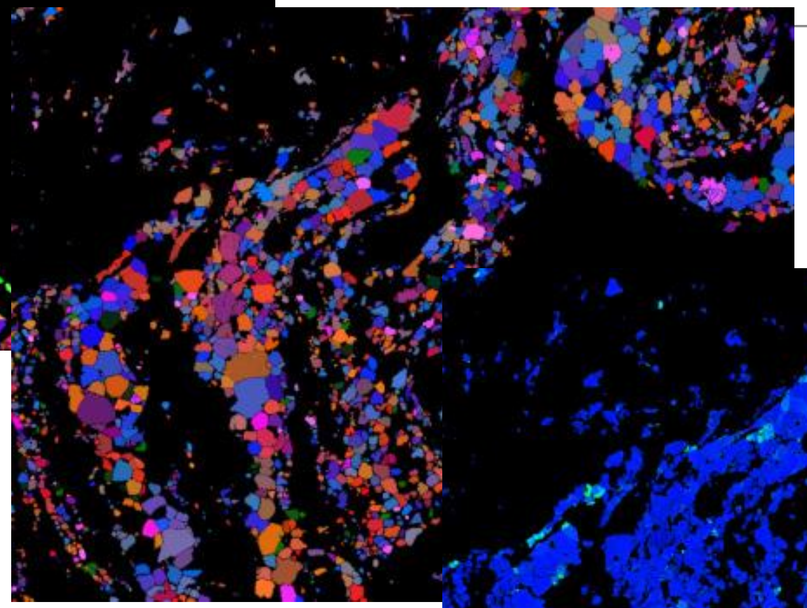


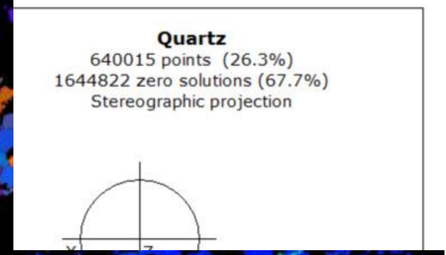


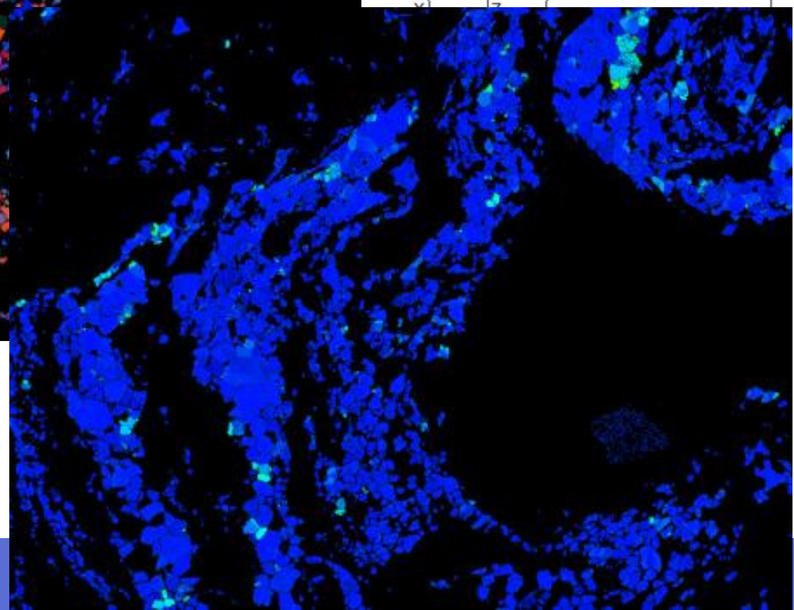






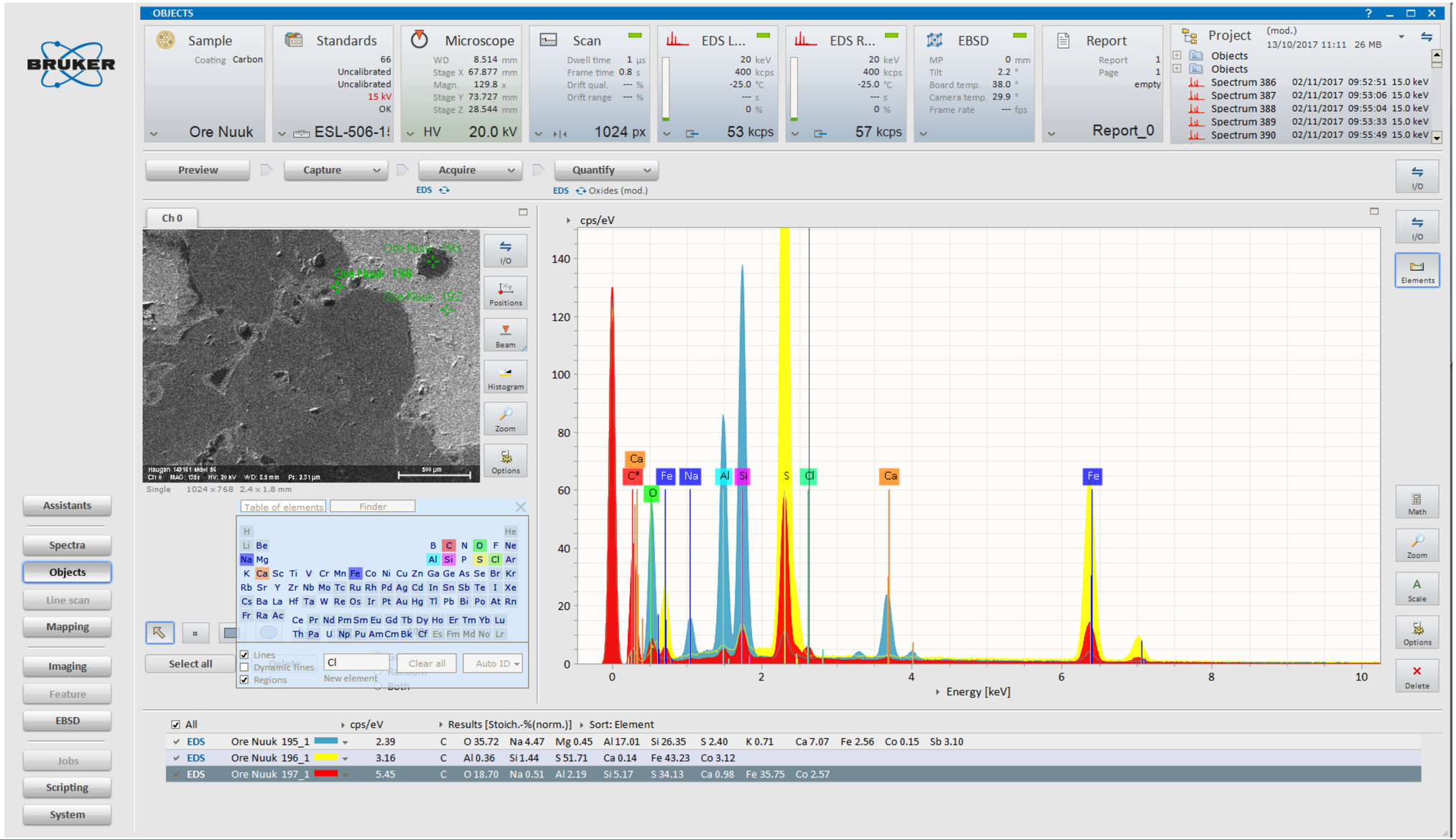






*Crystallographic orientation/preferred orientation
*Strain&stress in shear zones
*Directional growth on preferred surfaces
*Metamorphic overprint

Chemistry


OBJECTS
Sample
Coating Carbon
Ore Nuuk
Standards
66
Uncalibrated
Uncalibrated
15 kV
OK
ESL-506-1
Microscope
WD 8.514 mm
Stage X 67.877 mm
Magn. 129.8 x
Stage Y 73.727 mm
Stage Z 28.544 mm
HV 20.0 kV
Scan
Dwell time 1 µs
Frame time 0.8 s
Drift qual. --- %
Drift range --- %
1024 px
EDS L...
20 keV
400 kcps
-25.0 °C
--- s
0 %
53 kcps
EDS R...
20 keV
400 kcps
-25.0 °C
--- s
0 %
57 kcps
EBSD
MP 0 mm
Tilt 2.2 °
Board temp. 38.0 °
Camera temp. 29.9 °
Frame rate --- fps
Report
Report 1
Page 1
empty
Report_0
Project (mod.)
13/10/2017 11:11 26 MB
Objects
Objects
Spectrum 386 02/11/2017 09:52:51 15.0 keV
Spectrum 387 02/11/2017 09:53:06 15.0 keV
Spectrum 388 02/11/2017 09:55:04 15.0 keV
Spectrum 389 02/11/2017 09:53:33 15.0 keV
Spectrum 390 02/11/2017 09:55:49 15.0 keV
Preview
Capture
Acquire
EDS
Quantify
EDS Oxides (mod.)
I/O
Ch 0
Ore Nuuk 193
Ore Nuuk 196
Ore Nuuk 192
500 µm
Positions
Beam
Histogram
Zoom
Options
Single 1024 x 768 2.4 x 1.8 mm
cps/eV
Ca
C*
O
Fe
Na
Al
Si
S
Cl
Ca
Fe
Energy [keV]
Elements
Math
Zoom
Scale
Options
Delete
Assistants
Spectra
Objects
Line scan
Mapping
Imaging
Feature
EBSD
Jobs
Scripting
System
Table of elements
Finder
Select all
Lines
Dynamic lines
Regions
Cl
New element
Clear all
Auto ID
All
cps/eV
Results [Stoich.-%(norm.)]
Sort: Element
EDS Ore Nuuk 195_1 2.39 C O 35.72 Na 4.47 Mg 0.45 Al 17.01 Si 26.35 S 2.40 K 0.71 Ca 7.07 Fe 2.56 Co 0.15 Sb 3.10
EDS Ore Nuuk 196_1 3.16 C Al 0.36 Si 1.44 S 51.71 Ca 0.14 Fe 43.23 Co 3.12
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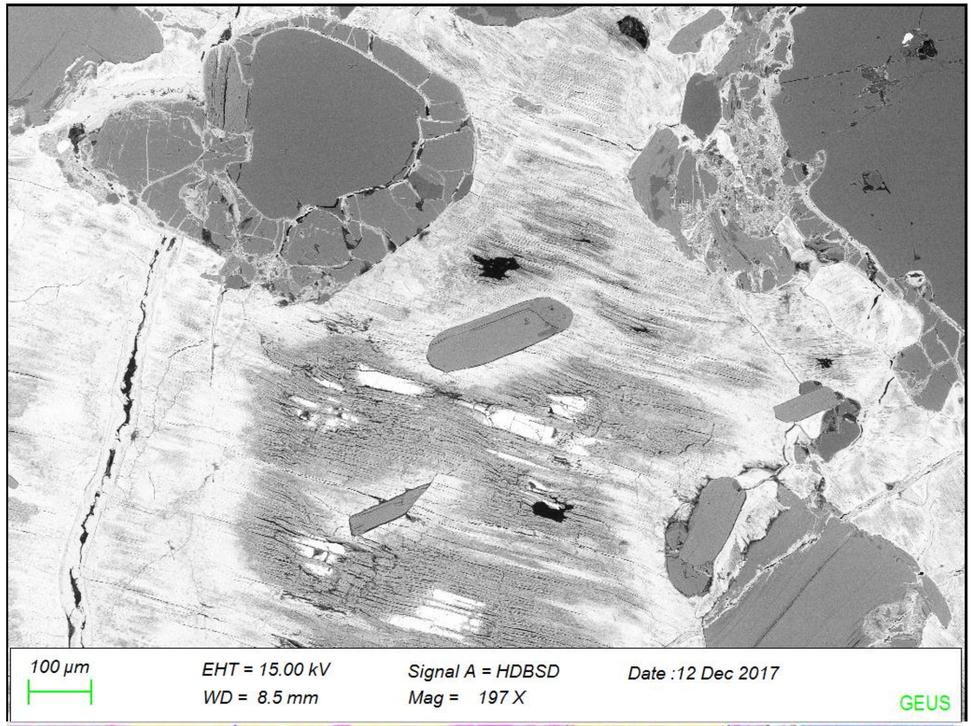
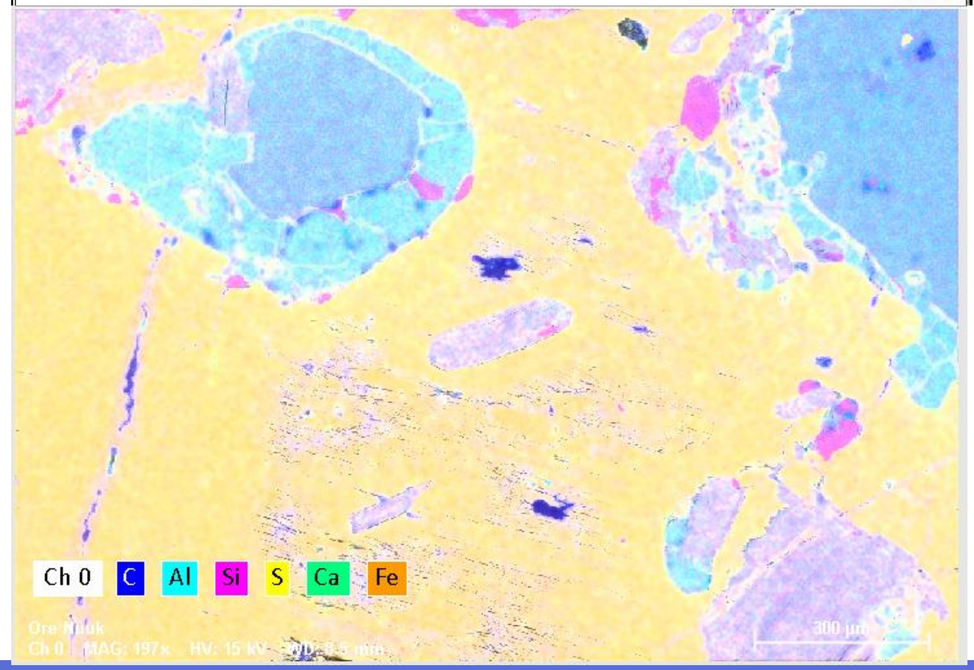
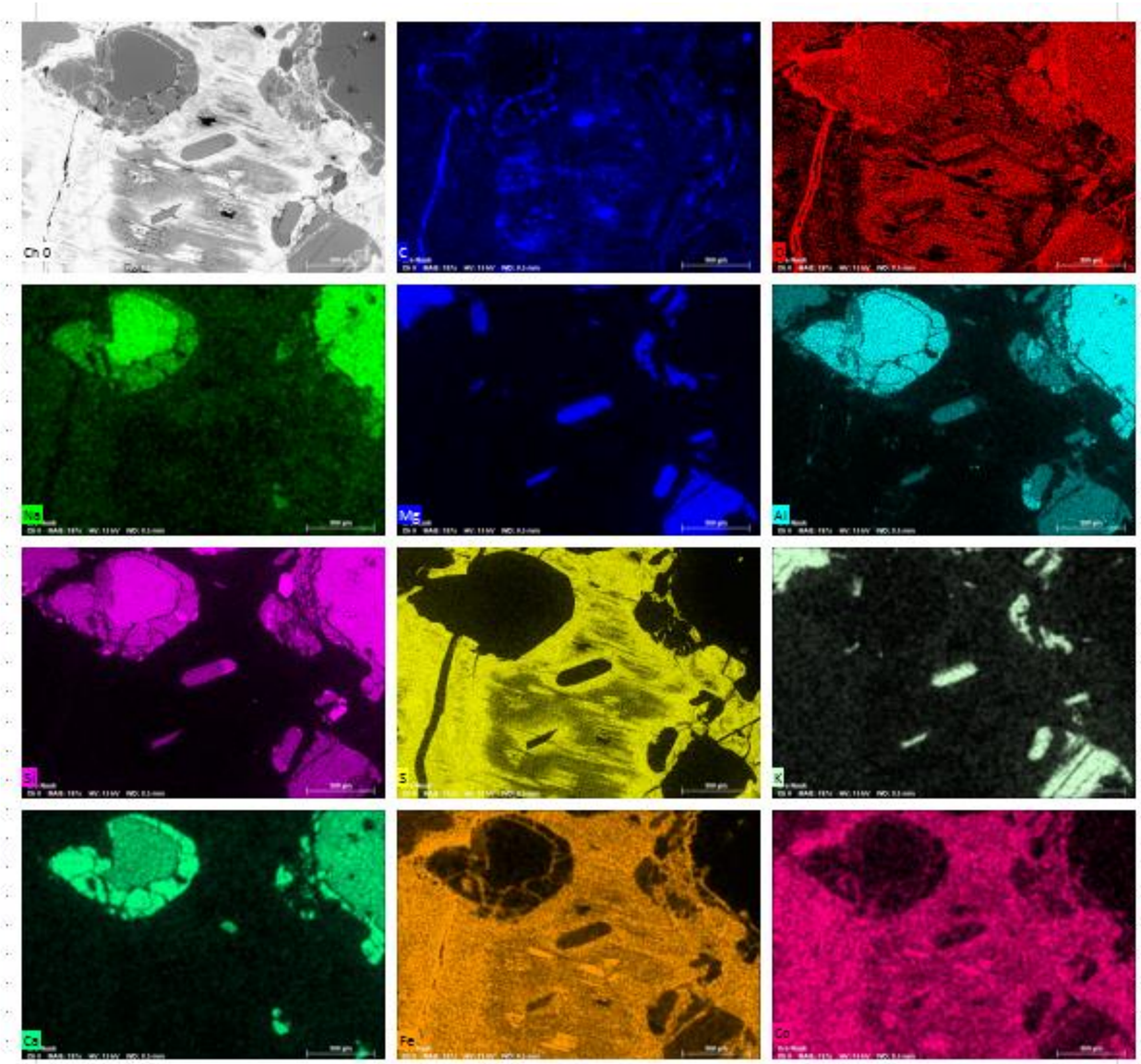
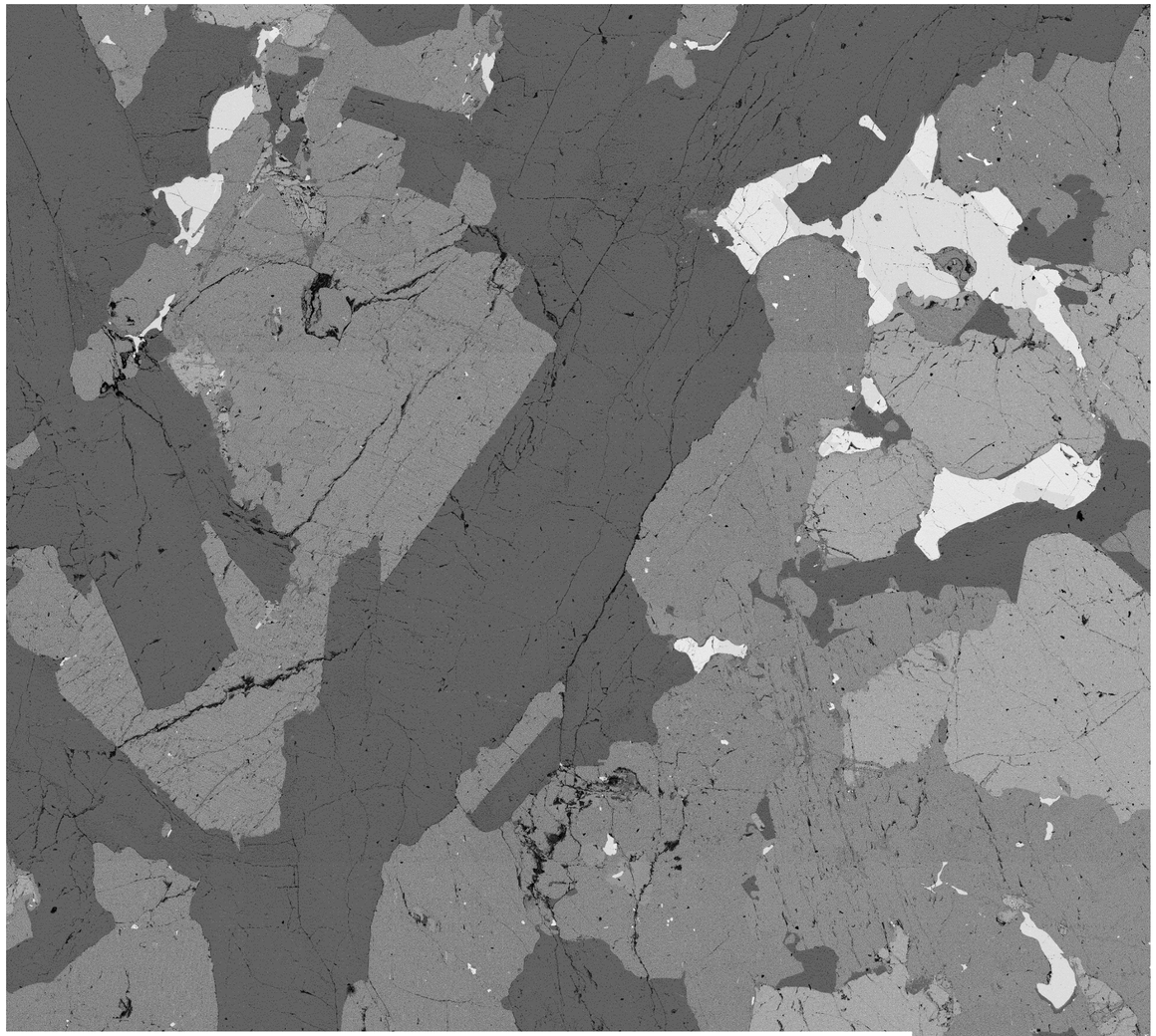
Chemistry


100 µm
EHT = 15.00 kV
WD = 8.5 mm
Signal A = HDBSD
Mag = 197 X
Date :12 Dec 2017
GEUS


Ch 0
C
Al
Si
S
Ca
Fe
300 µm

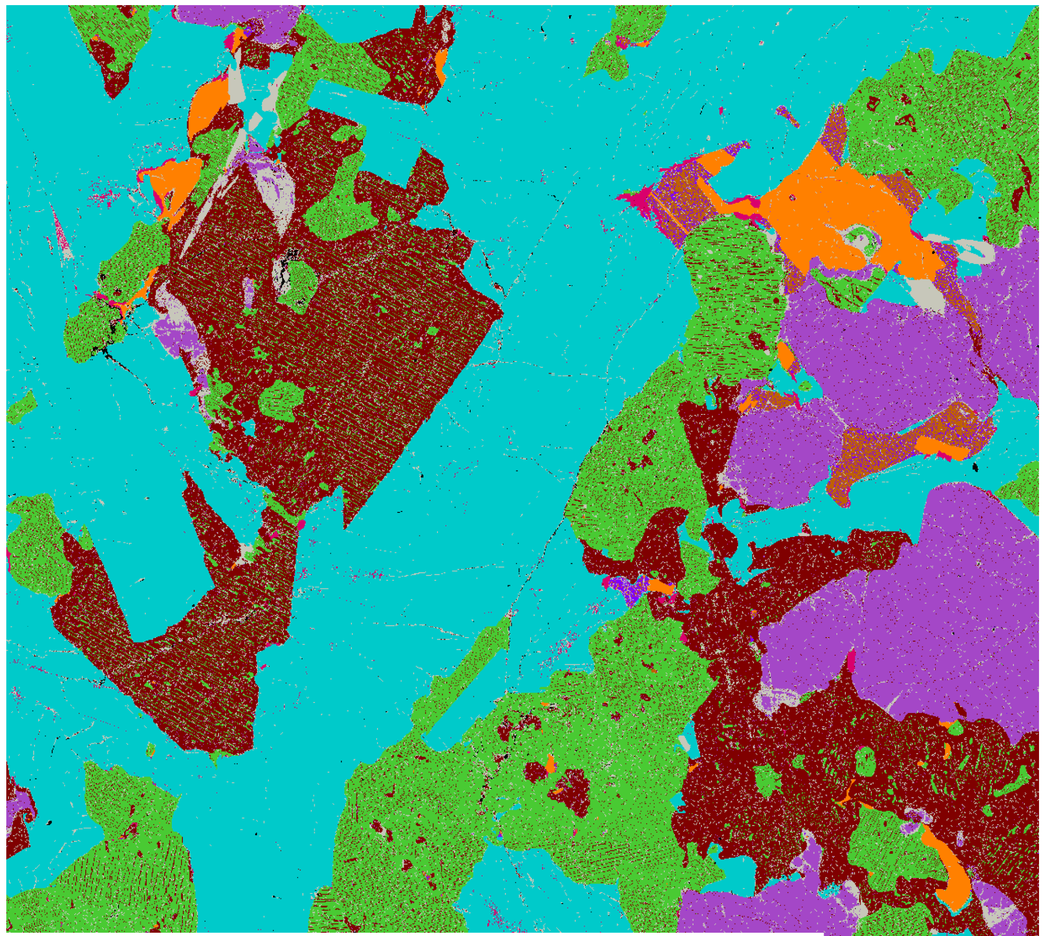

Ch 0
C
Na
Mg
Al
Si
S
K
Ca
Fe
Co

Automated Quantitative Mineralogy (AQM)



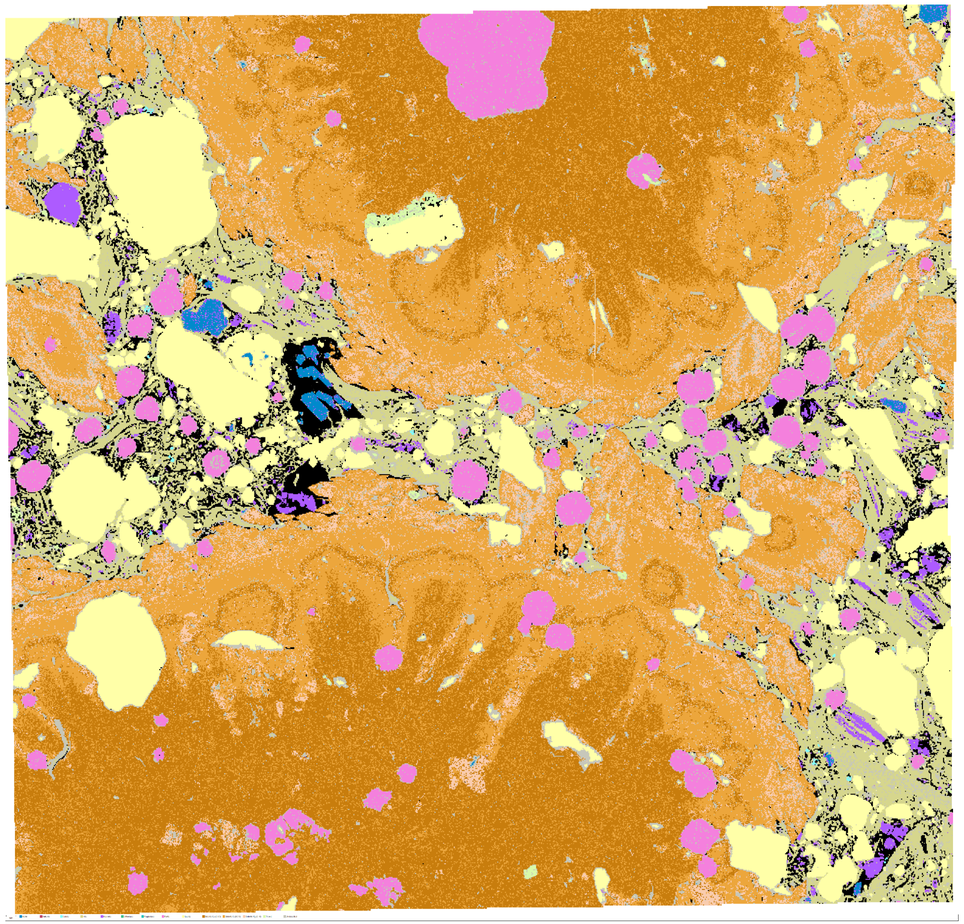
Backscattered electrons

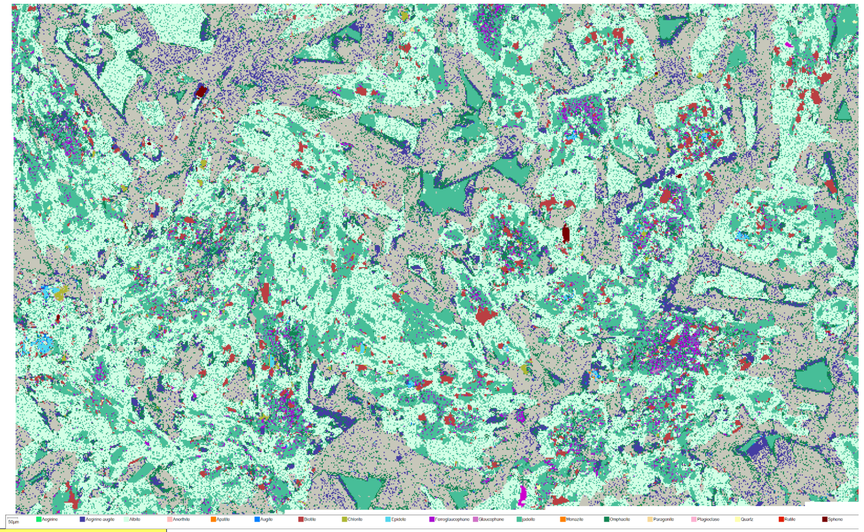
BSE image + chemistry with stepsize of few µm in a mosaic of images. Chemistry in each pixel => mineral



AQM mineral map

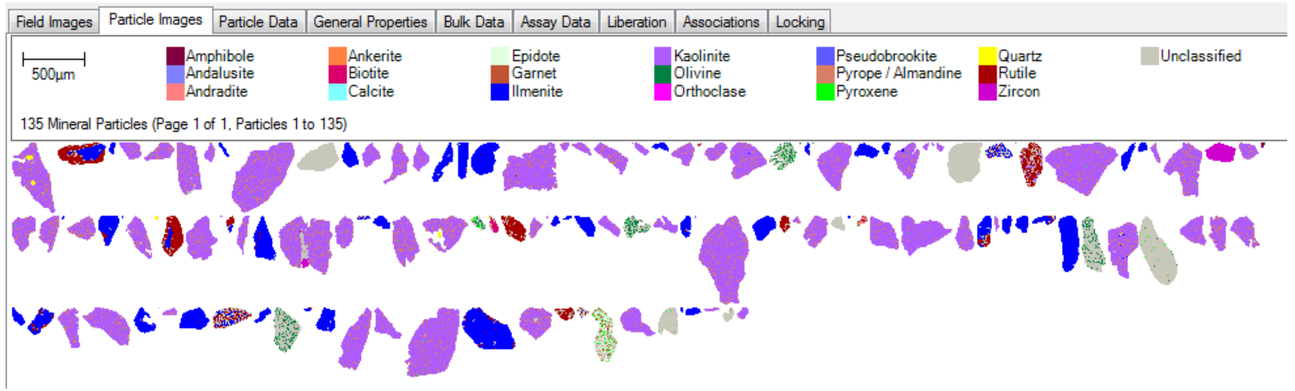
Automated Quantitative Mineralogy (AQM)





*Mineralogy of polished sections

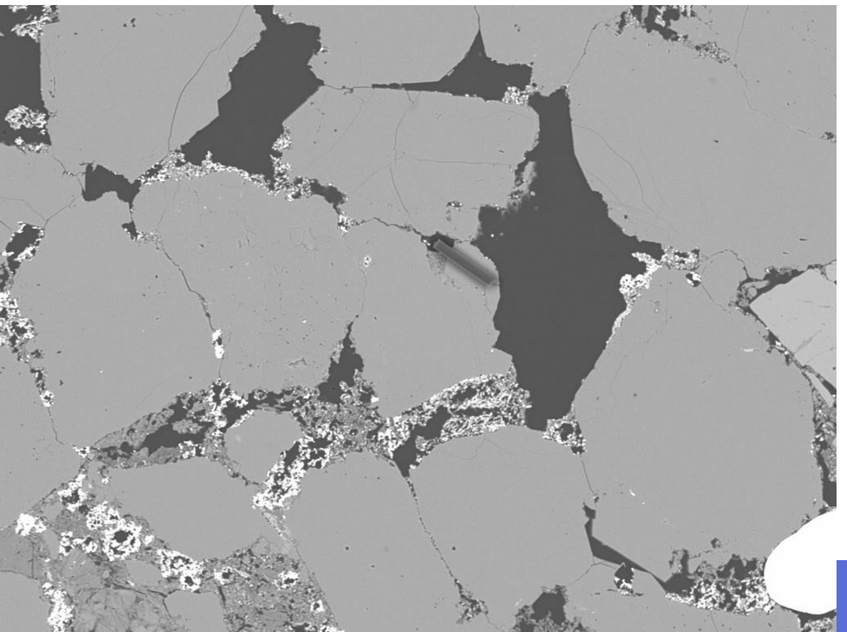
*BSE image + chemistry with stepsize of few µm in a mosaic of images. Chemistry in each pixel => mineral



Summary with focus on sandstone

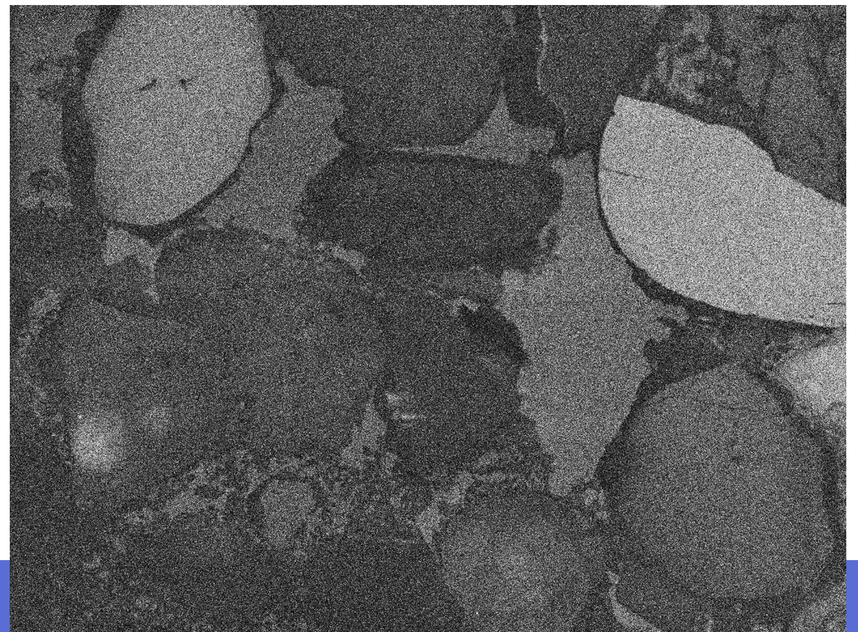
BSE image
Shows: material contrast

Application: separate quartz minerals (grey) from pores (black) and other minerals (other grey scale)



CL image
Shows: different phases of growth

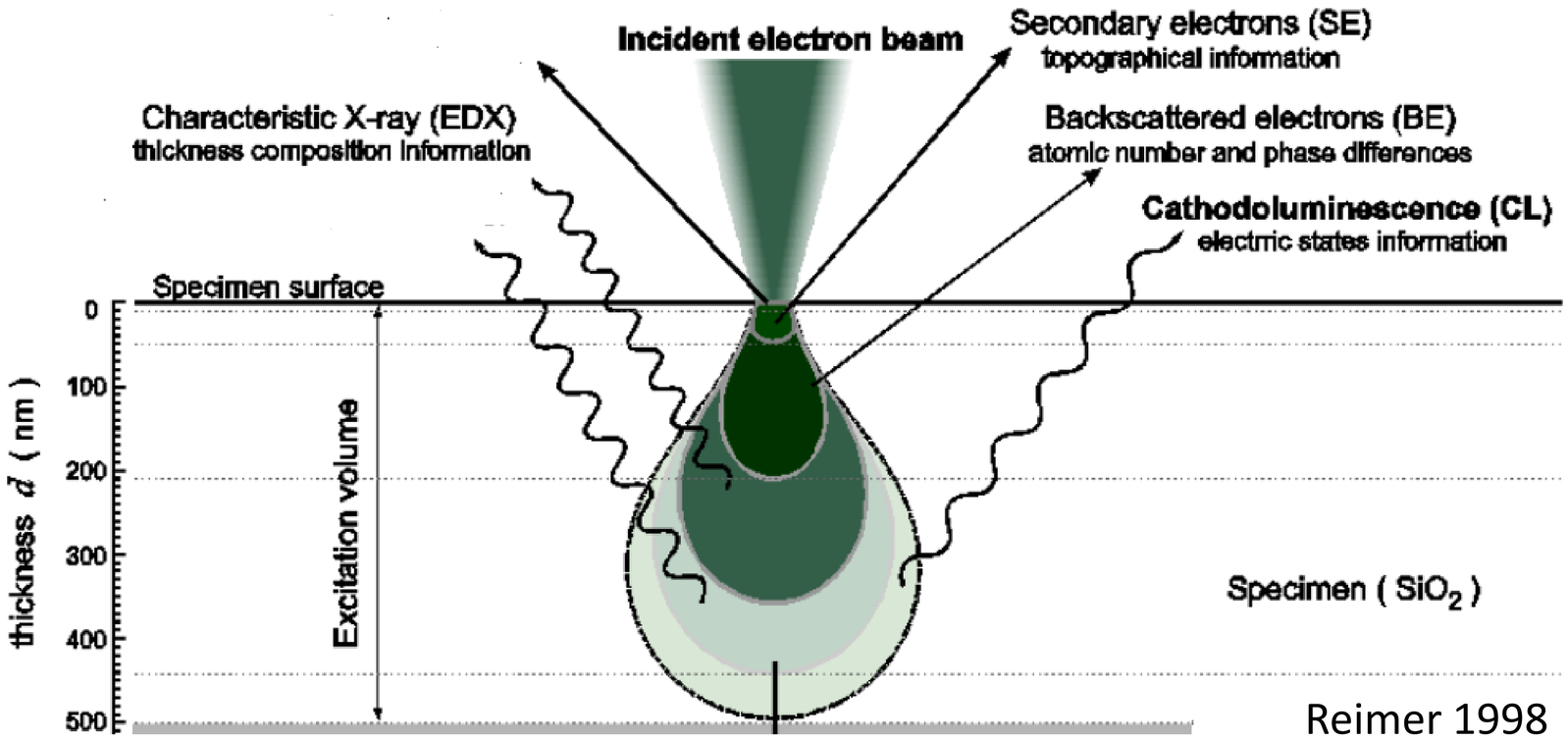
Application: separate cores of quartz minerals (light grey) from diagenetic overgrowths (dark grey)



Mineral map
Shows: mineralogy (false colours)

Application: determine of a grain is quartz, feldspar or something else

Why do CL images appear to be a little unsharp?



Reimer 1998

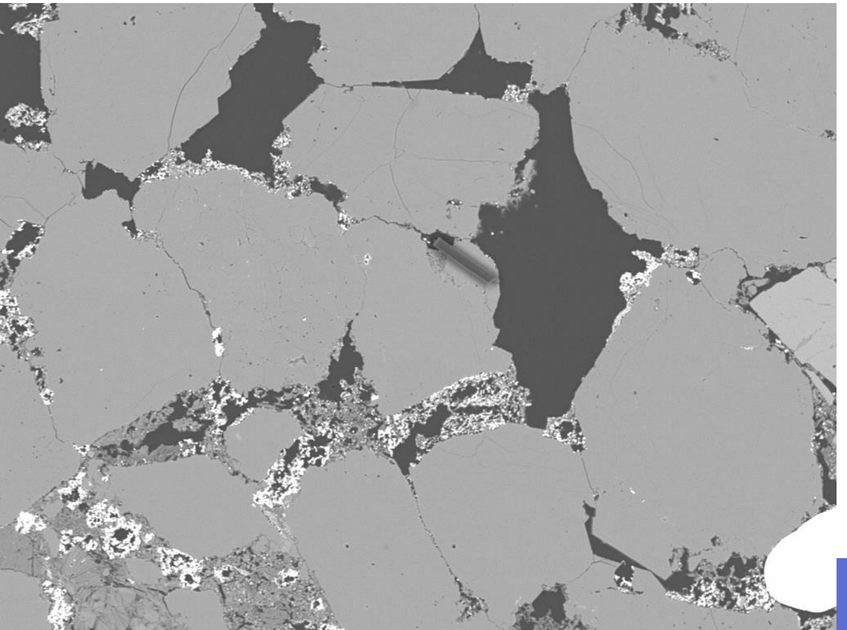
- The electron beam hits the sample and a range of different signals comes back to the SEM detectors. (slide 5)
- The area from which this information is coming is called the interaction volume.
- BSE (and SE) have a much smaller interaction volume than CL.

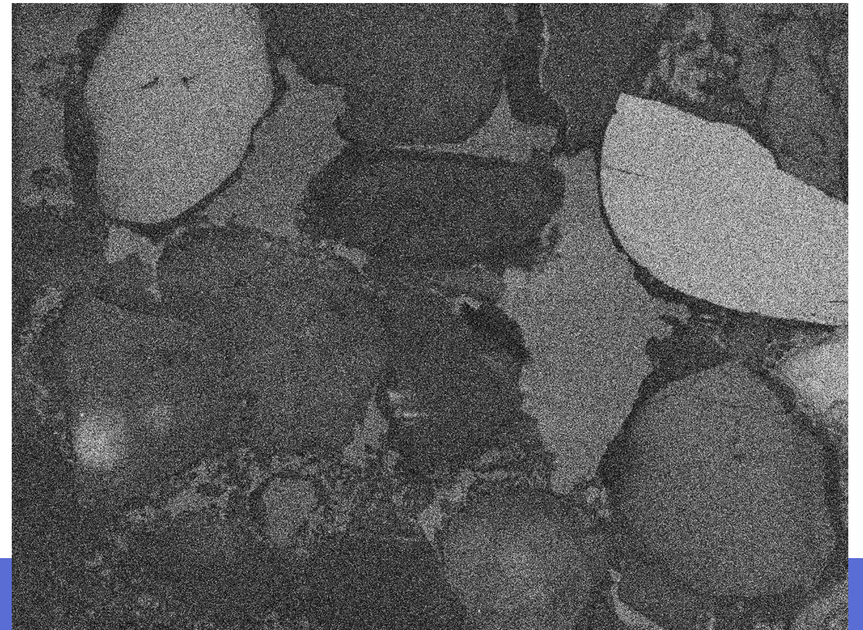
- If the studied features lies at an angle to the surface, it will be met by the electron beam at different depths and appear smeared out in the image. Therefore, it might appear unsharp.

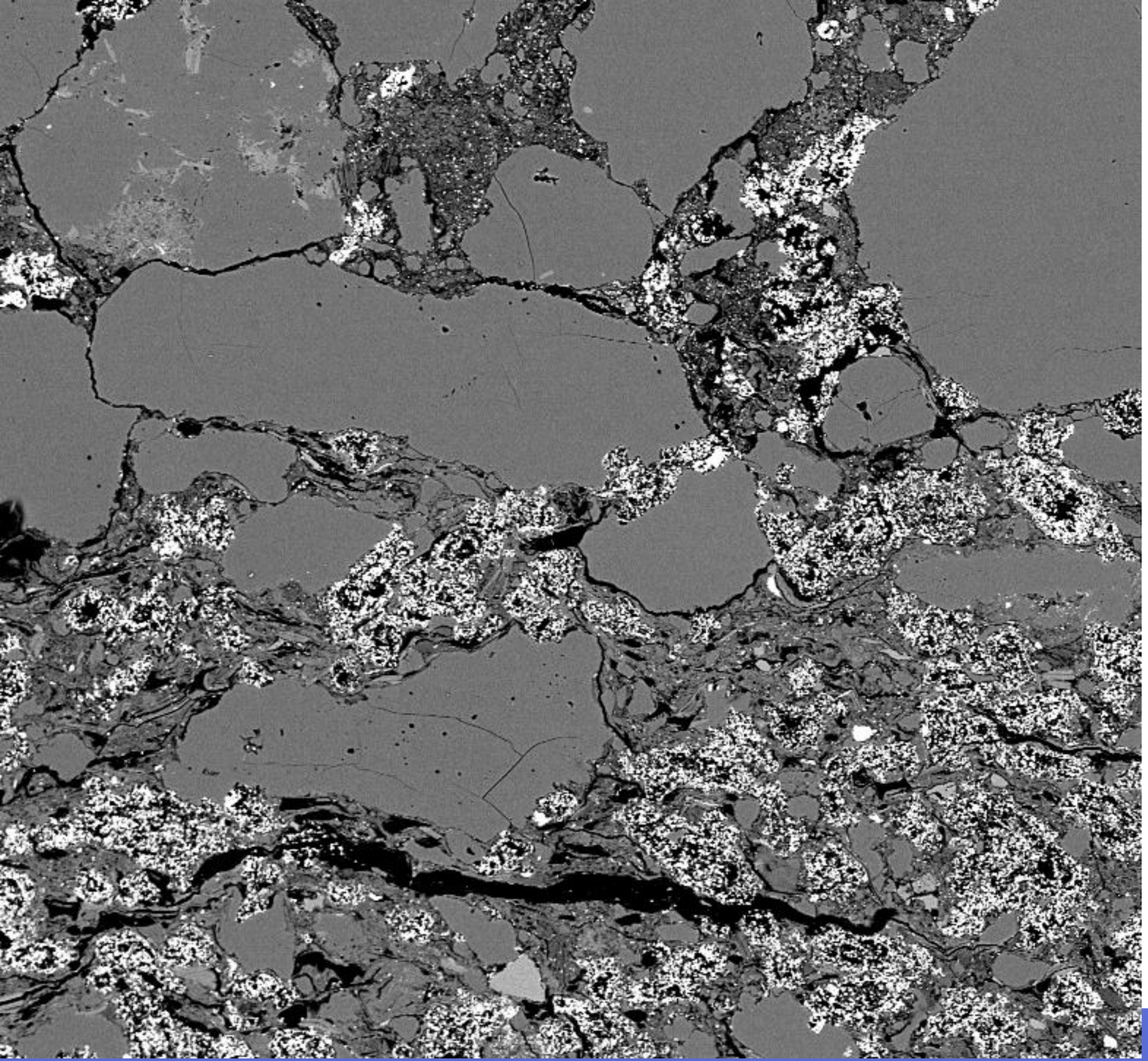
Why are the mineral maps so pixelated?

- Each pixel is an EDX analysis and takes ca. 20-30 ms in analysis + quantification + mineral interpretation time.
- Pixel size can be decreased to 0.25 µm
- There are 100s or 1000s of pixel in each image and 100s or 1000s of images in each dataset
- Usually all mineral maps in one dataset are put into a mosaic of 100s or 1000s images, at this scale the boundaries are smooth.
- Thus, this is a question of time and scale

Hackathon







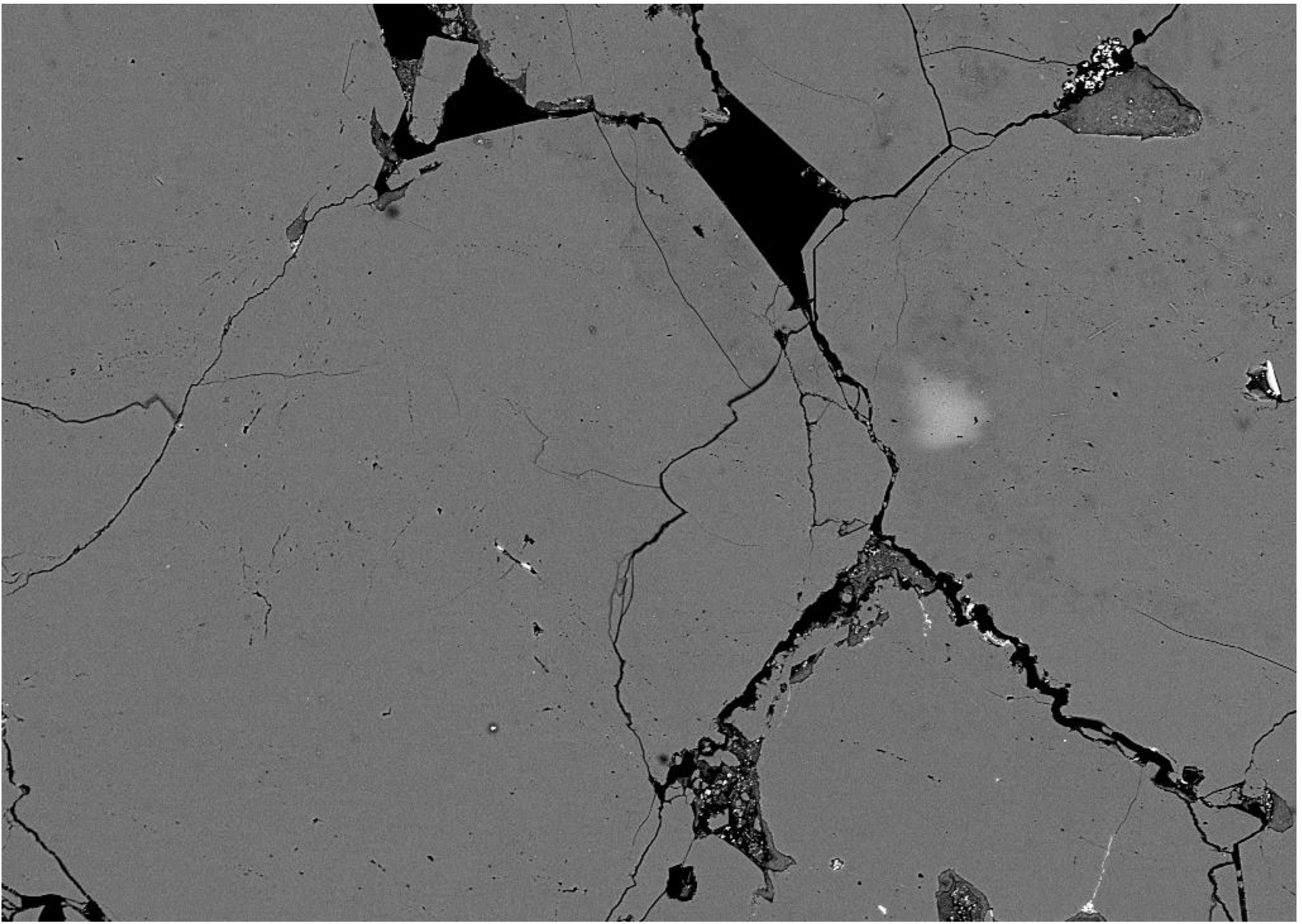
Geothermal reservoir characterisation

Characterization:

- quantification of the mineralogical composition
- knowledge of the minerals in the pores
- pre-drill predictions of porosity and permeability

Important for:

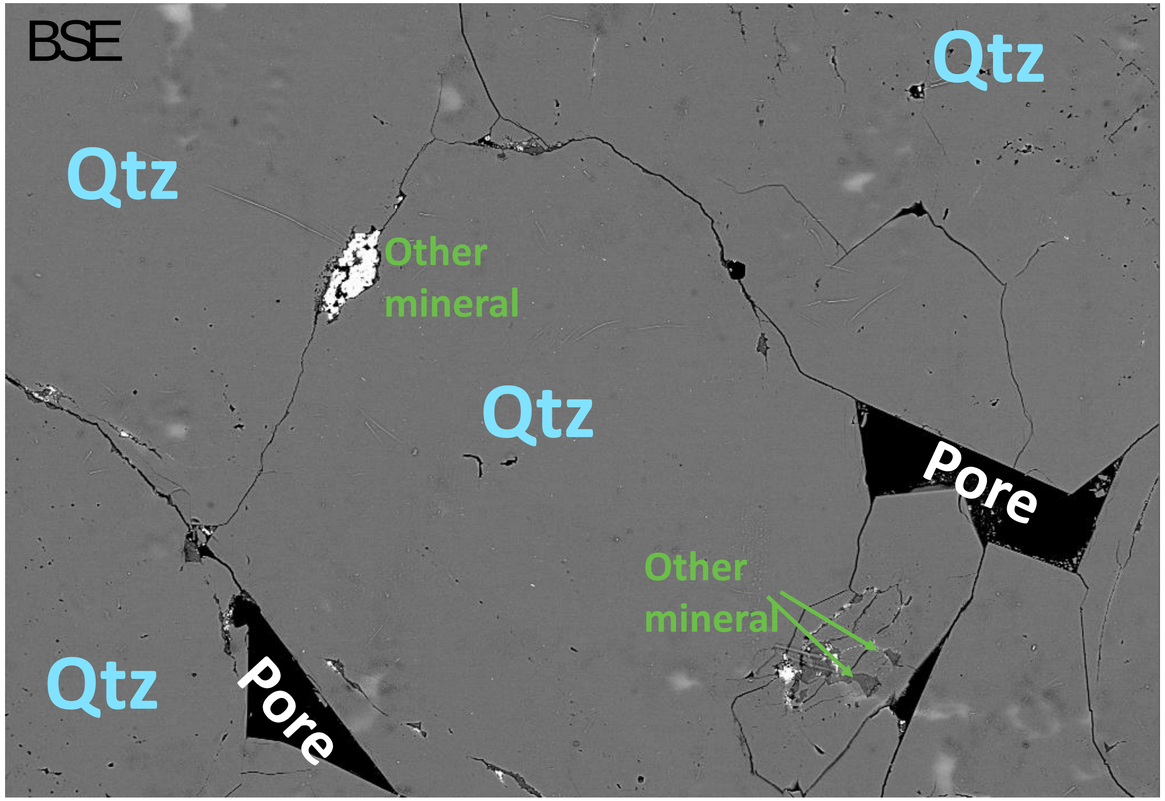
- designing geothermal plants and wells
- prevent scaling, corrosion, and clogging



Challenge

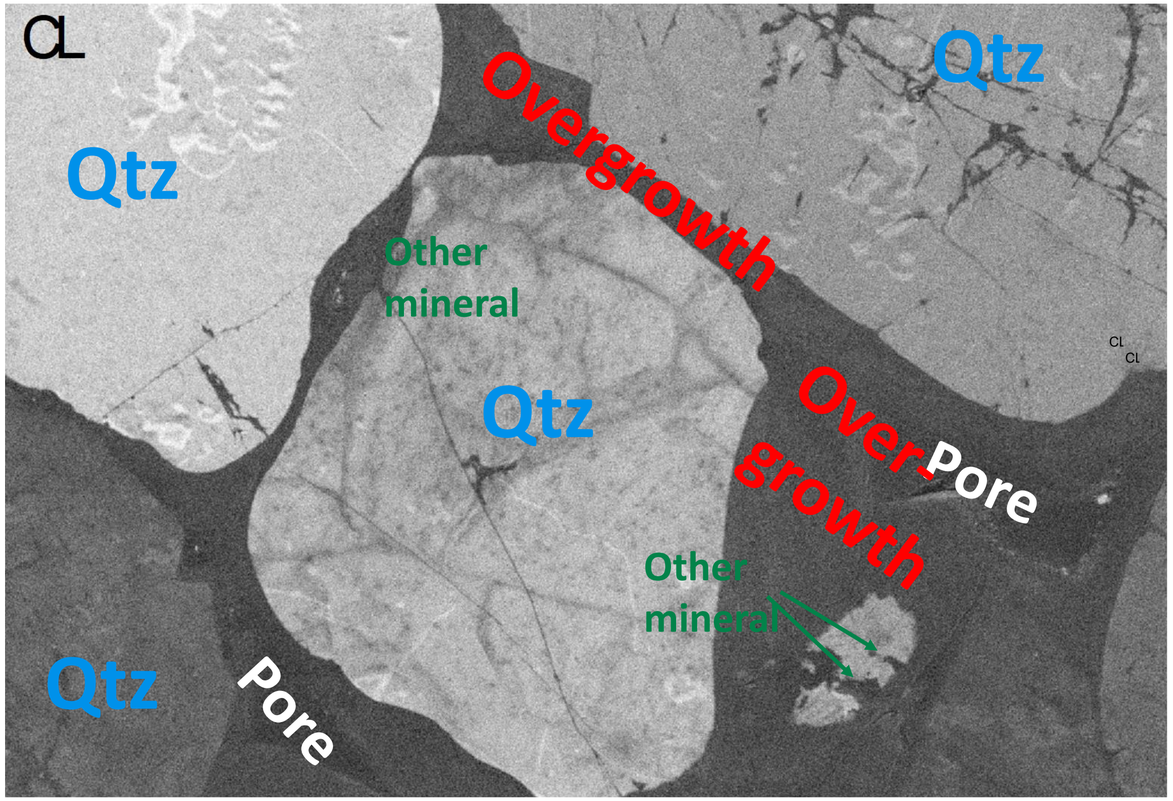
- Automated mineral quantification is routinely obtained by SEM
- For all sandstone reservoirs f.e. automated detection of the outline and area of the original sand grains and of their overgrowths formed during elevated temperatures is not possible.
- Relevant because precipitation of quartz overgrowths along the rim of quartz grains leads to decreased porosity and permeability, thus causing inferior reservoir quality.

What do we need? (Manual example)



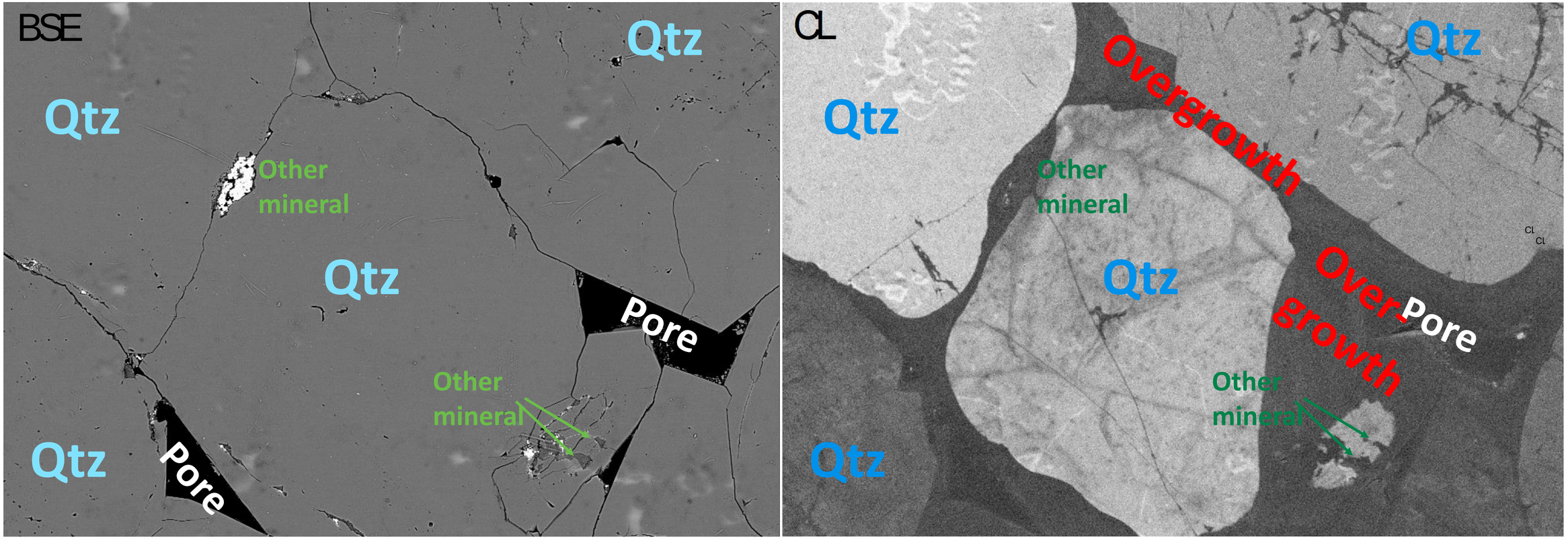
- We have a BSE image
- Showing quartz (grey) and pore space (black)
- Quartz is always grey, all quartz have the same grey value.
- Pores are always black
- Other minerals can be lighter and darker than quartz

What do we need? (Manual example)



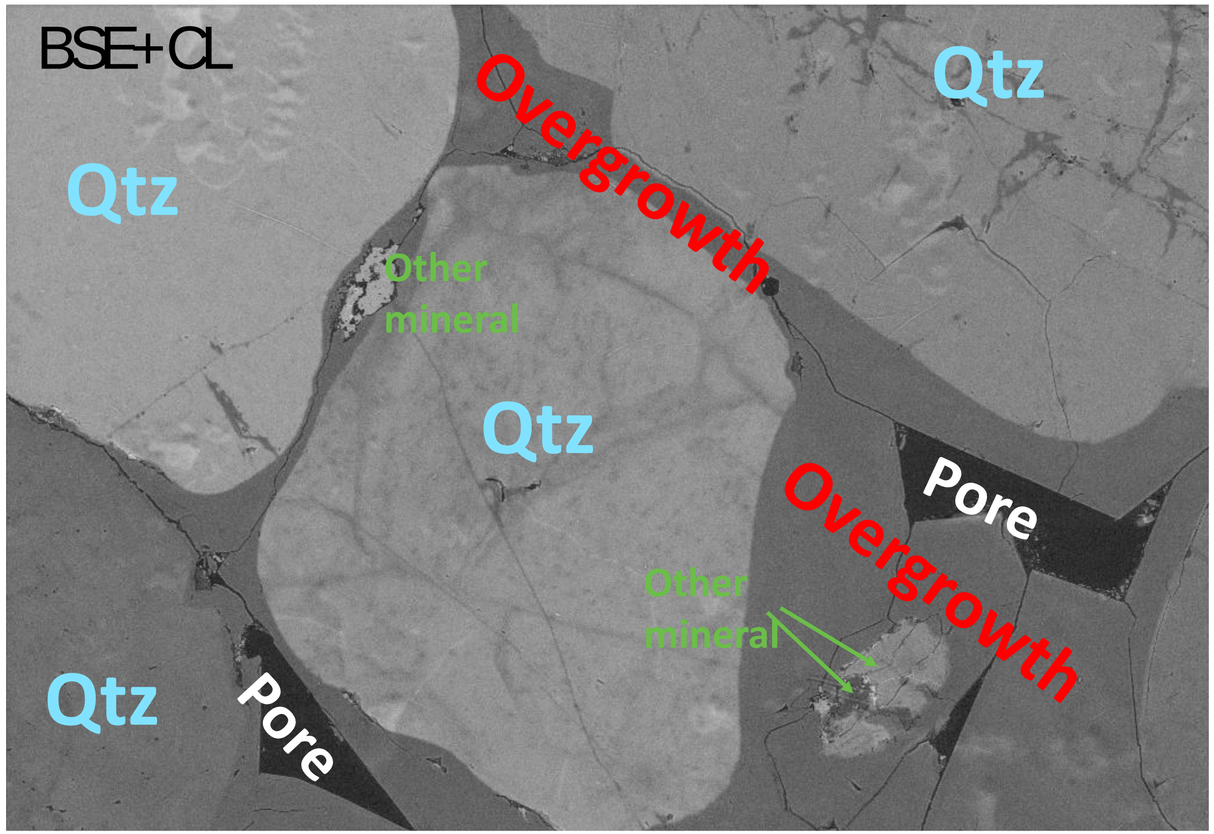
- We have a CL image (same area)
- Showing quartz core (white to dark grey), quartz overgrowth (dark grey) and pore space (near black)
- Quartz overgrowths are always dark grey, all quartz overgrowths (of one generation) have the same grey value.
- Pores are often near black
- Other minerals can be lighter and darker than quartz

What do we need? (Manual example)



We need information from both BSE and CL to be able to separate quartz cores (detrital), from quartz overgrowths (rims, authigenic) and from pore space

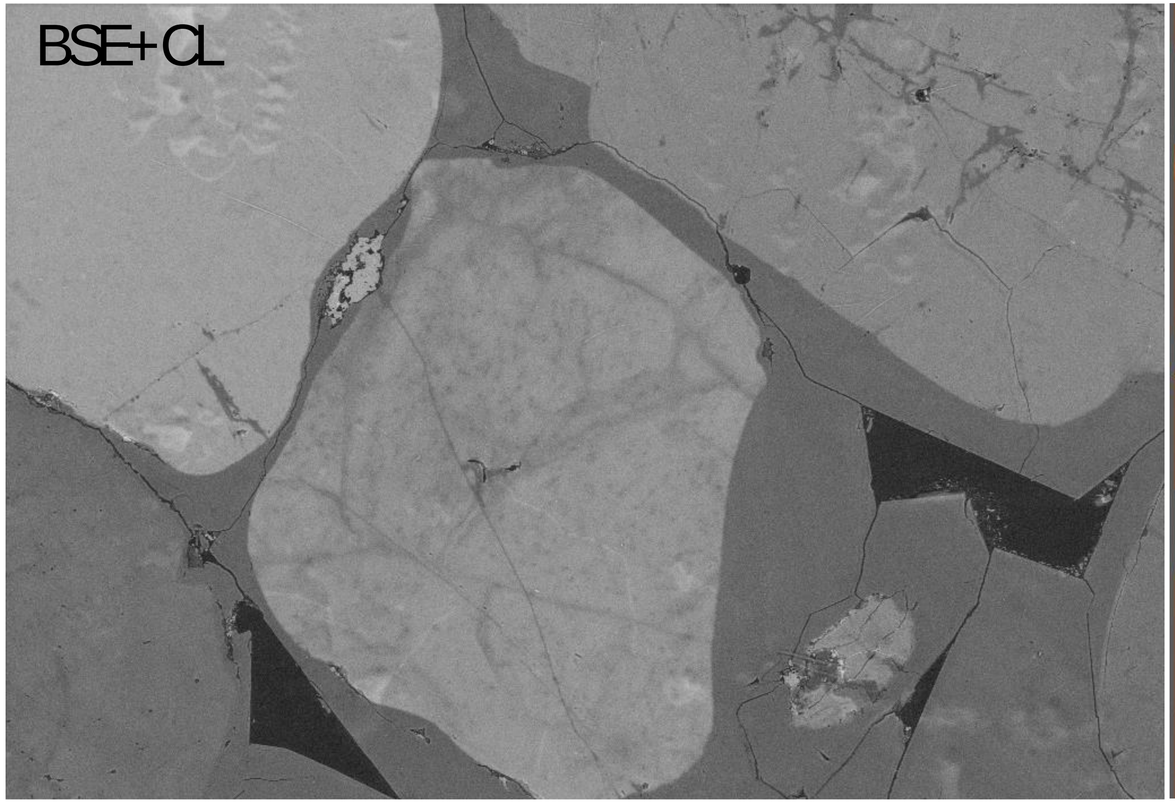
What do we need? (Manual example)

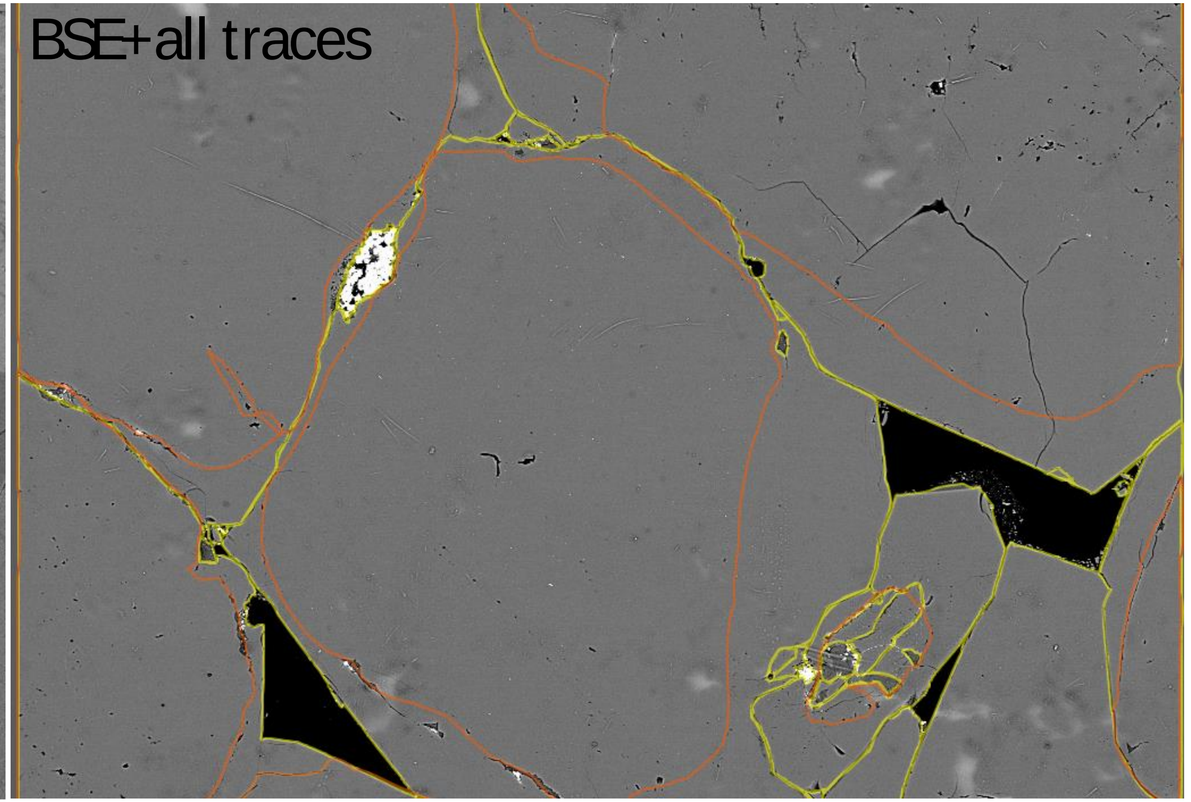


- Here the BSE and CL image are superimposed (commercial photo software)
- To separate out pores, BSE can be used
- To separate out overgrowths CL needs to be used

What do we need? (Manual example)

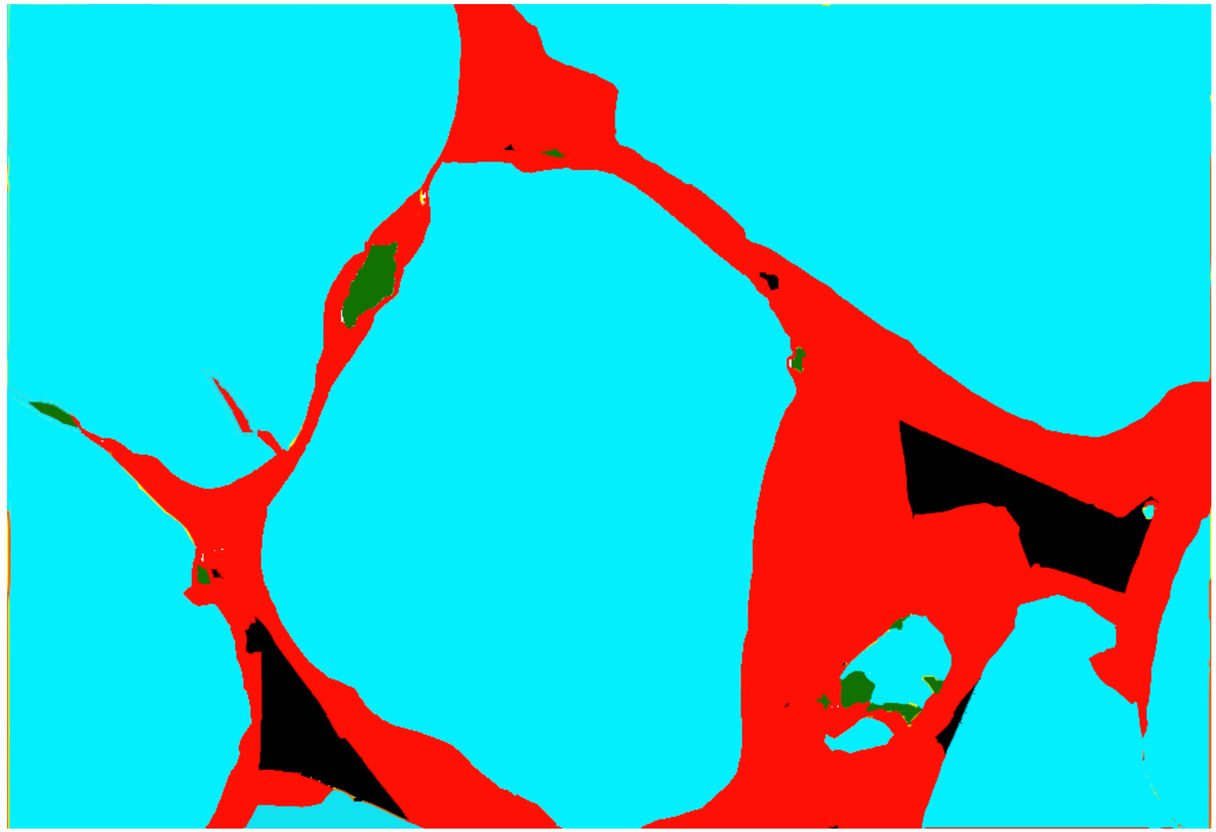
Traced lines:
Traced on BSE imag
Traced on CL image





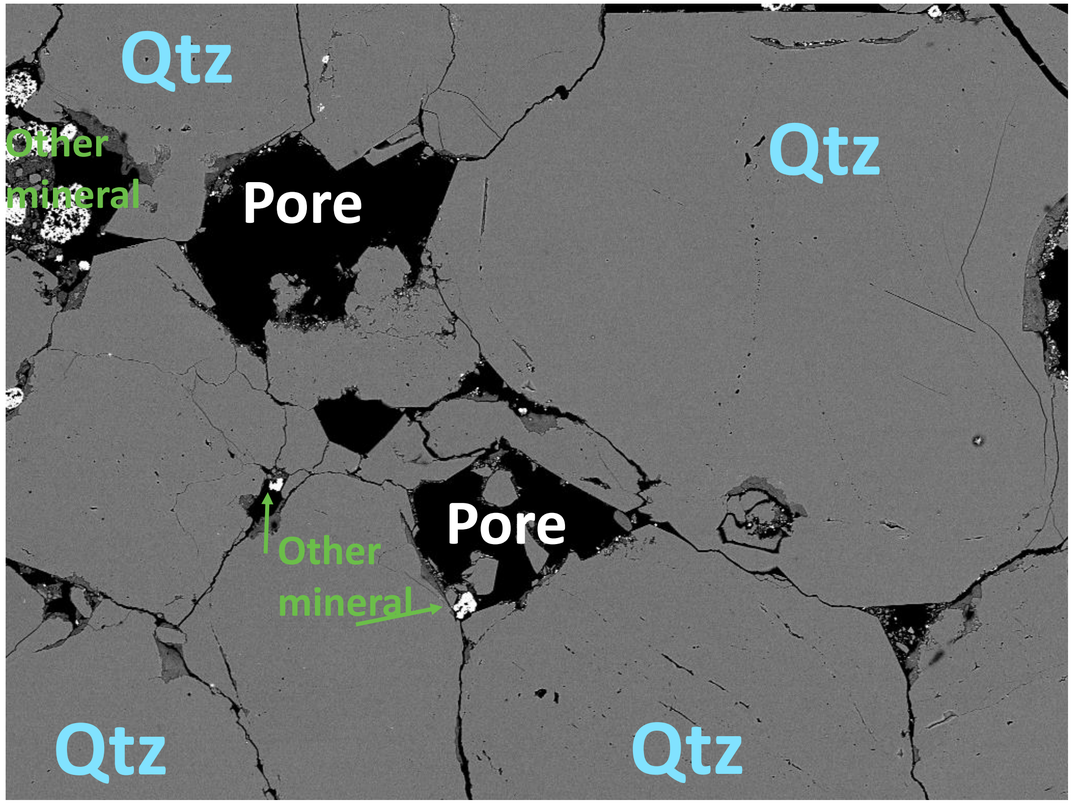
We need information from both BSE and CL to be able to separate quartz cores (detrital), from quartz overgrowths (rims, authigenic) and from pore space

What do we need? (Manual example)

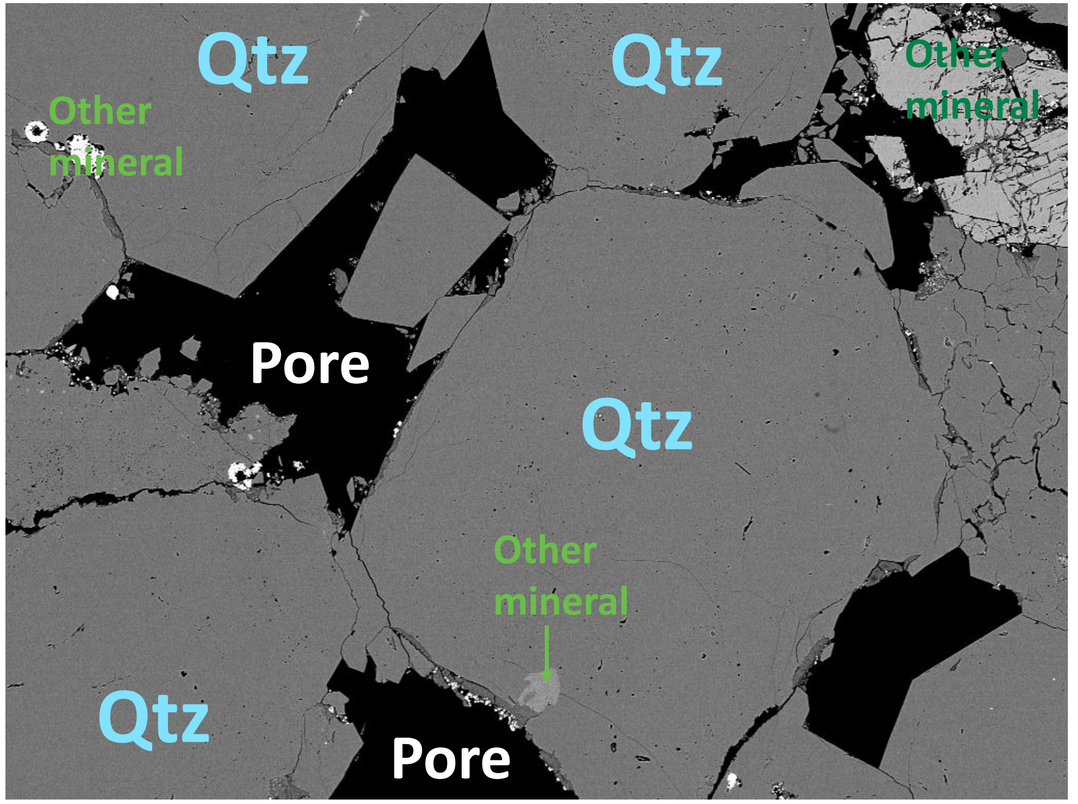


- Based on the traced quartz-pore boundaries (BSE) and the traced quartz core – quartz overgrowth boundaries, we can now index quartz, quartz overgrowth, pores and other minerals
- These indexed maps can be used to calculate the area/volume percentages for the assignment

More examples of BSE images with sandstone

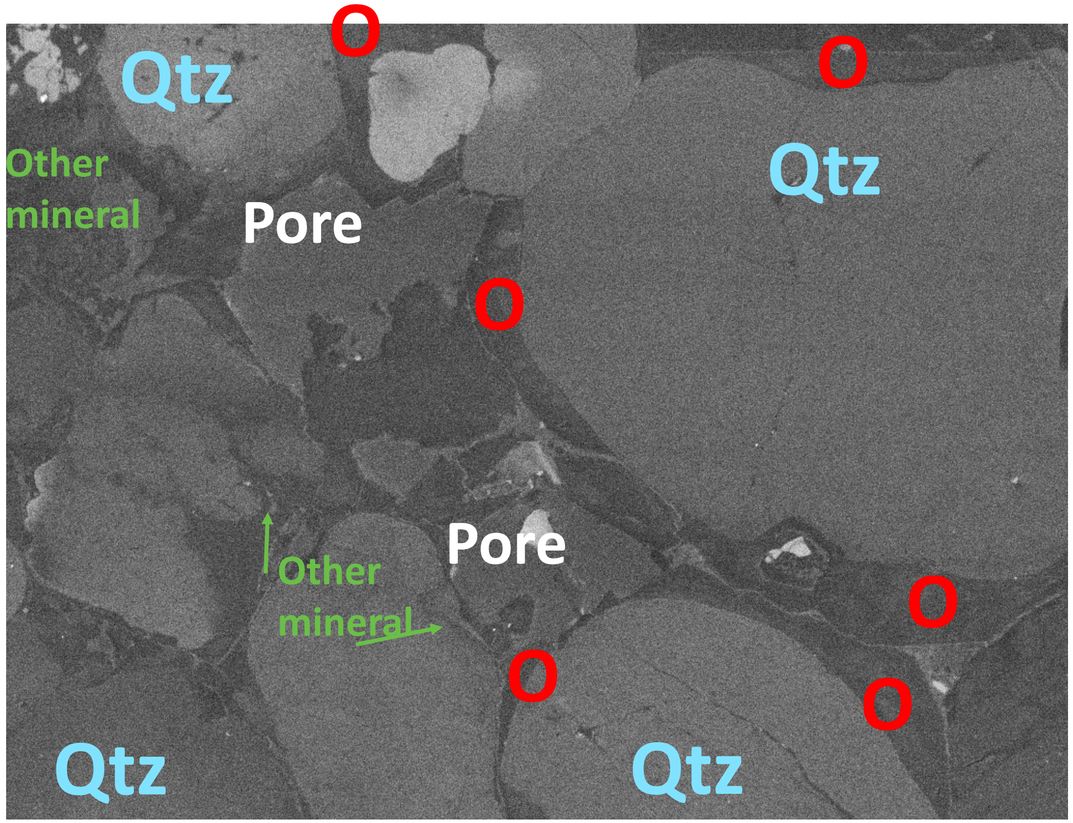


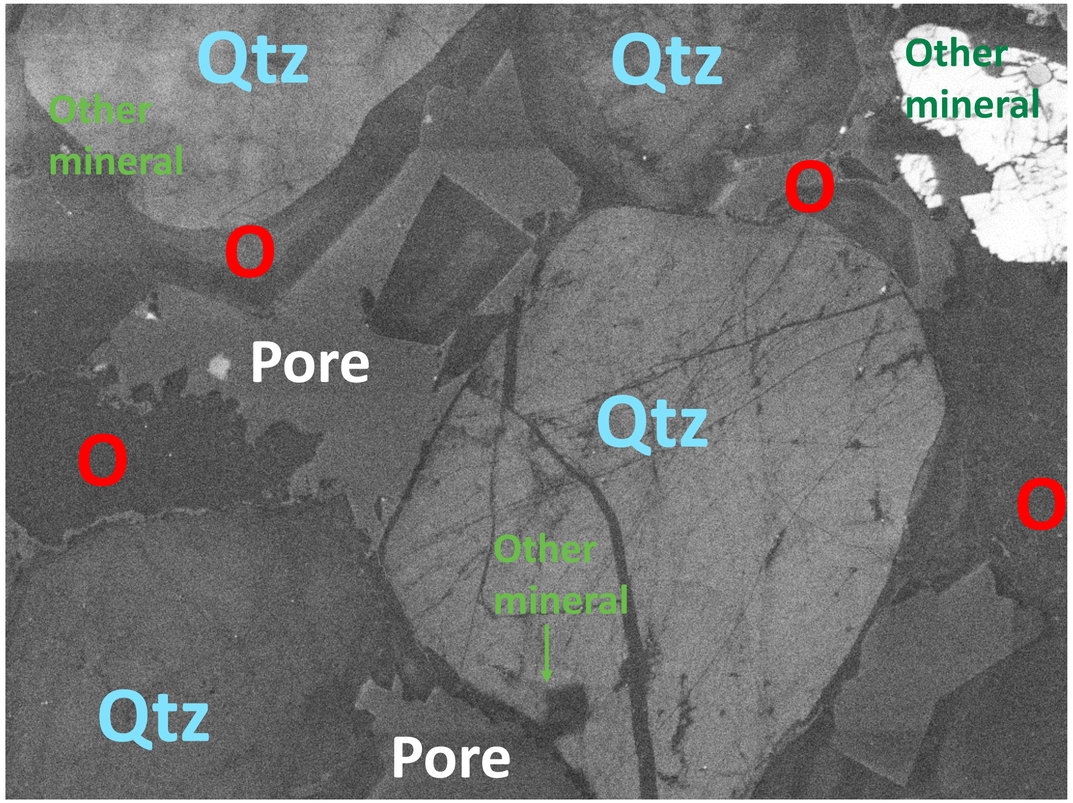
- Quartz (grey) and pore space (black)
- Quartz is always grey, all quartz have the same grey value.



- Pores are always black
- Other minerals can be lighter and darker than quartz

More examples of CL images with sandstone





- Showing quartz core (white to dark grey), quartz overgrowth (dark grey) and pore space (near black)
- Pores are often near black
- Quartz overgrowths are always dark grey, all quartz overgrowths (of one generation) have the same grey value.
- Other minerals can be lighter and darker than quartz

More examples with indexed maps

- 5 further examples for your reference in the next 10 slides

Image6_23
BSE

Minerals
Pore space

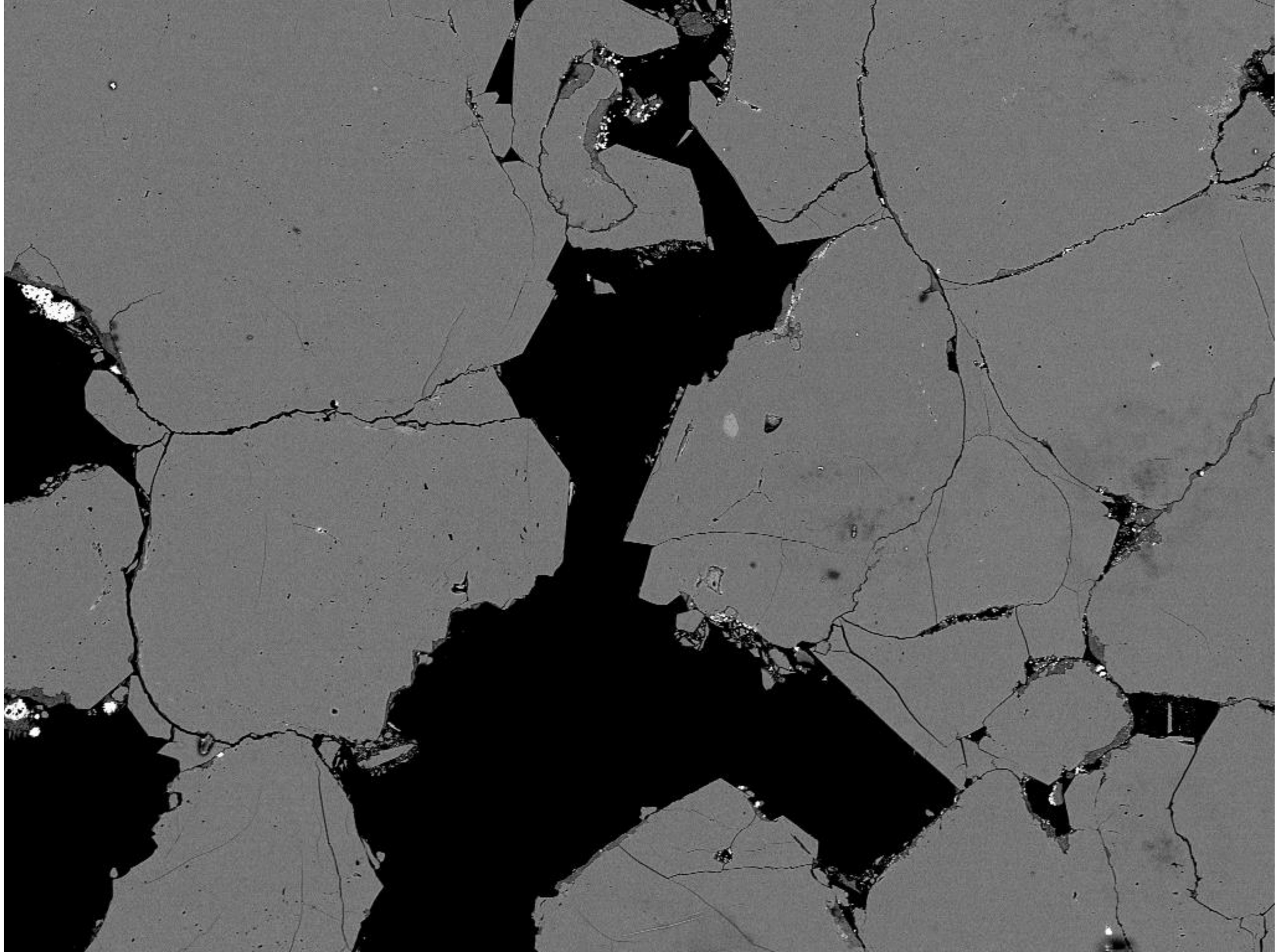


Image6_23
CL

Grain
Overgrowth
Pore space

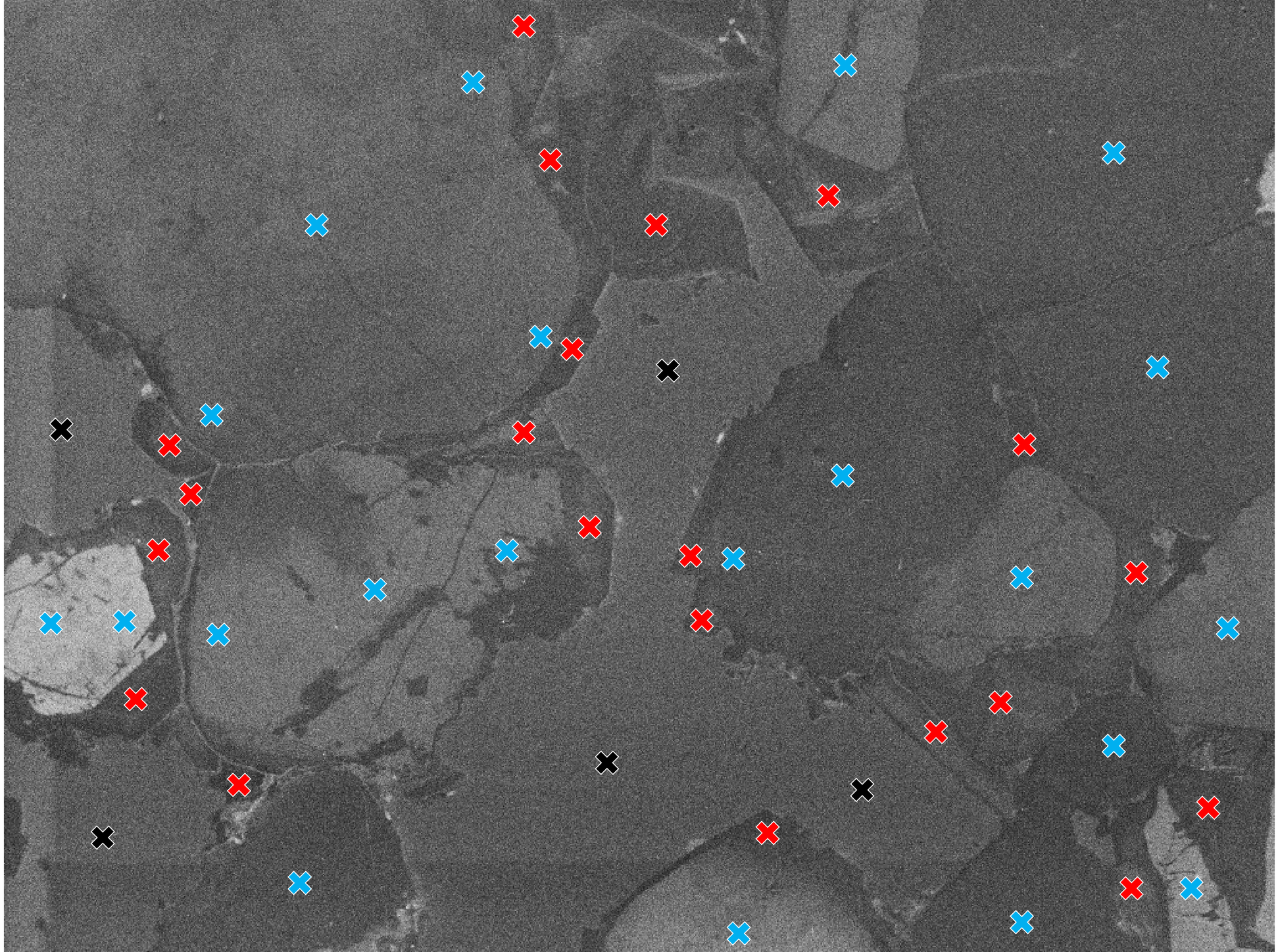


Image6_24
BSE

Minerals
Pore space

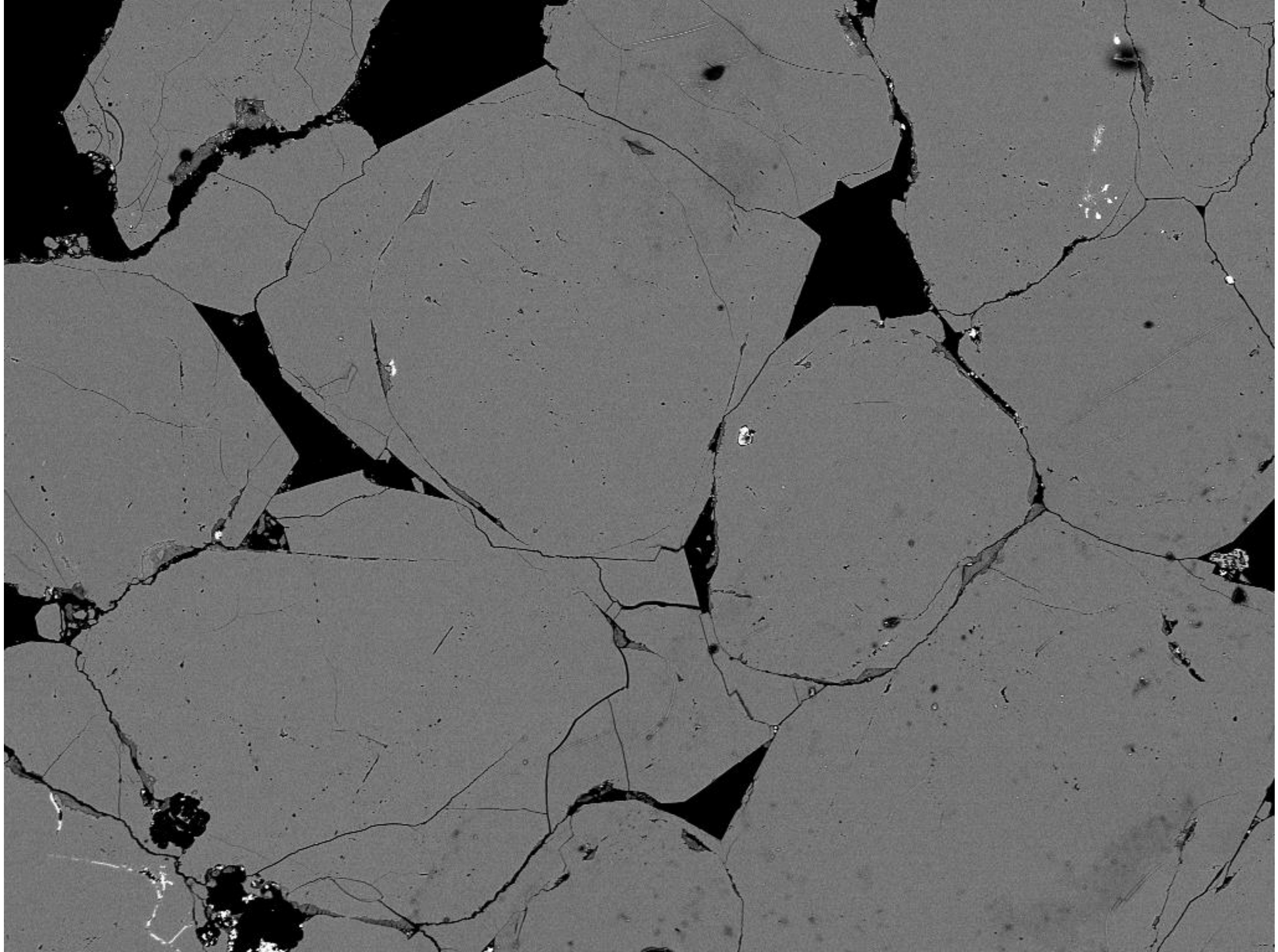


Image6_24
CL

Grain
Overgrowth
Pore space

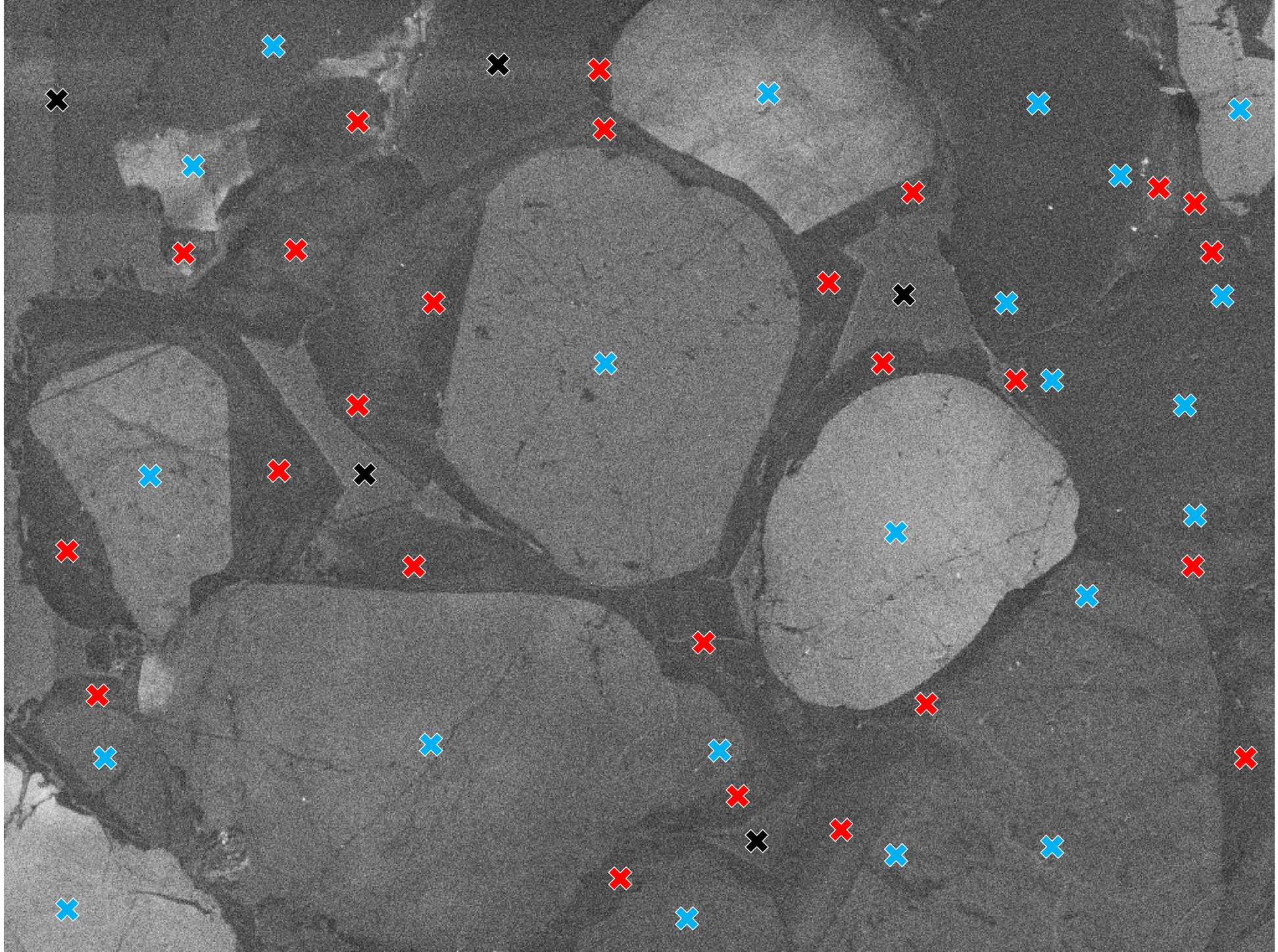


Image6_27
BSE

Minerals
Pore space

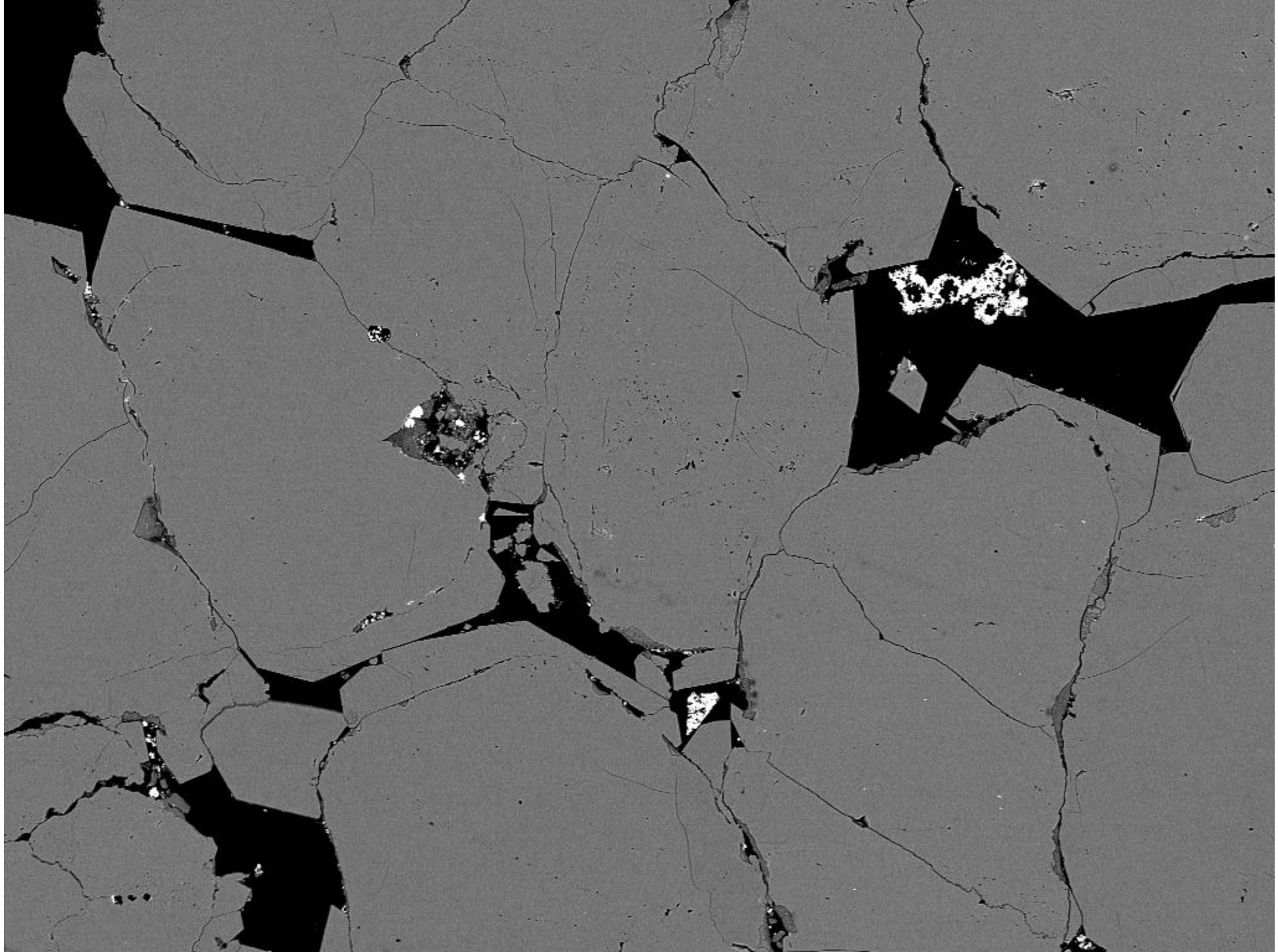


Image6_27
CL

Grain
Overgrowth
Pore space

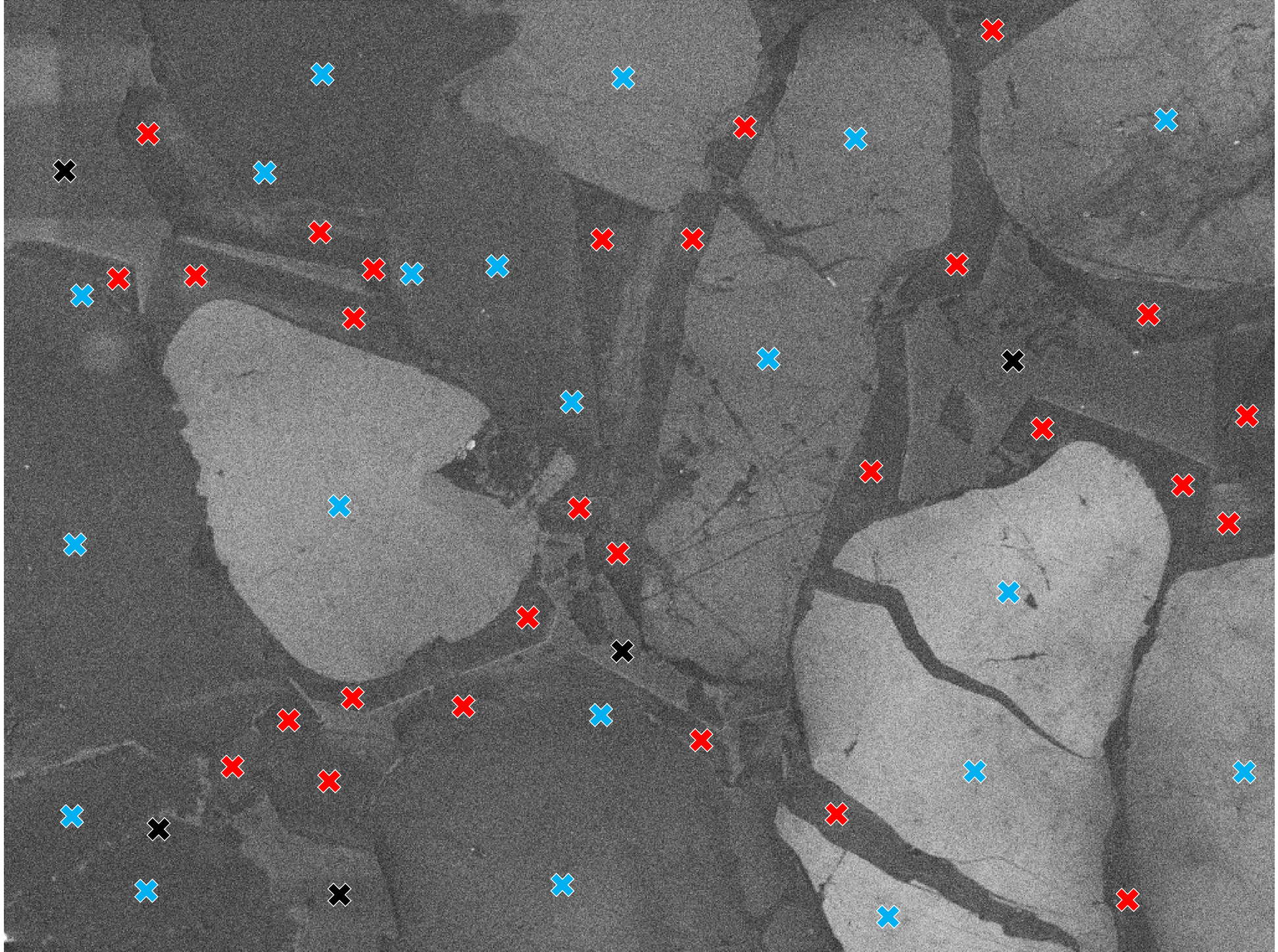


Image6_28
BSE

Minerals
Pore space

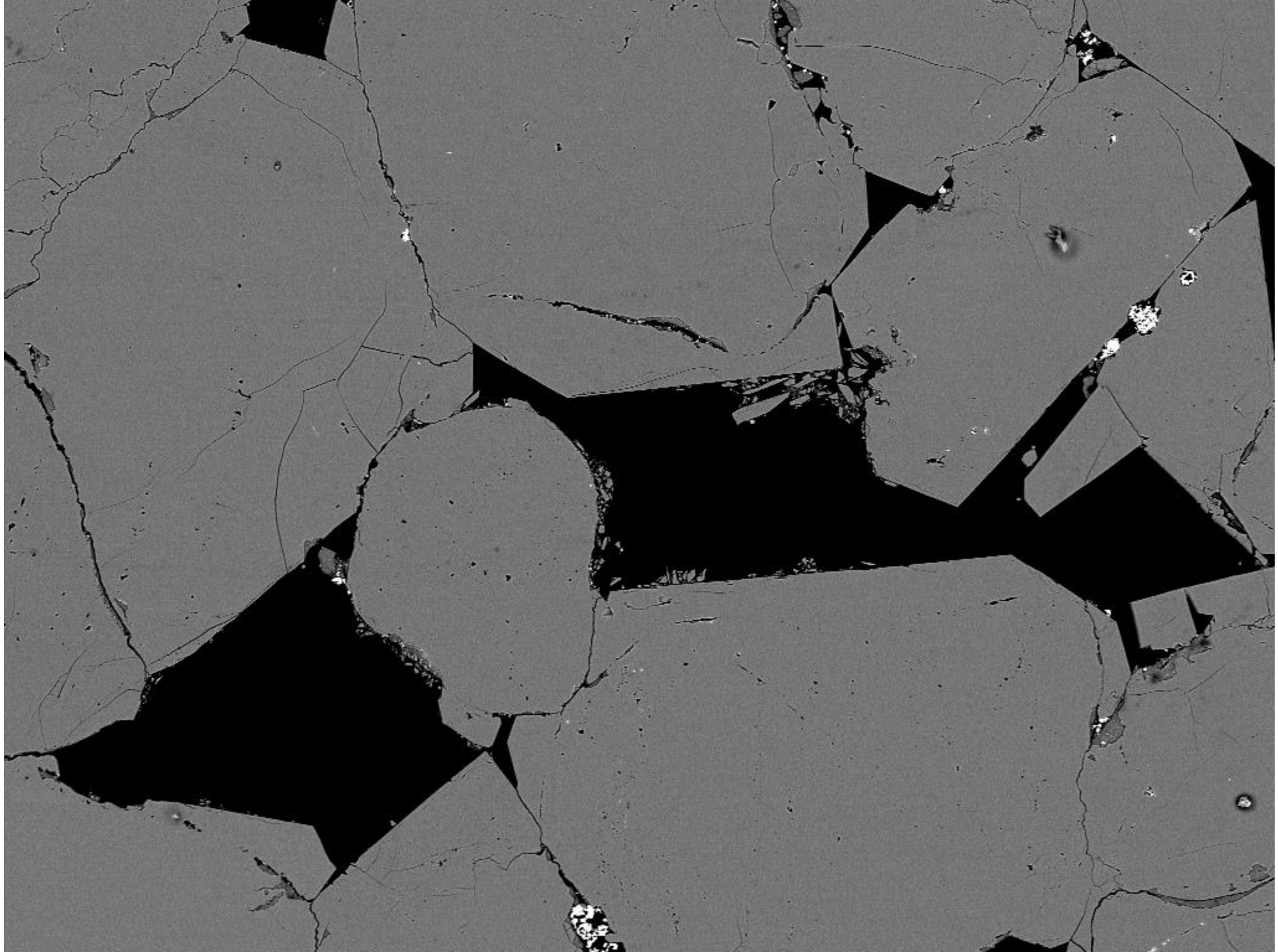


Image6_28
CL

Grain
Overgrowth
Pore space

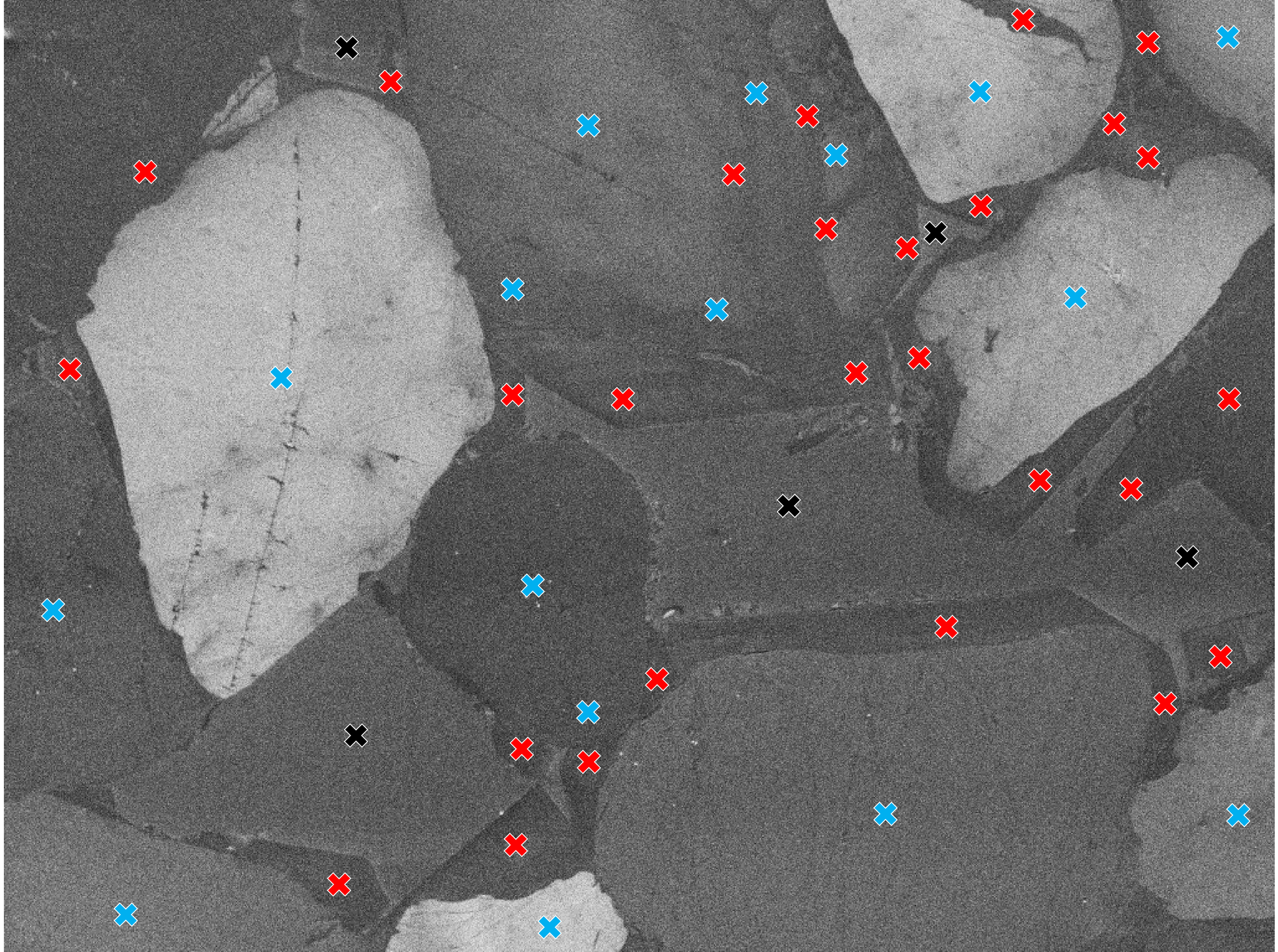


Image7_23
BSE

Minerals
Pore space

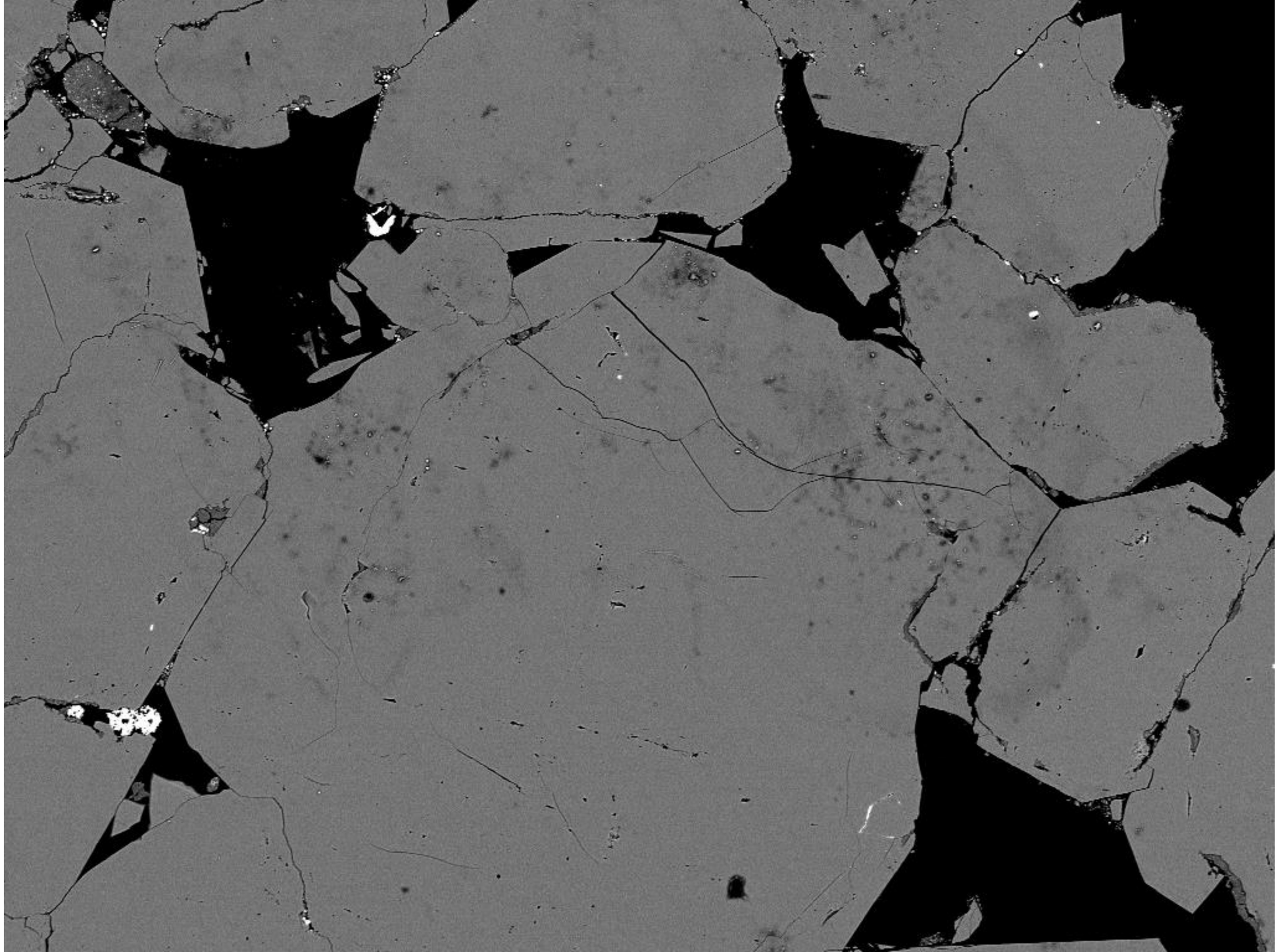
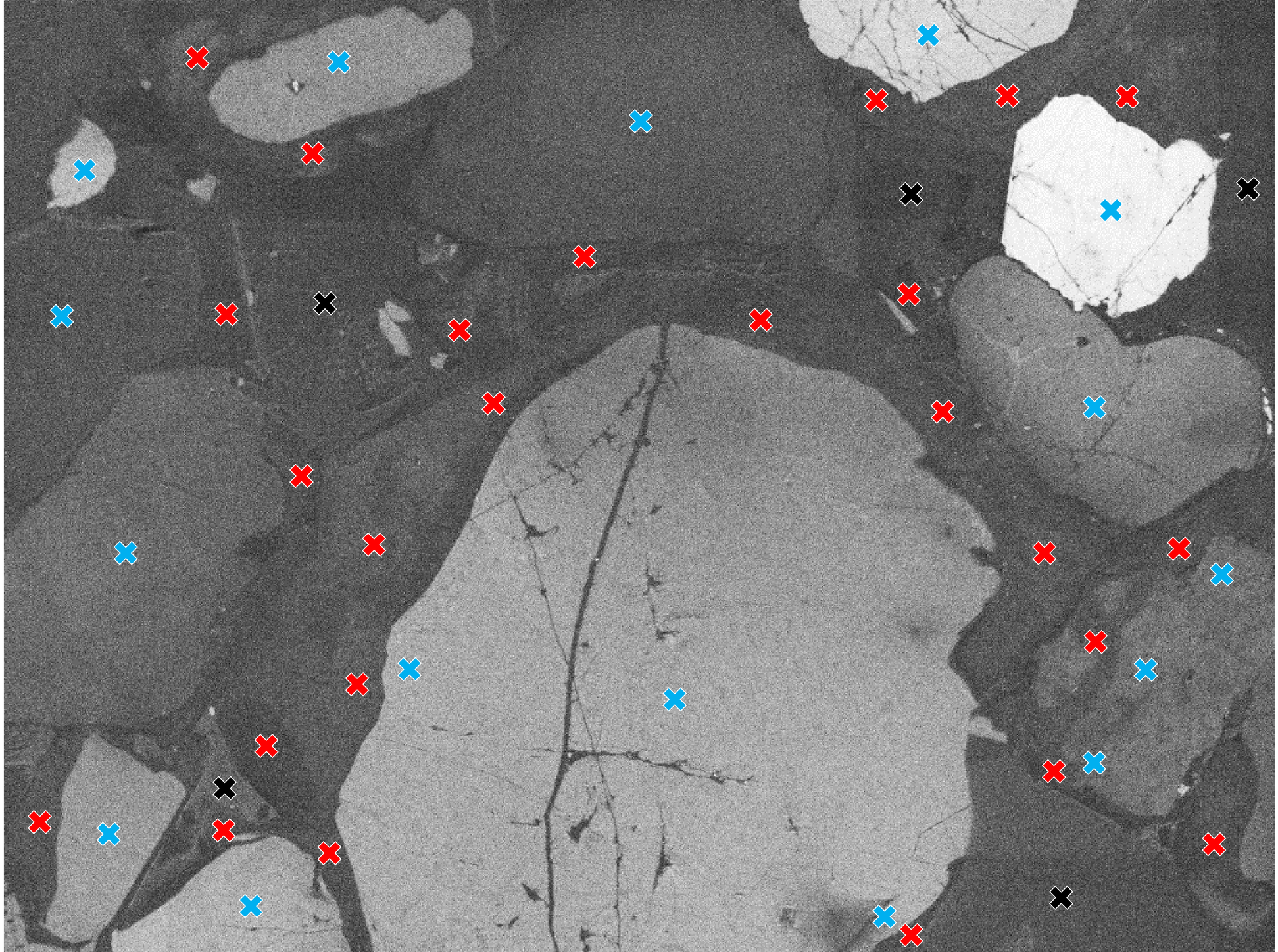
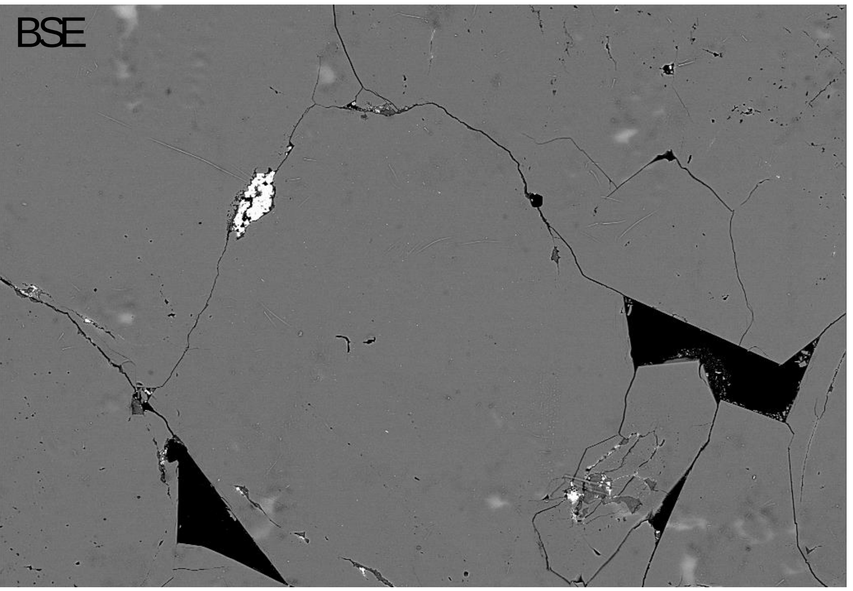


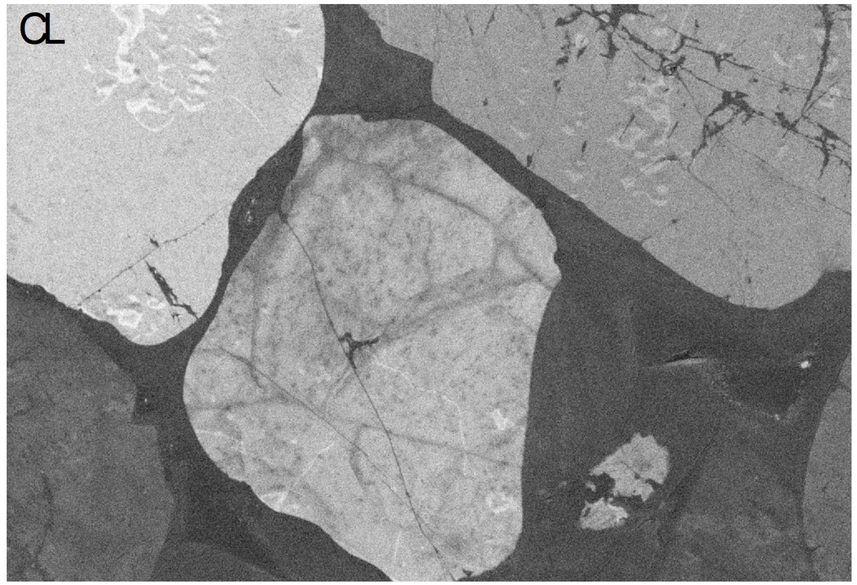
Image7_23
CL

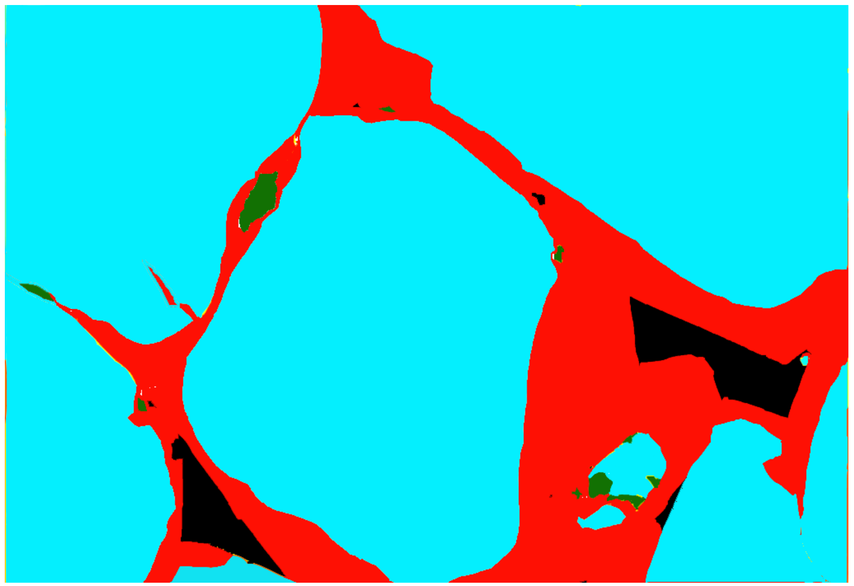
Grain
Overgrowth
Pore space



Summary of the above:

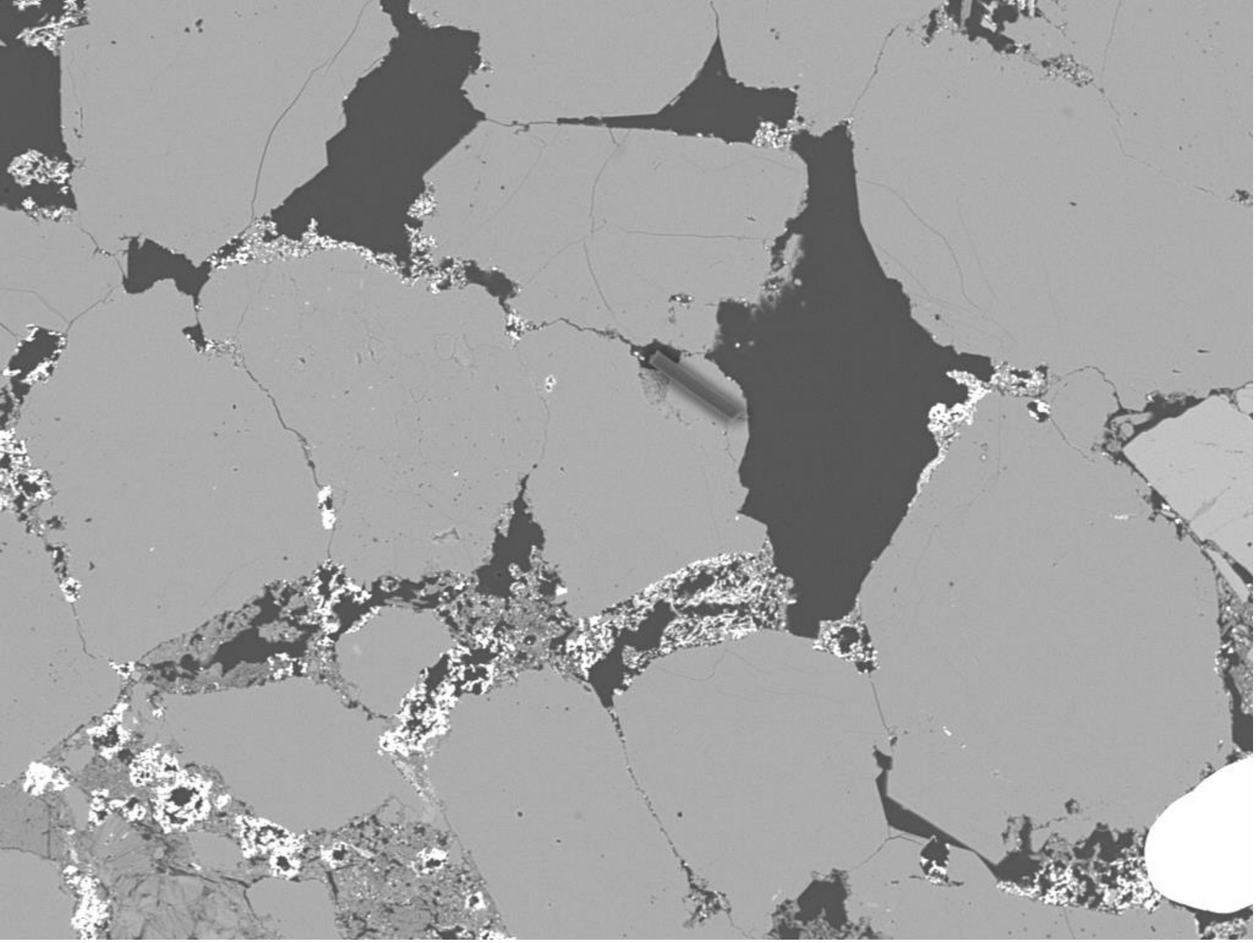


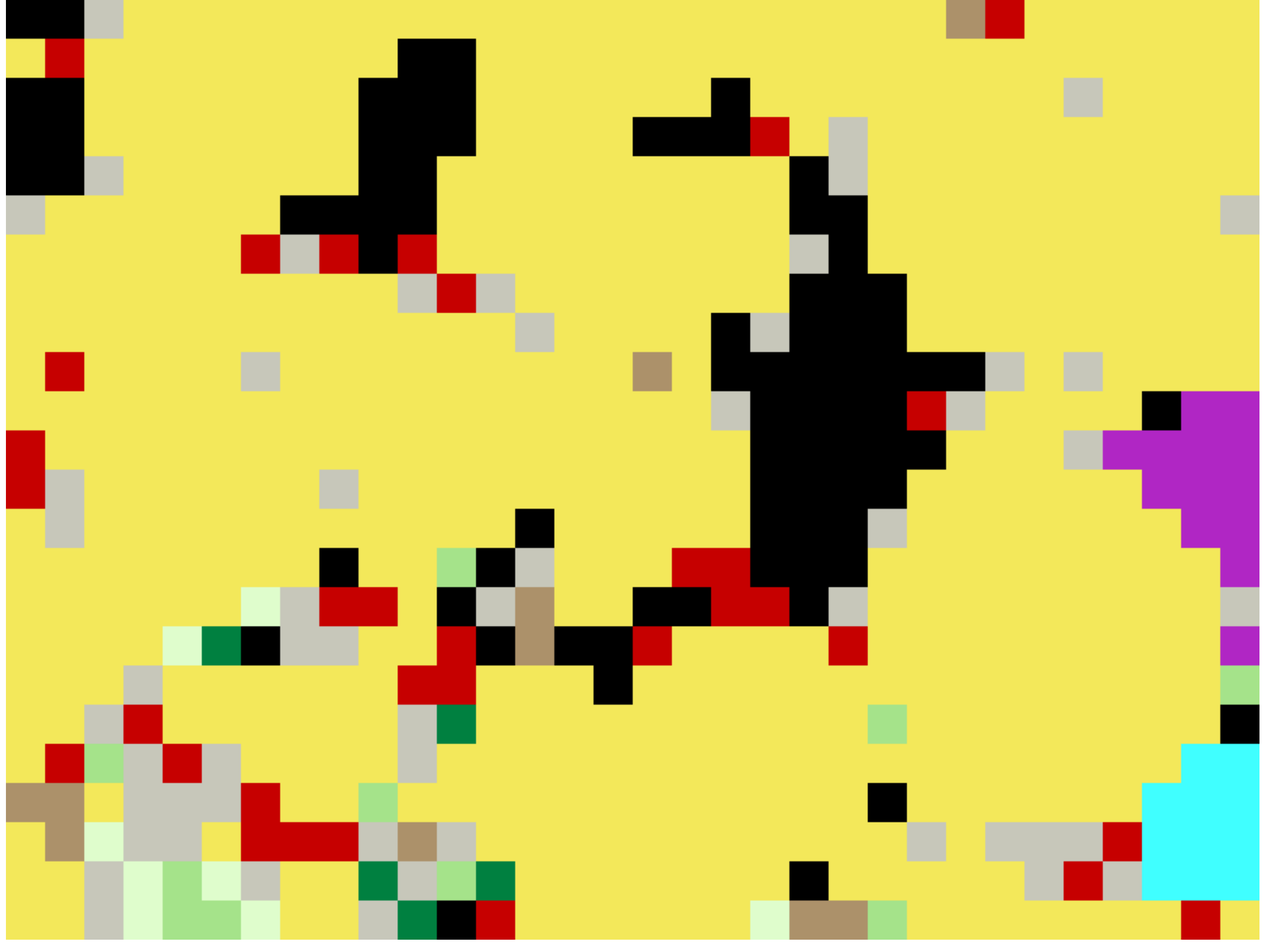




Combined information from both BSE and CL to be able to separate quartz cores (detrital), quartz overgrowths, and pore space

The indexed maps can be used to calculate the area/volume percentages for the assignment





quartz

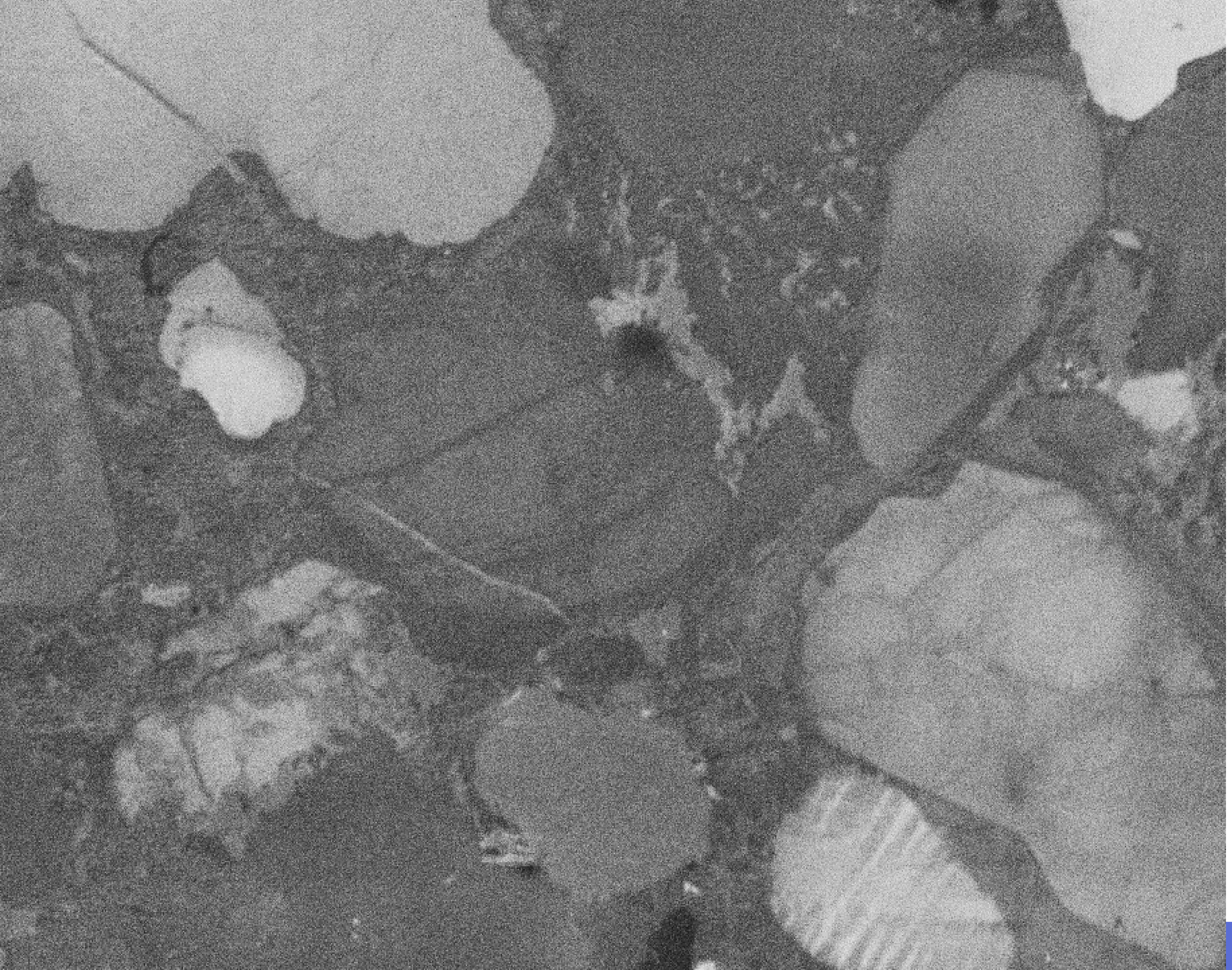
feldspar

pore

other mineral

Mineral maps:

- The dataset also provides Mineral maps for all BSE images
- These can be used to determine if a mineral is quartz, or ”other mineral than quartz”
- If you like a bigger challenge: try to determine overgrowths on feldspar minerals as well.
- Most sandstones have a significant number of minerals other than quartz, some of the datasets contain higher amounts of feldspar and clay minerals



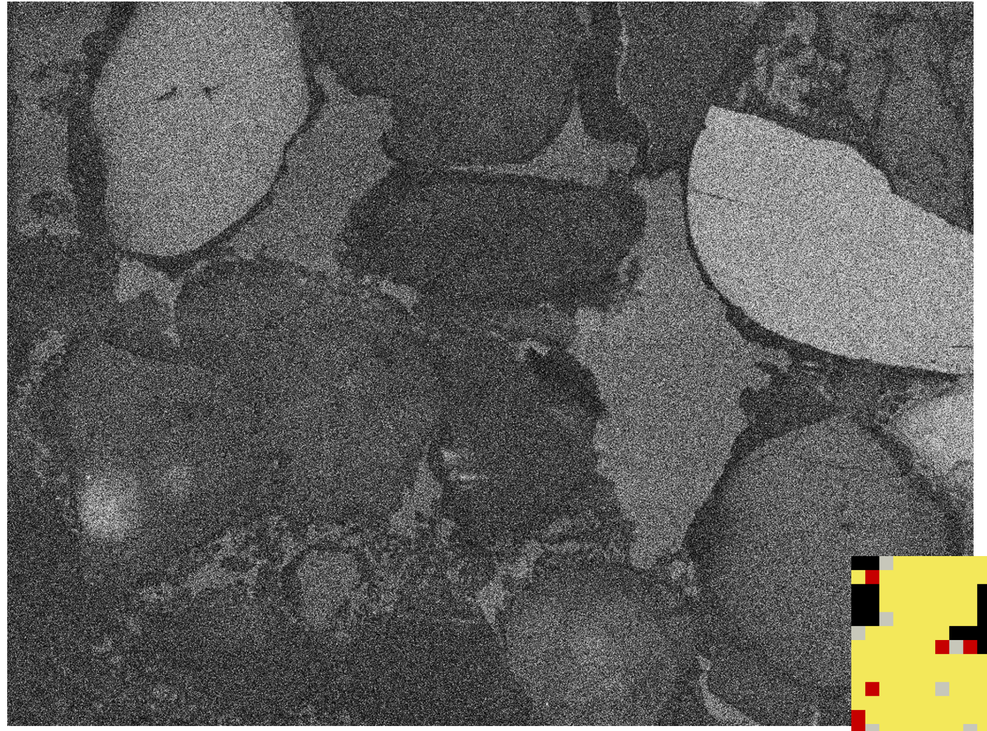
Assignment:

- Development of a method (in python script) that can be used to combine information from different types of SEM images to quantify the areas of quartz sand grains and quartz overgrowths and pore space.
- Machine learning, e.g., supervised or unsupervised learning based on a training set. Image analysis techniques.

Hackathon assignment

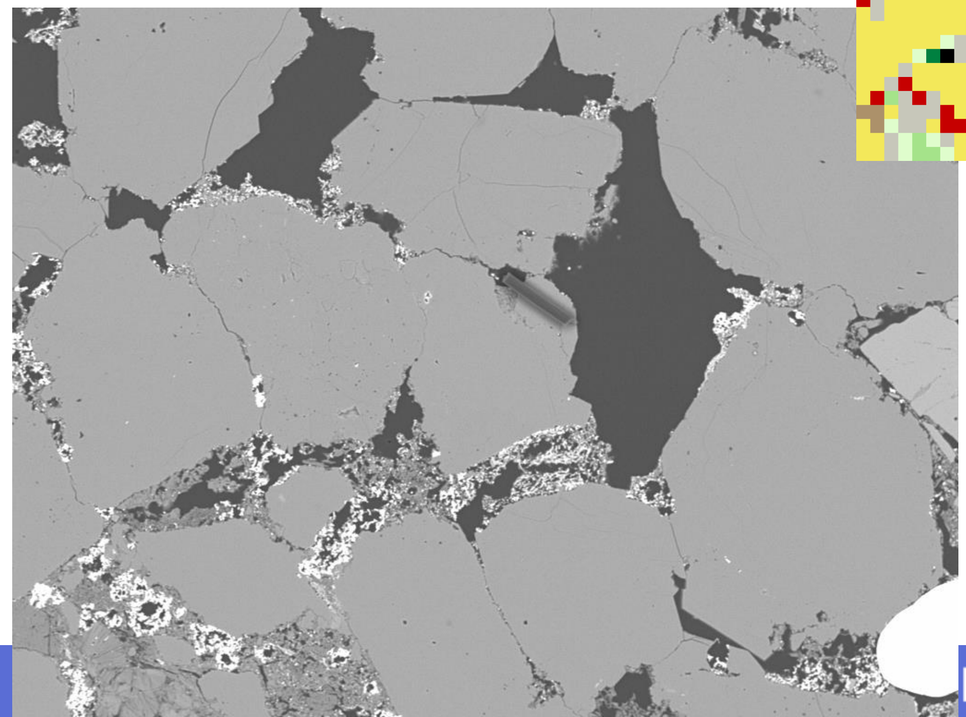
Define original grain, its overgrowth, and pore space using the available images

- Thousands of high-resolution SEM images are available, which comprise the input data for the hackathon.
- Distinguish grains and the pore space is best seen on backscattered electron (BSE) images. Porosity can be calculated from these images alone.
- Distinction between grain and overgrowth on CL images.
- Combine the information obtained from different types of SEM images (obtained with different detectors) and **create an automated identification of authigenic and detrital grains and pore space**
- The overgrowth volume can be calculated from the combined images
- In addition: mineral maps allow identify quartz from other minerals. If your method works for quartz, try other minerals like feldspars as a bonus



CL

Mineral map



BSE

Practical information on the dataset

- The dataset has a DOI:

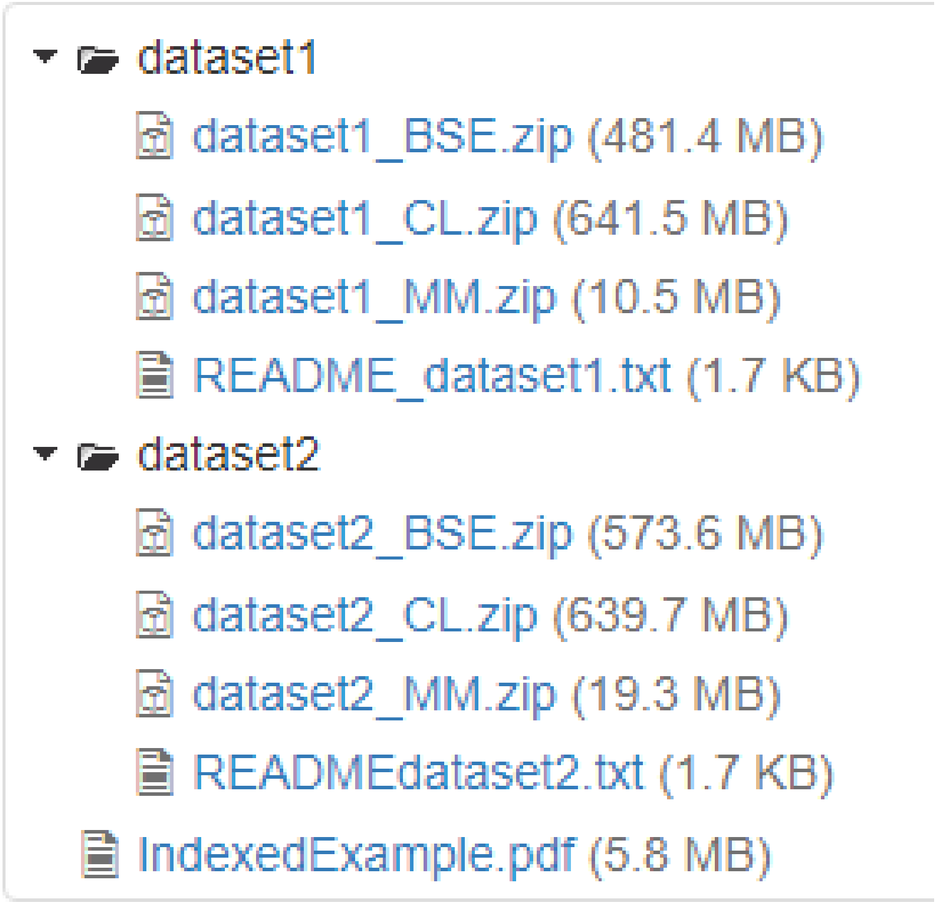
Keulen, Olivarius & Andrianov 2022, "Scanning electron microscope images dataset for geothermal reservoir characterisation", https://doi.org/10.22008/FK2/5TWAZK, GEUS Dataverse

- The dataset is published under a creative commons license Attribution-NonCommercial-NoDerivatives 4.0 International. See here for details: CC BY-NC-ND 4.0
- More data will be added before the end of the bootcamp (check for updates)

- After this slide we list a number of things that you might want to be aware of:

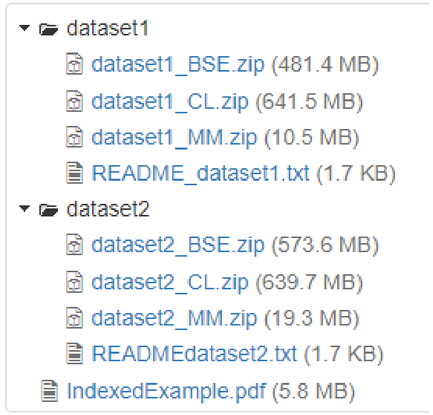
Structure of the dataset

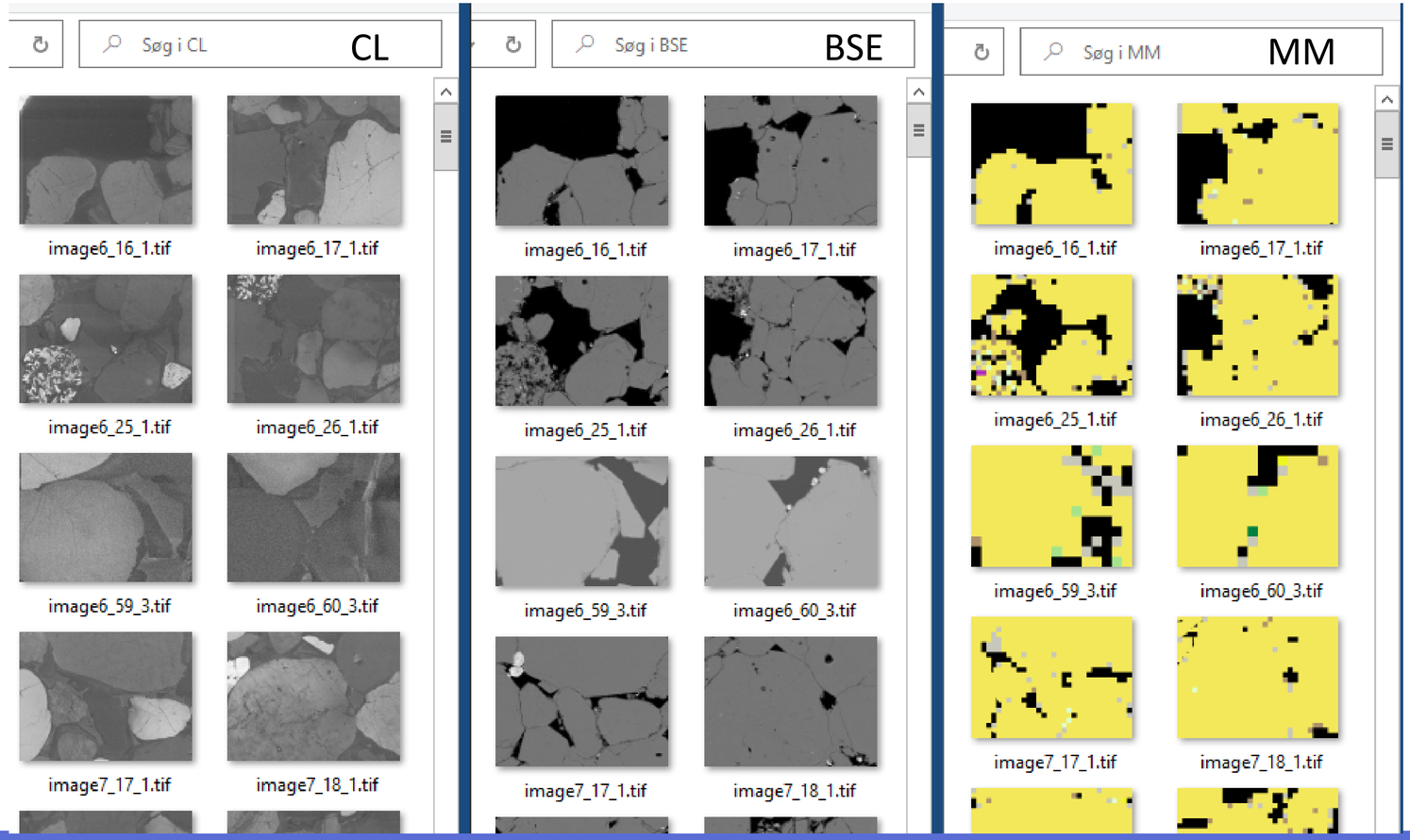
- Three sets of images for each sample area:
  - BSE, CL, Mineralmap for each area
- Differences between datasets:
  - Dataset 1: Easiest dataset with nearly only quartz and large overgrowths
  - Dataset 2: Dataset with two minerals: quartz and feldspar, that can easily be separated in the BSE image, clear overgrowths
  - Dataset 3: More minerals precipitated in the pores, both lighter and darker than quartz in the BSE image
  - Dataset 4: Mainly quartz minerals, but with smaller overgrowths and less contrast between the detritial and authigenic parts of the quartz grains.



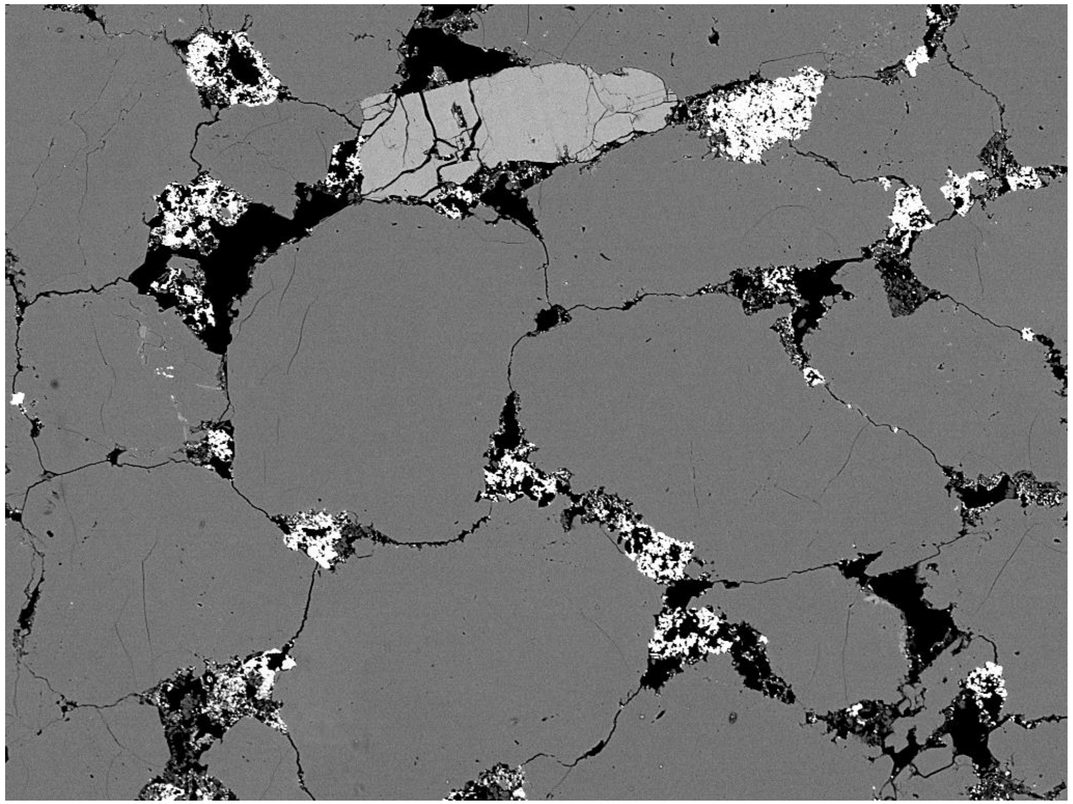
Structure of the dataset

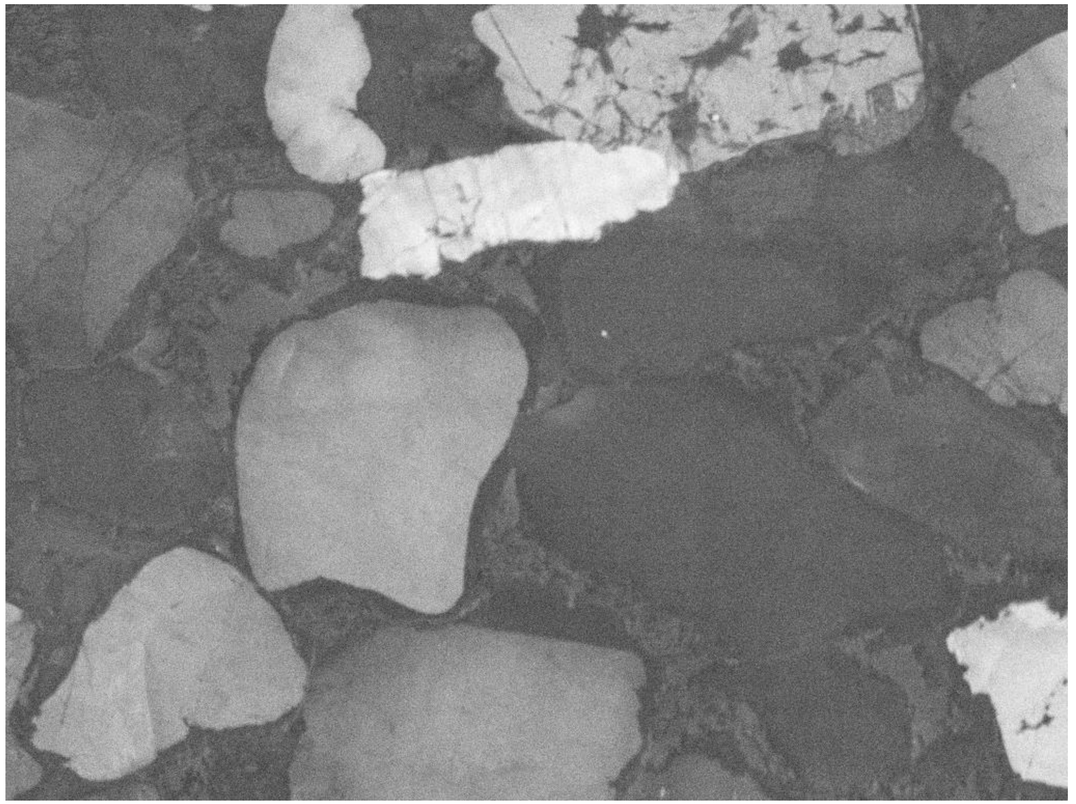
- Three sets of images for each sample area:
  - BSE, CL, Mineralmap (MM) for each area
- Image names:
  - Same image name for corresponding CL, BSE, and MM images
  - ImageX_Y_Z:
    - X and Y are coordinates in a mosaic of images
    - Z is the run number, dataset were produced over several days
    - Image of the same run can be stitched into a mosaic
    - Stitching is not part of the assignment, but feel free to try





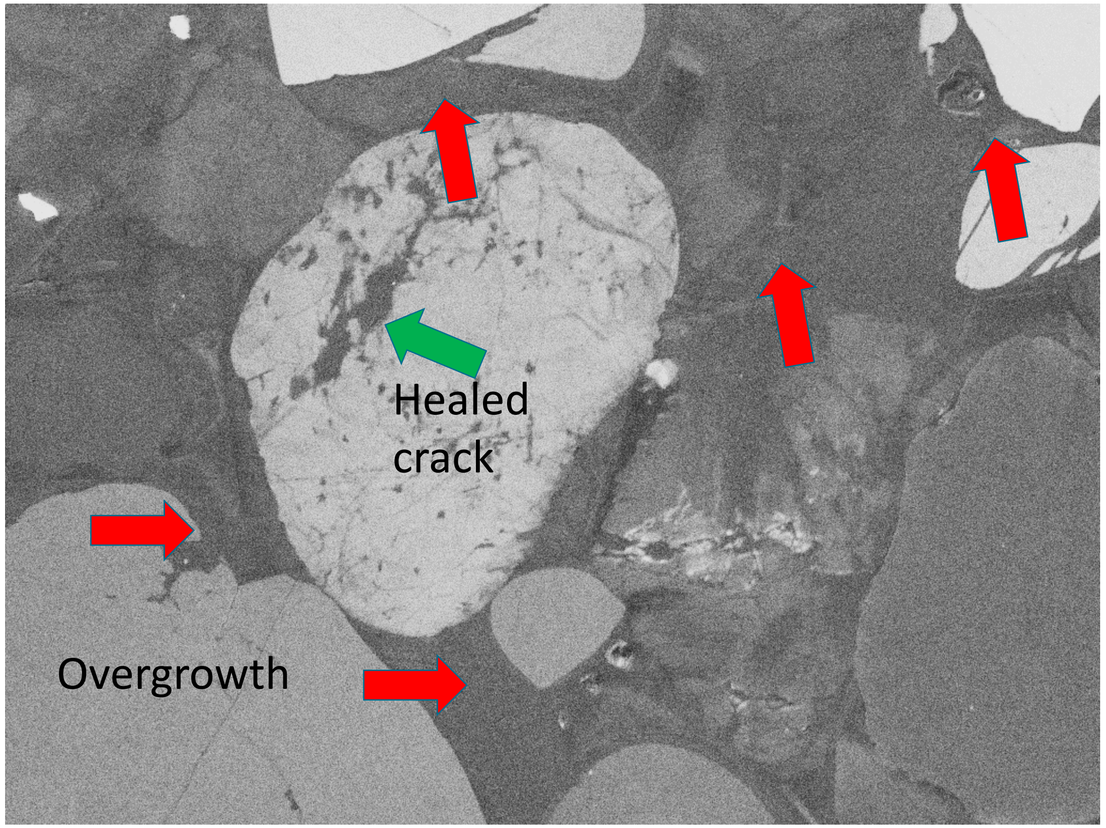
Offset between BSE (+ Mineral map) and CL

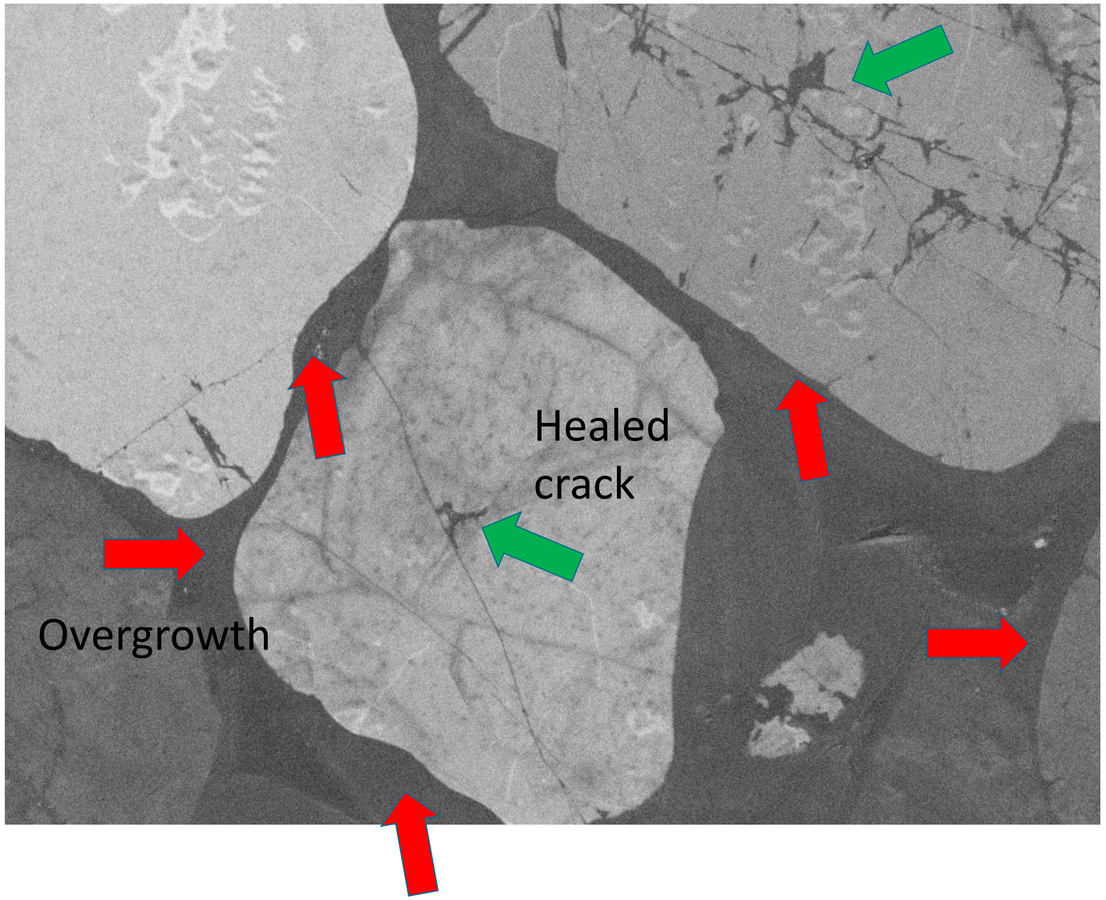




The BSE and CL images do not overlap 100%. When overlapping, they need a translation. Images within one dataset might need a different translation, as the dataset was produced over several days (they have a different run number in their image name: ImageX_Y_**Z**).

Examples of overgrowths versus healed cracks



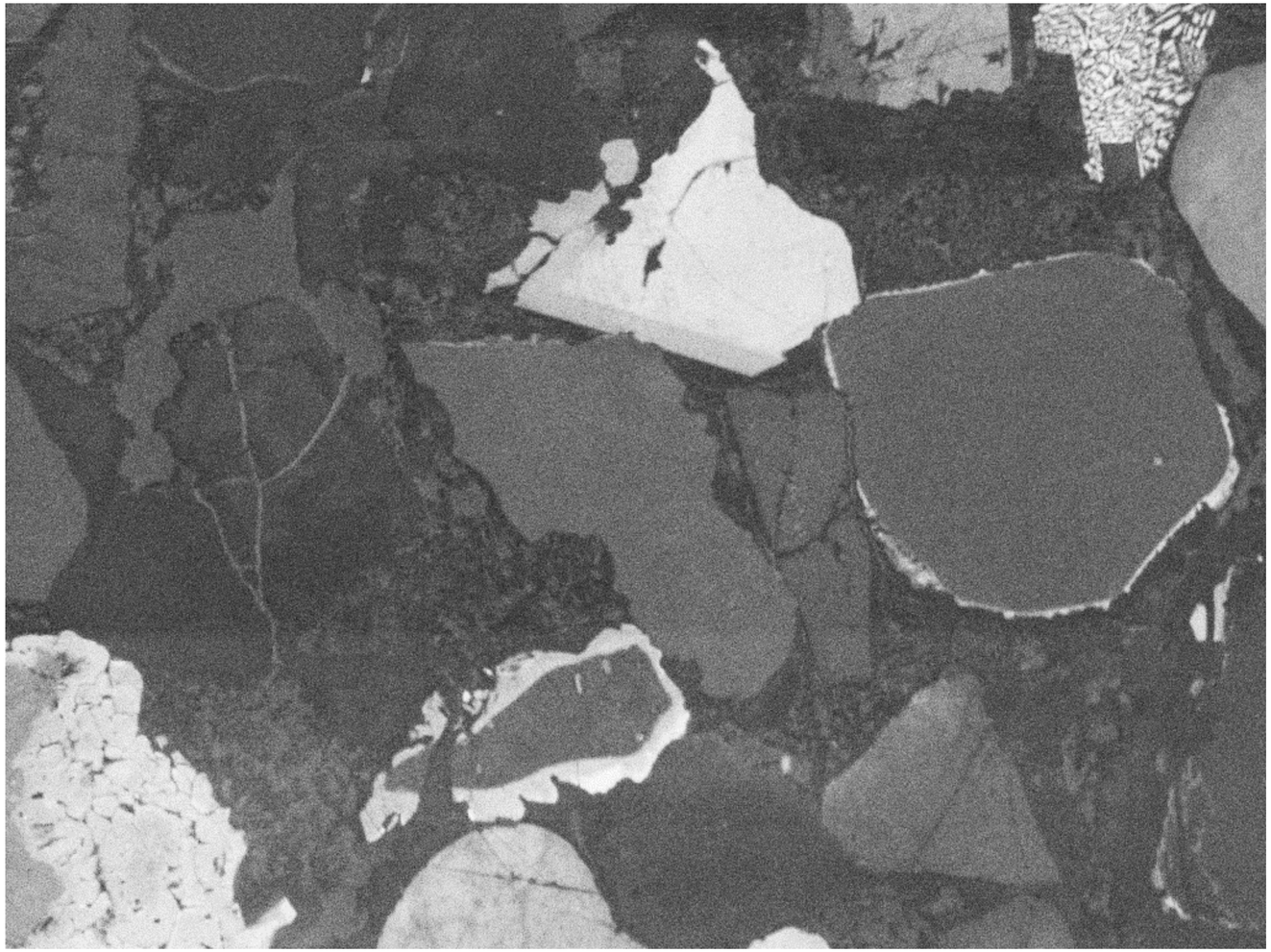


Cathodoluminescence image:
Shows growth phases

Healed cracks are **not** overgrowths: they usually form earlier in geological time

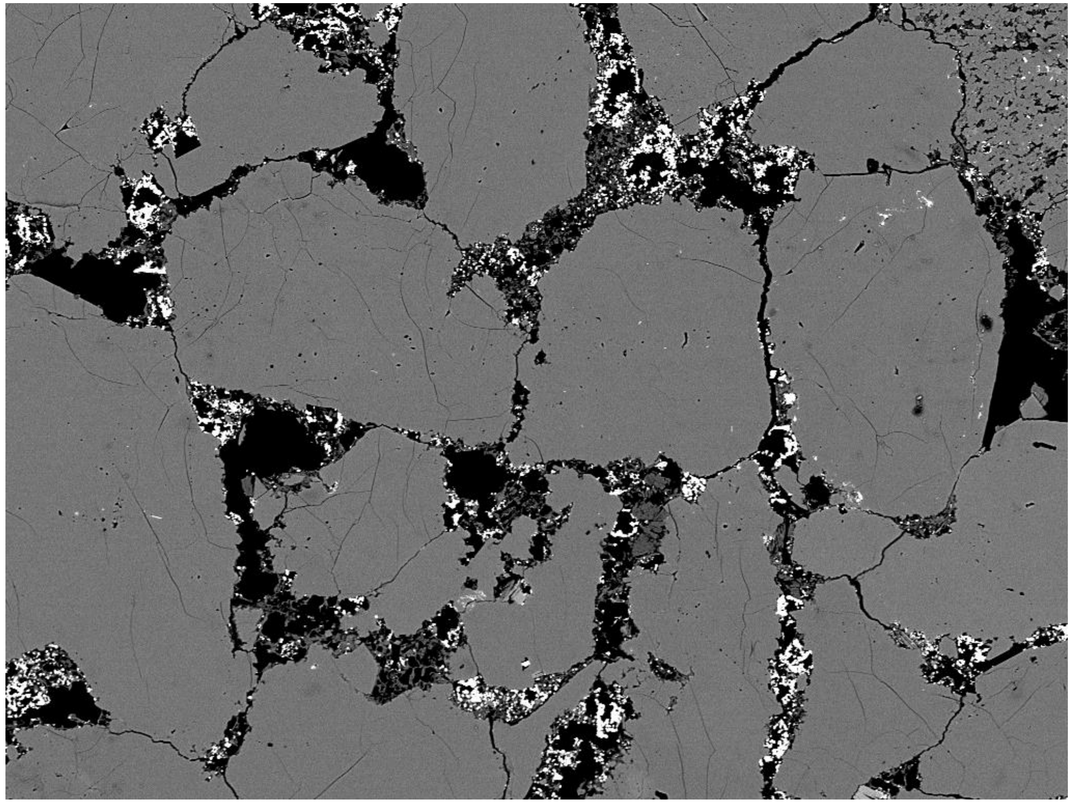
White rim in CL image

- Very few samples have a white overgrowth rim
- This is caused by fluids with a different composition.
- These overgrowths can be ignored… only consider the overgrowths that are dark grey.



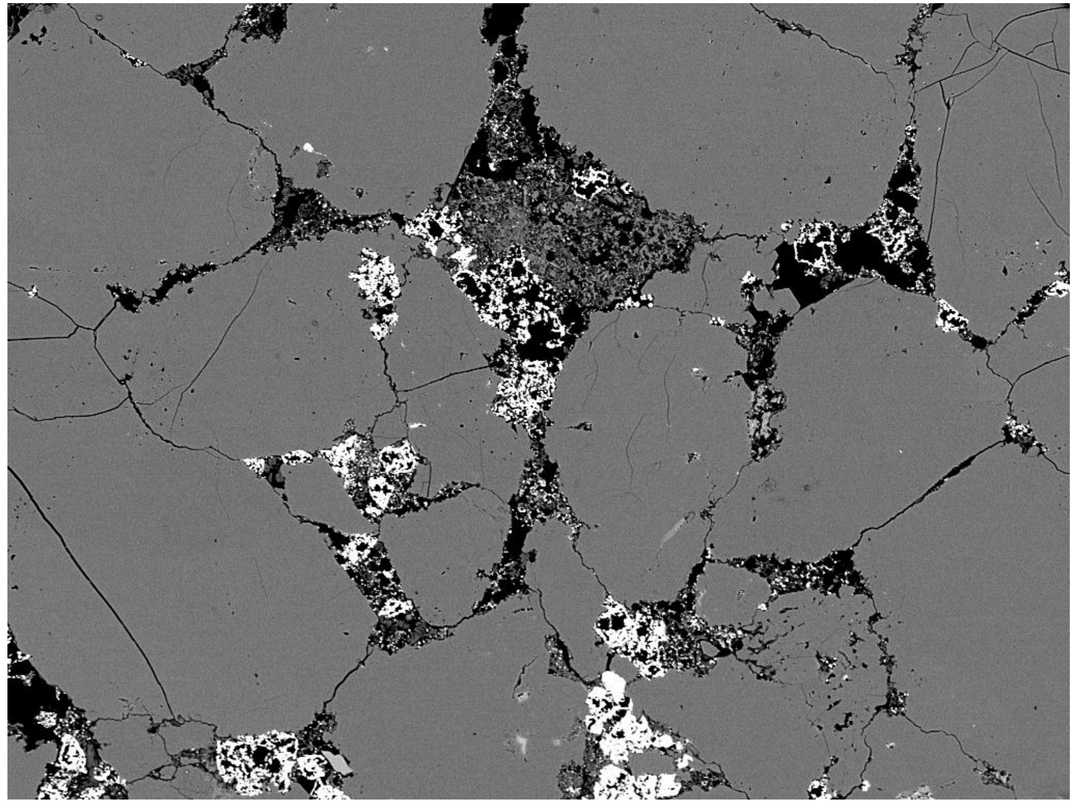
Area and volume

- Porosity is usually expressed as a volume measure
- SEM images are 2D, thus can only provide an area measure
- If sandstone is homogeneous, the area and volume correlate
- Assume the sandstones provided are homogeneous



Area and volume

- Grains touching edges are not represented completely. As we are not considering grain size, but an area %, you can include the grains touching edges



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Q&A

Please, type your Question in the Zoom Chat

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