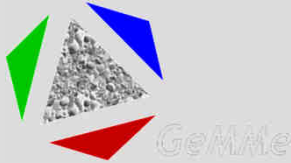


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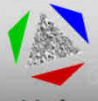


Automated mineral mapping in optical ore microscopy

Accuracy and limitations

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Frankfurt

Eric PIRARD
Université de Liège
GeMMe - *Georesources & Geolmaging*

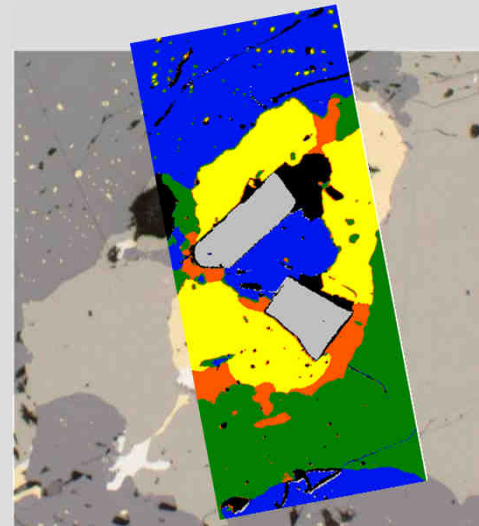


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Automated Mineral Mapping

- Sampling
- Imaging
- Mineral Identification



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Frankfurt

Automated Mineral Mapping

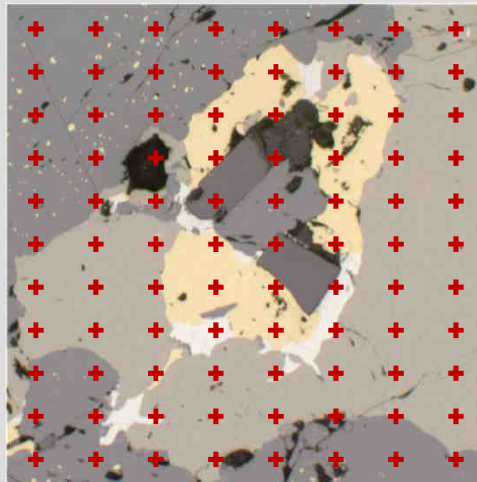
- Imaging

- Spatial Sampling

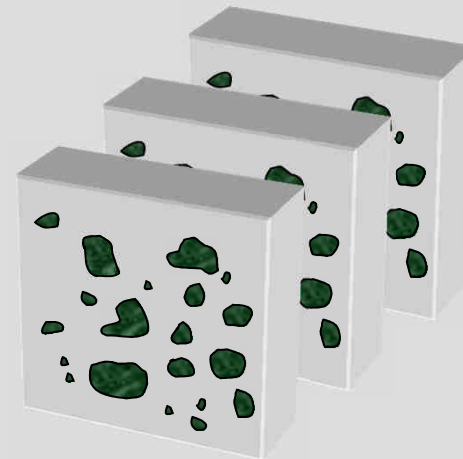
- A random point sampling gives an unbiased estimator of the volume proportion of a phase (α) in a solid

1st Principle of Stereology (Delesse, 1848)

$$P_P^\alpha = A_A^\alpha = V_V^\alpha$$



*Systematic sampling on a
"random" section*

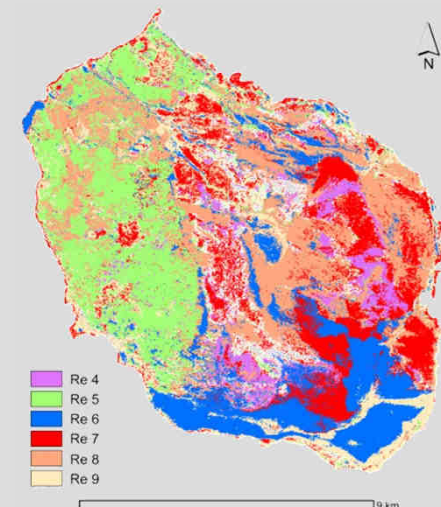
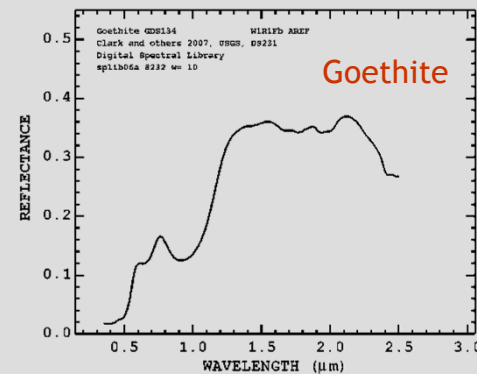
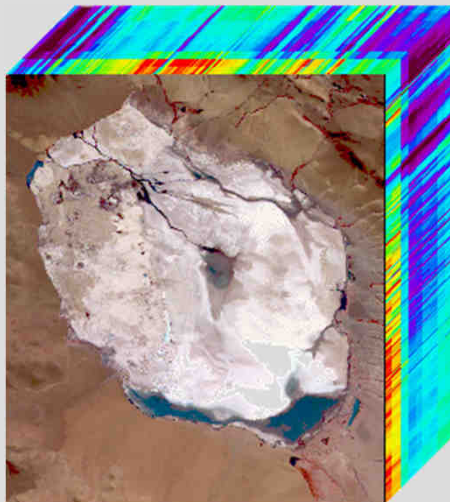


"Do more less well"



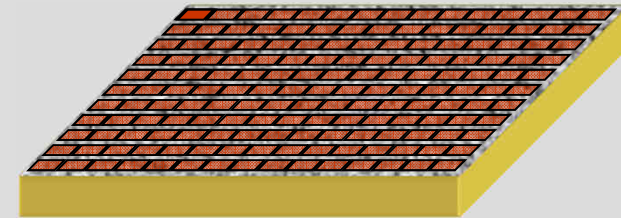
Automated Mineral Mapping

- Sensing the mineral target
 - Sensing principle
 - » Ex. X-ray fluorescence; light absorption; atomic force; ...
 - Signal processing and interpretation
 - » Database of spectra; Characteristic rays (K_{α} ,...)

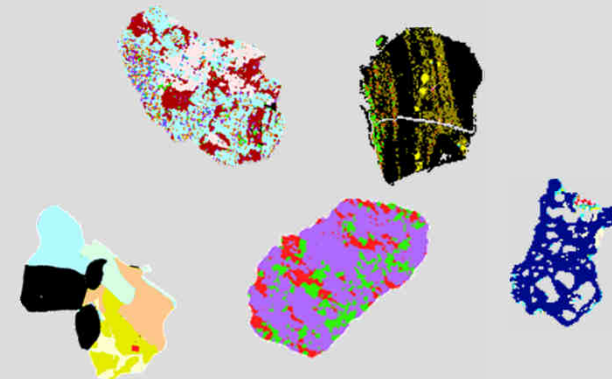


Automated Mineral Mapping

- Whiskbroom imaging mode
 - Scanning beam
 - *or moving sample*



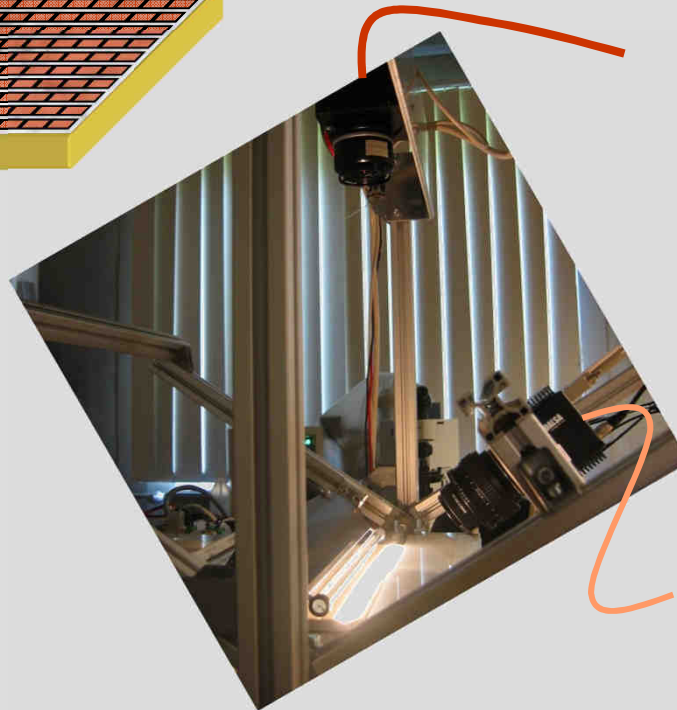
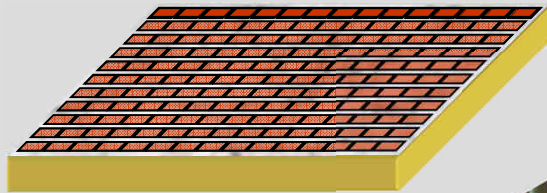
Ex. Scanning Electron Microscopy



Result of EDX mapping © QEM SCAN

Automated Mineral Mapping

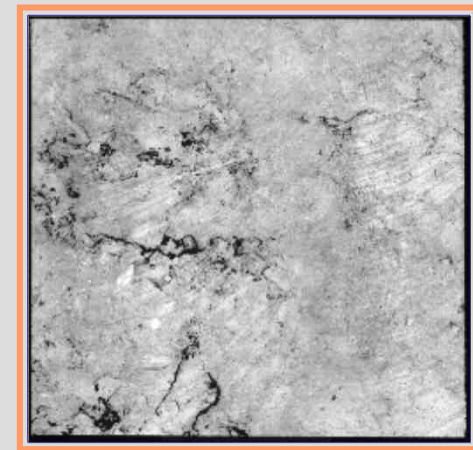
- Pushbroom imaging mode
 - Scanning linear sensor



Industrial vision of « marble » tiles



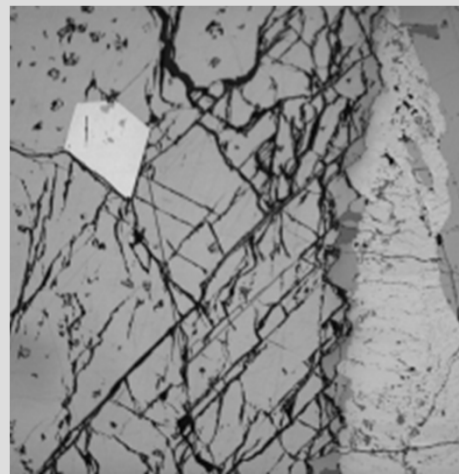
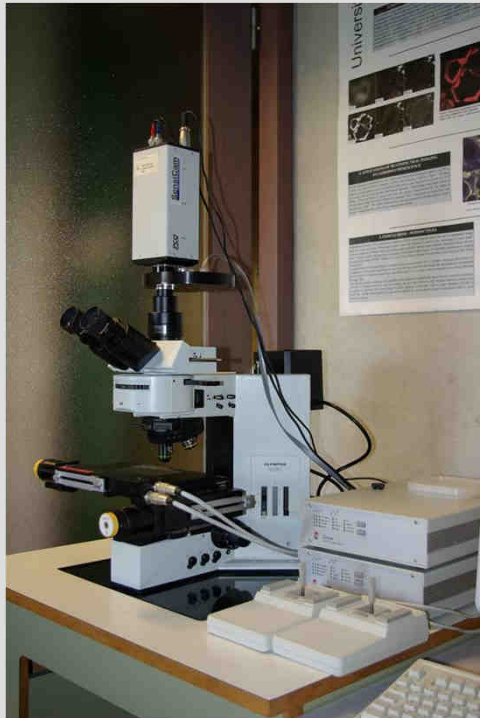
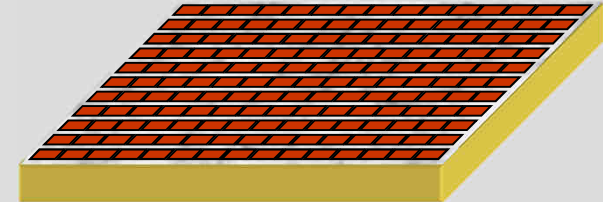
Diffuse reflectance imaging



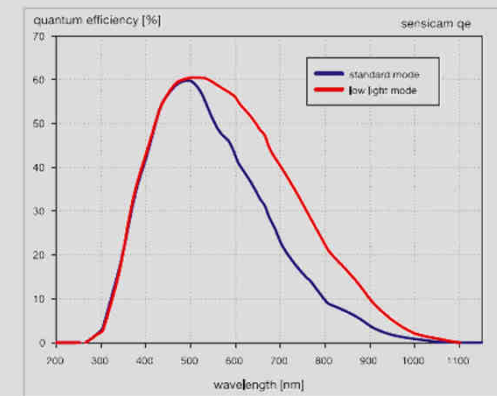
Specular reflectance imaging

Automated Mineral Mapping

- Array imaging mode
 - CCD/CMOS camera



Reflected Light Microscopy



Typical Quantum Efficiency
for an Si-detector

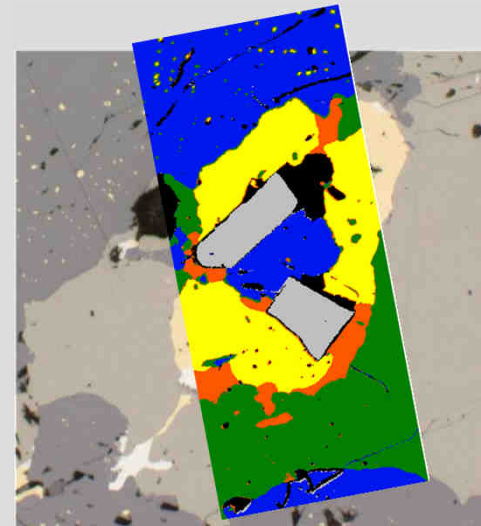


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Photonic Ore Microscopy

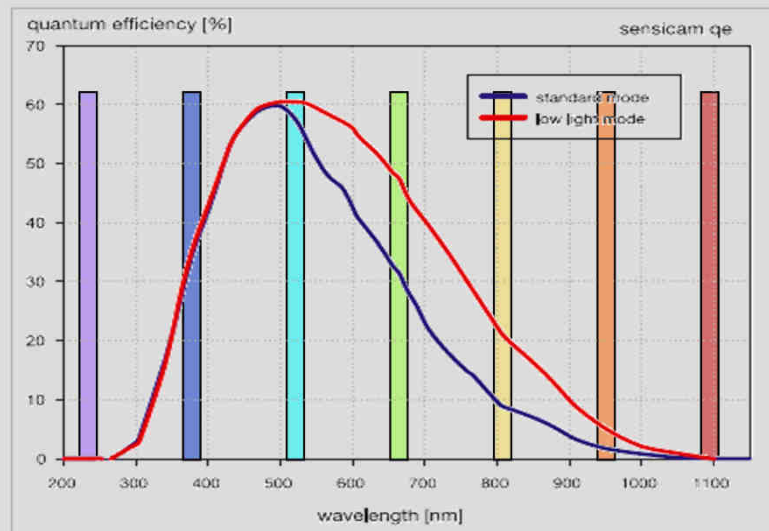
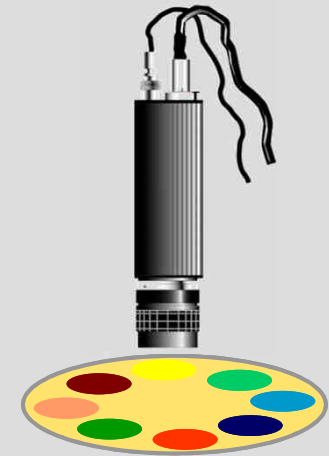
- Photons
- Filters
- Reflectance database



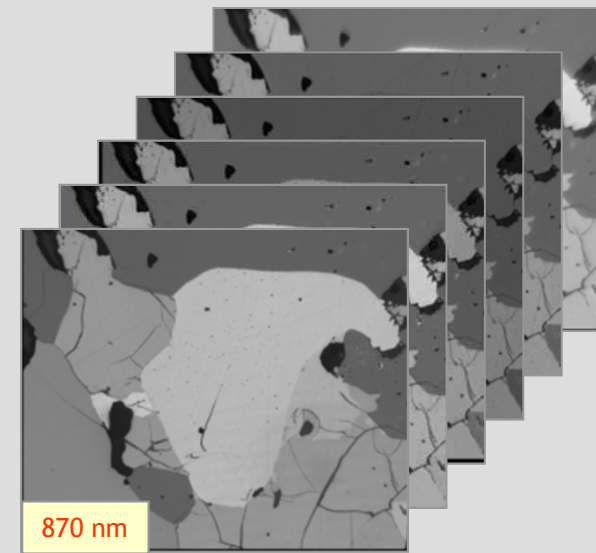
EMC2012
Frankfurt

Photonic Ore Microscopy

- MultiSpectral Imaging
 - Conventional Ore Microscope
 - » Objective transmittance >50% @ 1100nm
 - Scientific grade CCD camera
 - » Spectral sensitivity 350nm-1000nm
 - Filter wheel
 - » Interference filters @ 50 nm spacing



Typical Quantum Efficiency Curve for an Si-detector



Multispectral Image

Photonic Ore Microscopy

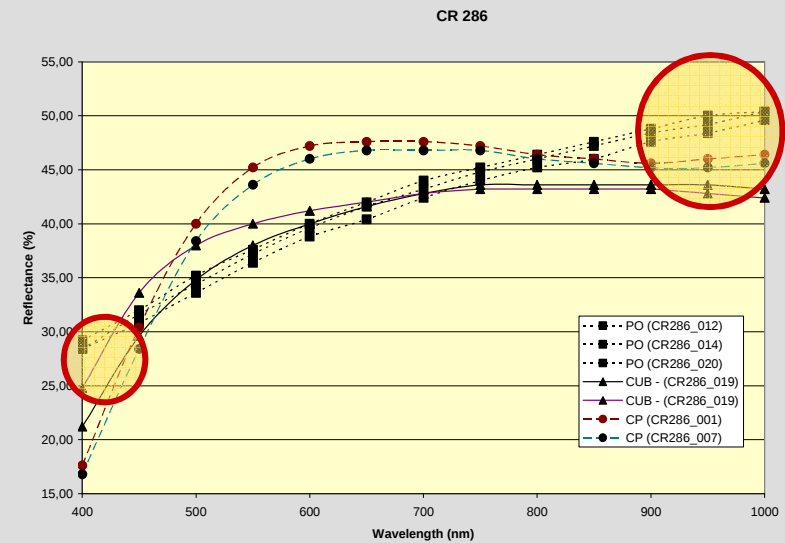
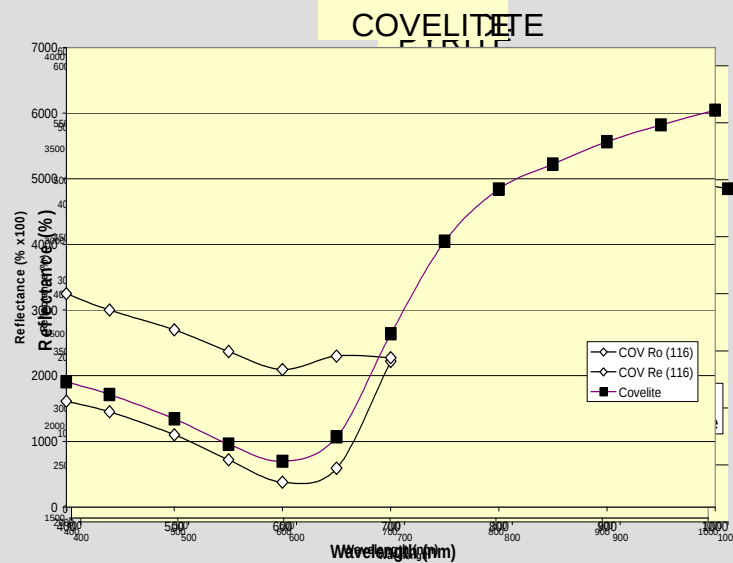
- MultiSpectral Imaging

- Calibration

- » Correction for uneven illumination
 - » Measure of reflectance standard

- Correlation with Specular Reflectance Database

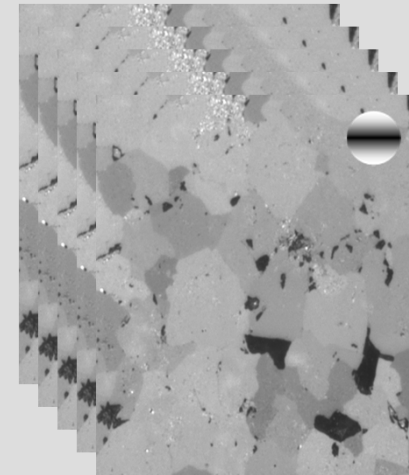
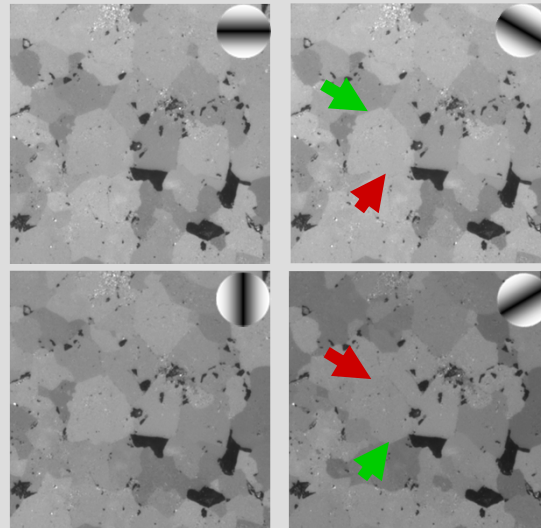
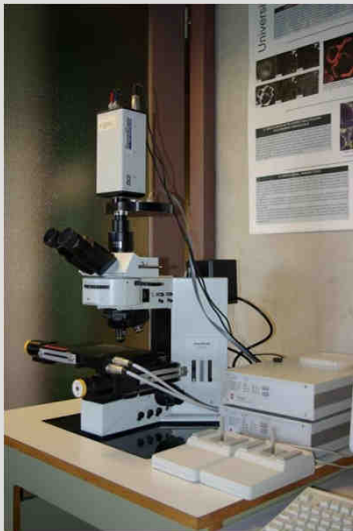
- » Quantitative Data File - QDFIII (Criddle & Stanley, 1993)
 - » Extension to 1000 nm (Brea et al., IMA, 2010)



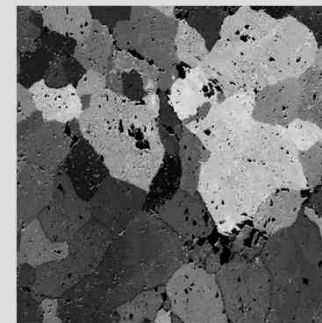
Enhanced Pyrrhotite-Cubanite discrimination

Photonic Ore Microscopy

- MultiRadial Imaging
 - Rotating incident polarizer
 - » “Information” about crystal anisotropy



Multiradial Image



“Bireflectance” Image

$$B = \text{Max}\{P_{x,y}^{\theta}\} - \text{min}\{P_{x,y}^{\theta}\}$$



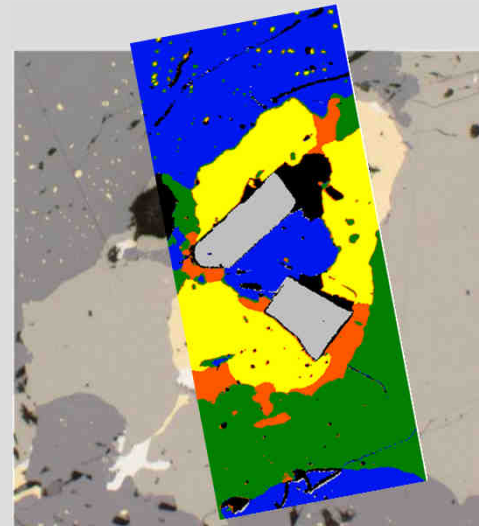
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Applications

- Epithermal Cu-Au
- Stratiform Cu
- Carbonate rocks

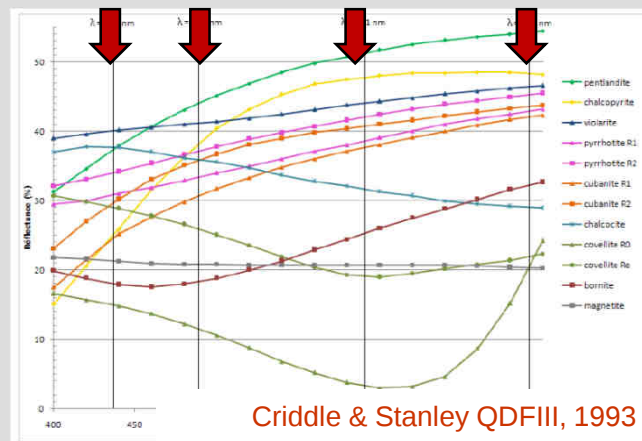
EMC2012
Frankfurt



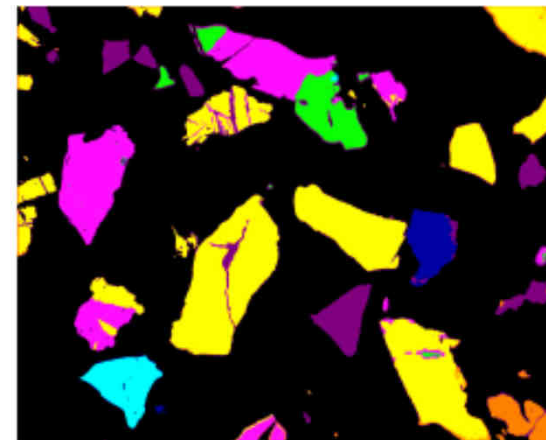
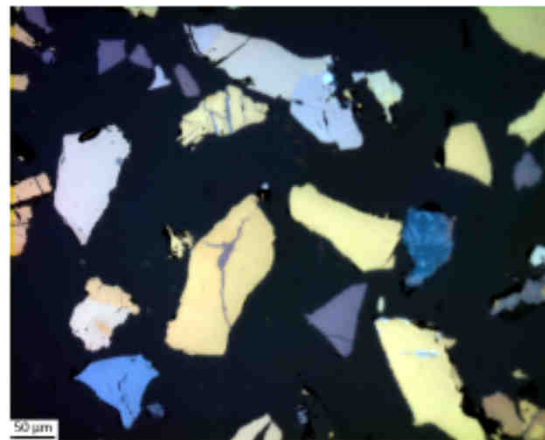
Wavelength Selection

- Phalaborwa : Cu-Ni Sulphides

» @ 437nm; 489nm; 591nm; 692nm (10nm FWHM)



Pentlandite
Chalcopyrite
Violarite
Pyrrhotite
Cubanite
Chalcocite
Covellite
Bornite
Magnetite



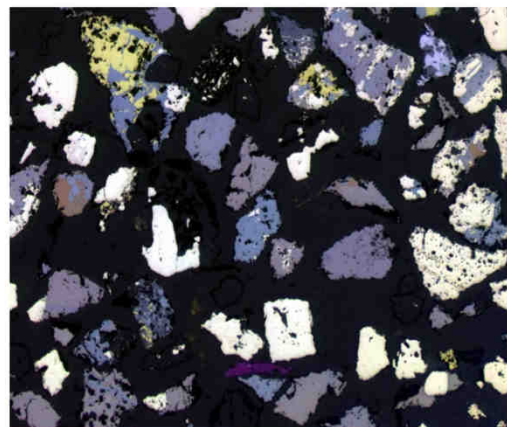
■ Résine
■ Bornite
■ Chalcopyrite+Bornite
■ Chalcopyrite
■ Magnétite
■ Violarite
■ Pyrrhotite
■ Cubanite
■ Chalcocite
■ Pentlandite
■ Covellite

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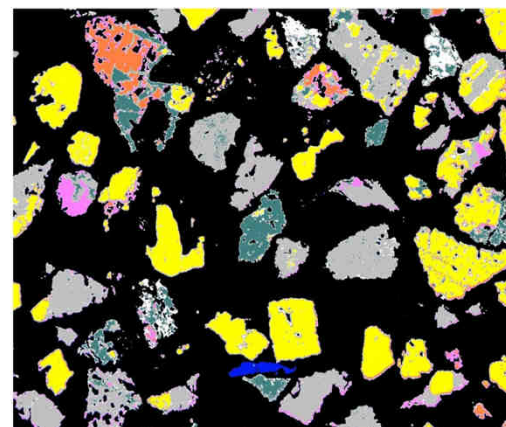
Califice A., 2008

- Chelopech : Epithermal Cu-Au Paragenesis

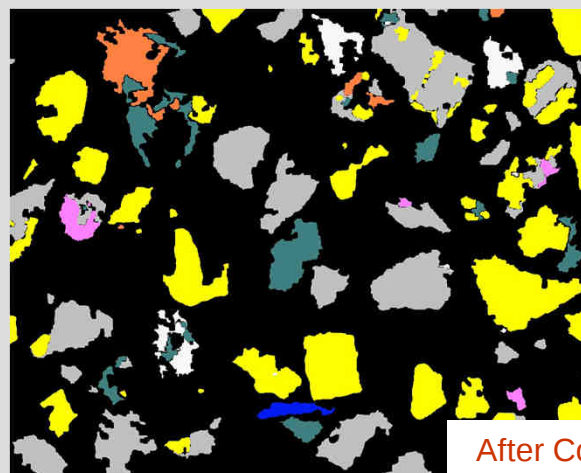
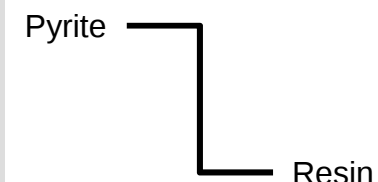
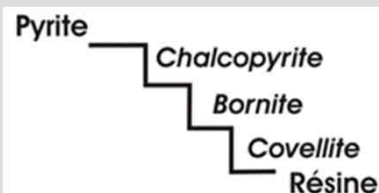
False Colour Image



Maximum Likelihood Classification

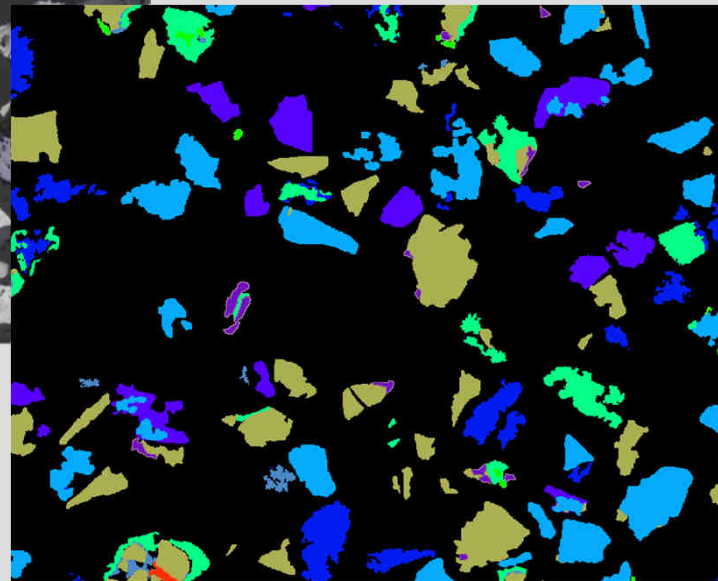


- Pyrite
- Résine+gangue
- Covellite
- Enargite
- Chalcopryrite
- Galène
- Tennantite
- Bornite



After Conditional Geodesic Propagation

-
- Figure 1 is a line graph showing the evolution of the relative concentration of various minerals in the solid phase of a magmatic-hydrothermal system as a function of temperature. The x-axis represents temperature in degrees Celsius (400 to 1000), and the y-axis represents relative concentration in percent (0.0 to 100.0). The minerals tracked are Chalcocite, Chalcopyrite, Covellite, Cuivre natif, Cuprite, Digenite, Goethite, Hematite, Malachite, and Pyrite. Pyrite concentration increases sharply from 400°C to 600°C and then plateaus near 90%. Chalcocite and Chalcopyrite concentrations decrease as temperature increases. Malachite and Covellite concentrations increase significantly above 600°C.
- | Température (°C) | Chalcocite | Chalcopyrite | Covellite | Cuivre natif | Cuprite | Digenite | Goethite | Hematite | Malachite | Pyrite |
|------------------|------------|--------------|-----------|--------------|---------|----------|----------|----------|-----------|--------|
| 400 | 35 | 15 | 10 | 40 | 25 | 28 | 22 | 15 | 10 | 40 |
| 500 | 30 | 35 | 15 | 45 | 22 | 25 | 20 | 18 | 10 | 50 |
| 600 | 28 | 45 | 10 | 50 | 20 | 22 | 18 | 15 | 10 | 80 |
| 700 | 25 | 45 | 10 | 50 | 18 | 20 | 15 | 12 | 10 | 90 |
| 800 | 22 | 42 | 35 | 48 | 15 | 18 | 12 | 10 | 35 | 90 |
| 900 | 20 | 40 | 45 | 45 | 12 | 15 | 10 | 8 | 45 | 90 |
| 1000 | 18 | 38 | 48 | 42 | 10 | 12 | 8 | 5 | 48 | 90 |

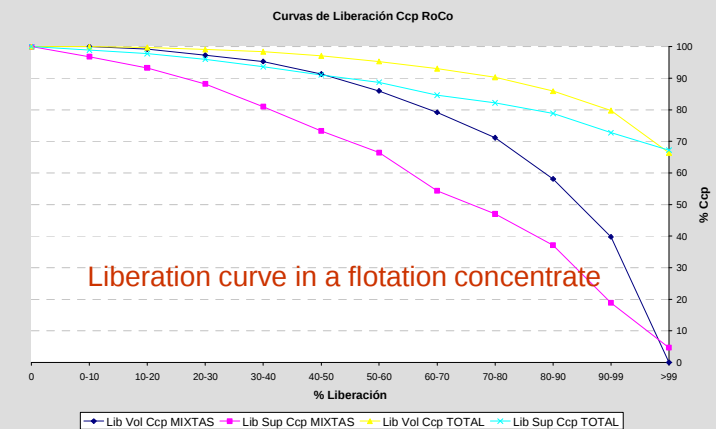
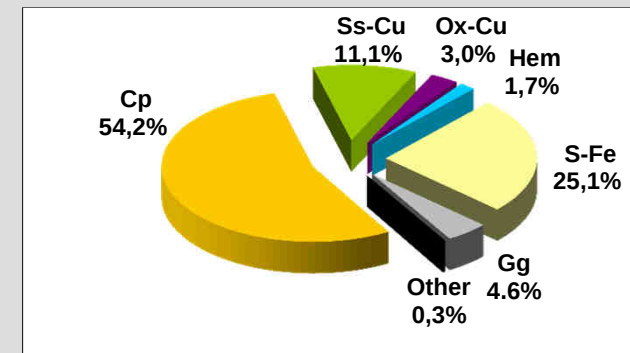
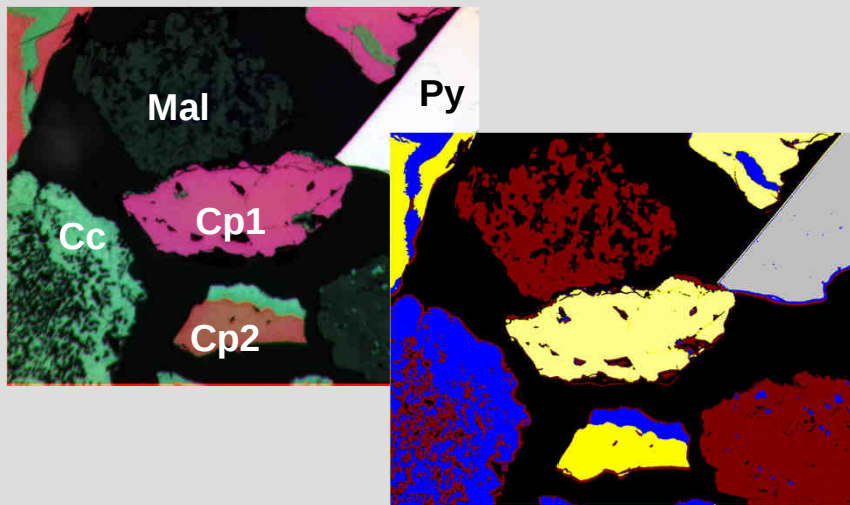


Chalcopyrite (A)
Chalcopyrite (B)
Copper
Cuprite
Digenite
Malachite
Chalcocite
Rutile
Molybdenite
Pyrite

Siebels K., 2012

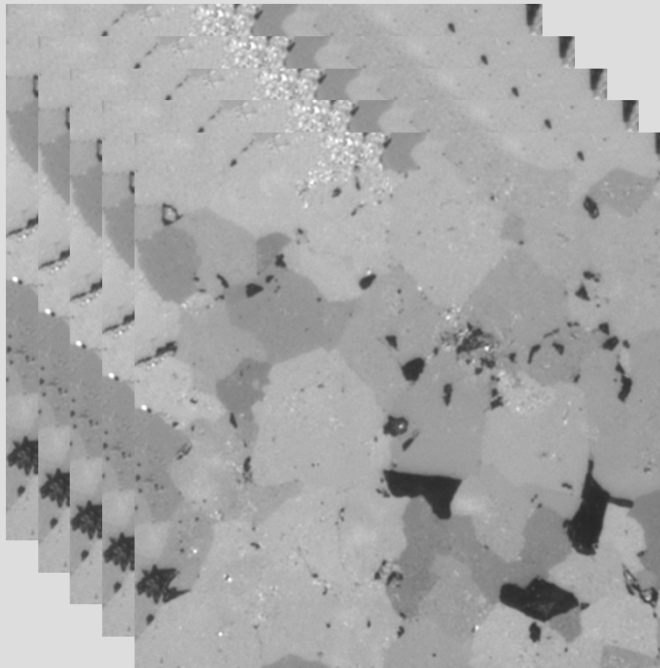
Modal Analysis

- Kansanshi : Stratiform Cu
 - Supergene (mixed) zone
 - » Secondary Cu sulphides,
 - » Malachite,...



Microstructure Analysis

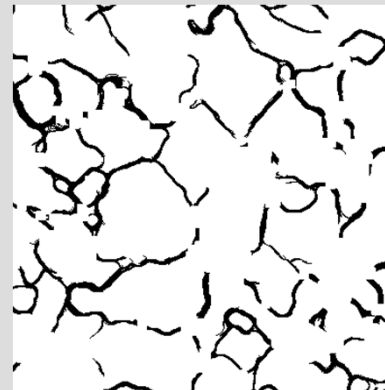
- Carbonate Rock



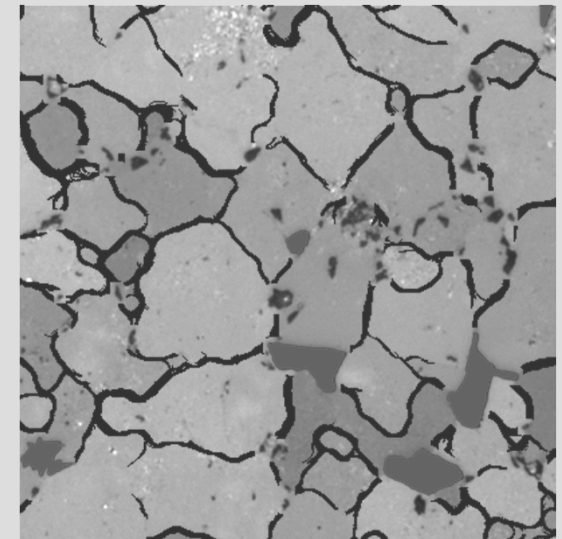
Multiradial Image



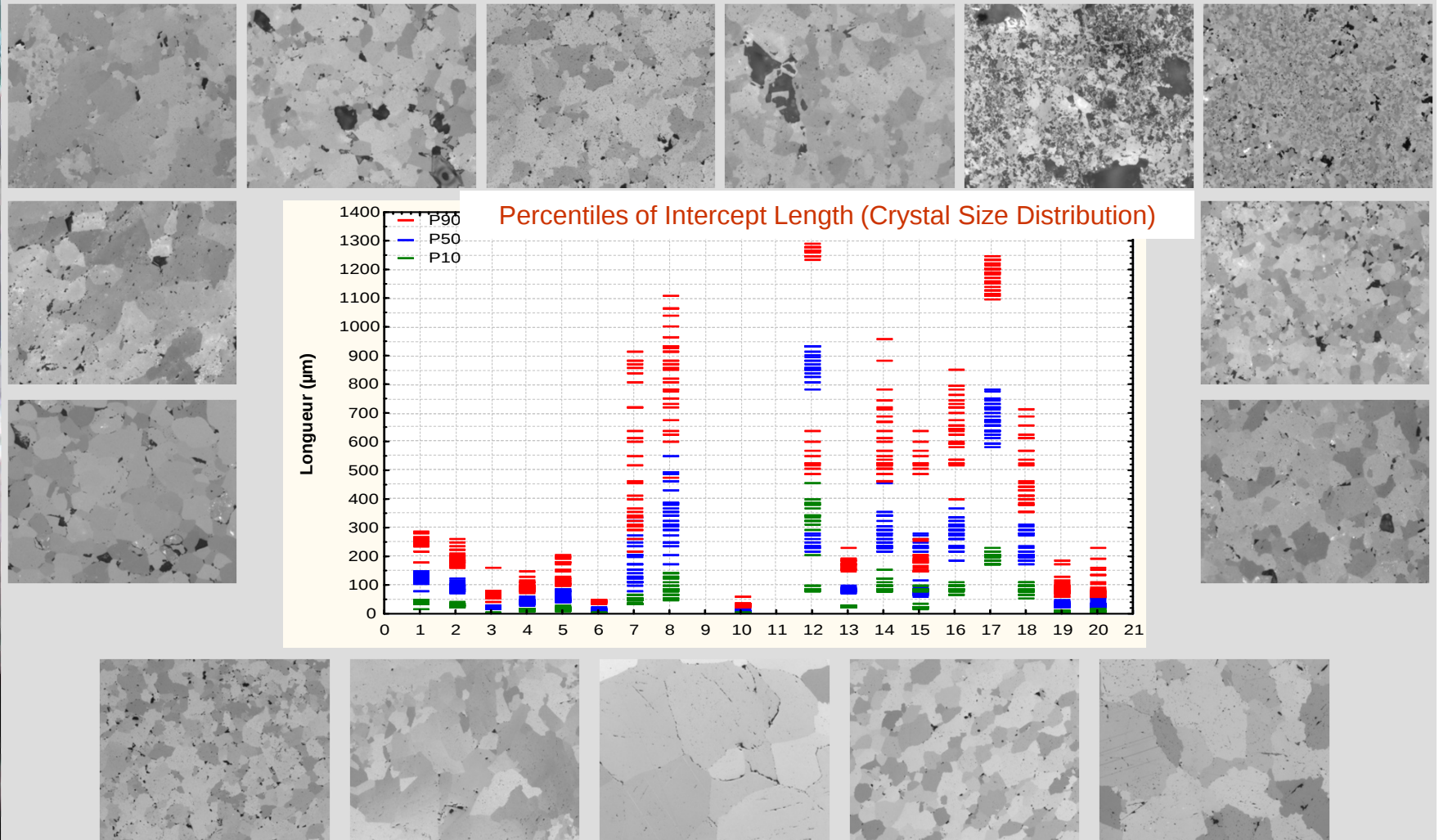
Porosity

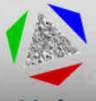


Grain Boundaries (gradient)



- Carbonate Rock



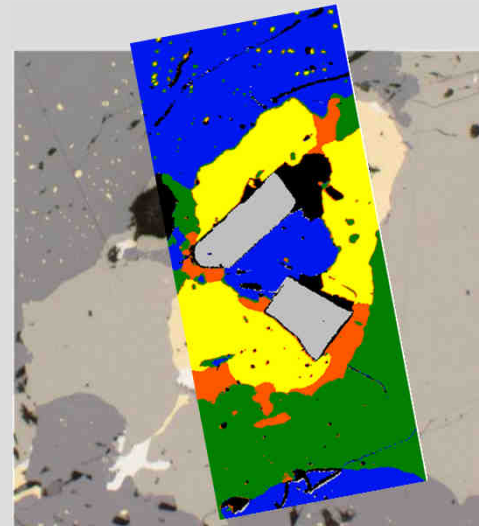


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Accuracy & Limitations

- Visual check
- Chemistry, XRD
- Comparison with SEM
- Round Robin



Accuracy & Limitations

- Validation

- Visual

- » Point counting; Time Consuming; Subjective;...

- Chemistry

- » Balance; Limited mineralogy; ...

- XRD

- » Major minerals;...

- Round Robin Test

- » Interlaboratory test on « similar samples »

- » Detailed statistics of inter/intra variability

- » Initiative of IMA-CAM

Accuracy & Limitations

- Comparison with Automated EM-based Mineralogy

- QEM-SCAN/MLA

- High resolution (PGE, Au)
 - Non-stoichiometric minerals (Lcx)
 - Trace / Precious elements partitioning
 - Gangue mineralogy
 - Process mineralogy oriented software

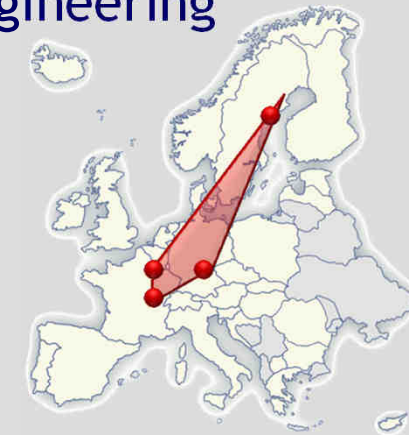
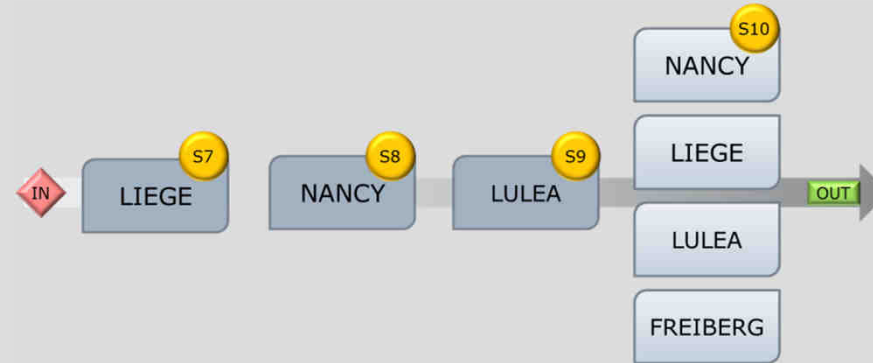
- Optics

- Cheap technology
 - Fast imaging
 - Large samples (*do more less well!*)
 - Good discrimination in some critical ores
 - » Iron oxide; Ni-Cu sulfides; ...
 - Multiradial imaging
 - » Grain size analysis
 - » Crystal orientation (*EBSD for the poorest*)



EMERALD Erasmus Mundus

- European Master Degree in Georesources Engineering



- Innovative education in « Geometallurgy »
 - » Mineral Resources Characterization - Processing - Modelling - Management

- Worldwide network of associated universities

» Moscow, Queensland, Capetown, Hacceteppe, Minas Gerais, UChile, Kazakhstan,...



- Supported by major mining companies

Application Deadline
31 Dec 2012
gemme@ulg.ac.be