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GeMMe Resourceful Engineers

Towards Automated Mineralogy 4.0

Eric Pirard, Hassan Bouzahzah

ZEISS MINERALOGIC - 1st User's Meeting


WELCOME
ZEISS Mineralogic Users Meeting
All Roads Lead to Liege – ESA / NASA NightPod - 8 Déc 2012

Resourceful Engineers

GeMMe

- 30+ Research Staff
- 3 M€ annual turnover
  - *40% industrial partners*

- *Resource*
  - Particular attention given to **MINERAL** and **METALLIC RESOURCES**
  - Interest for both **MINING** and **URBAN MINING**
- *Efficiency*
  - Contribute to developing a more **CIRCULAR ECONOMY**
  - Privilege a **HOLISTIC** approach of the material cycle
  - Put engineering to the service of a more **SUSTAINABLE** societal project
- *Engineering*
  - Contribute to the **EDUCATION** of creative and open-minded engineers
  - Be a source of **TECHNOLOGICAL INNOVATION** for increased recovery of valuable metals

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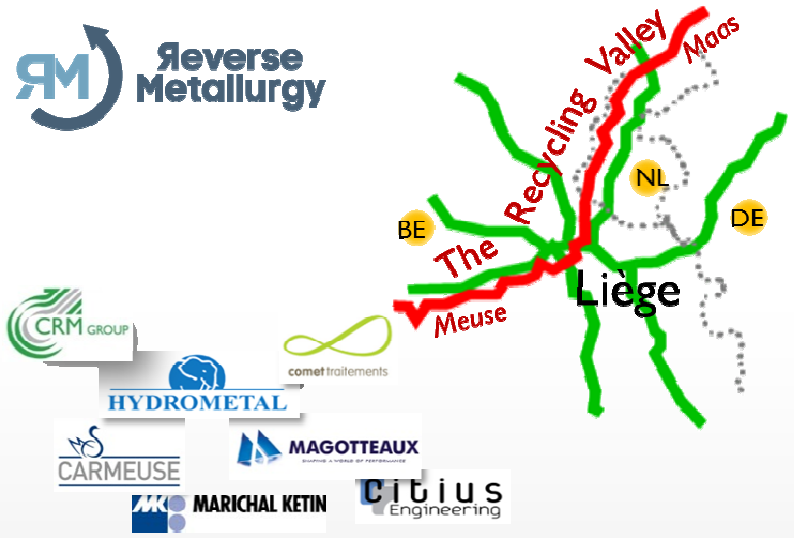
Knowledge Innovation Communities

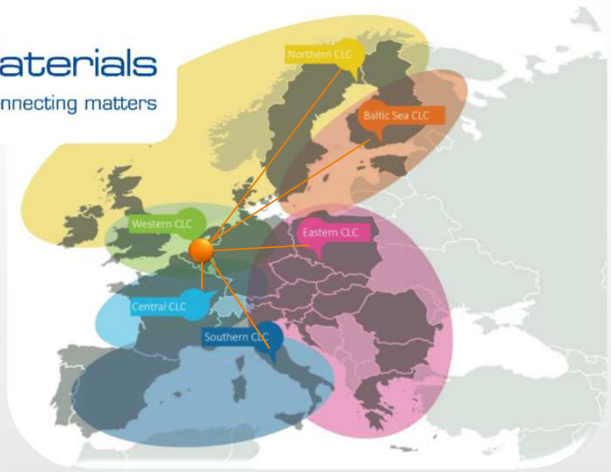
GeMMe

- Core-Partner of
  - Reverse Metallurgy (61 M€/5yrs)
    - Walloon Region
  - EIT Raw Materials (3 G€/7yrs)
    - Europe

Reverse Metallurgy



eit RawMaterials
Connecting matters



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EDUCATION

Education

PhD SUMMER SCHOOL

Entrepreneurship and Circular Economy

LIFELONG LEARNING EDUCATION

Geometallurgy
Hydrometallurgy

MASTER IN GEORESOURCES ENGINEERING

Innovative Education in Geometallurgy

EMERALD
ERASMUS MUNDUS MASTER IN GEORESOURCES ENGINEERING

WIDER SOCIETY LEARNING

Raw materials in my cellphone

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RESEARCH

Research

SMART SORTING

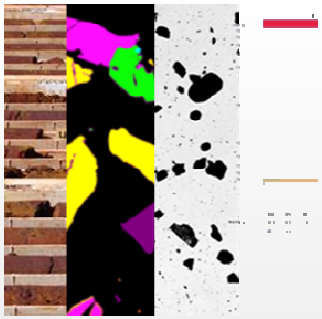
Advanced 3D imaging and hyperspectral sorting

PHYSICAL PRE-PROCESSING

Energy-Efficient fragmentation and conditioning

GEOMETALLURGICAL CHARACTERIZATION

Process oriented "mineralogical" mapping



BIO - HYDROMETALLURGY

Resource efficient processes for end-of-life goods

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User's Meeting

- Share good practices
- Suggest recommendations for improvements
- Develop cross-validation
- …

Ceci n'est pas un pixel

Microscopical Information System

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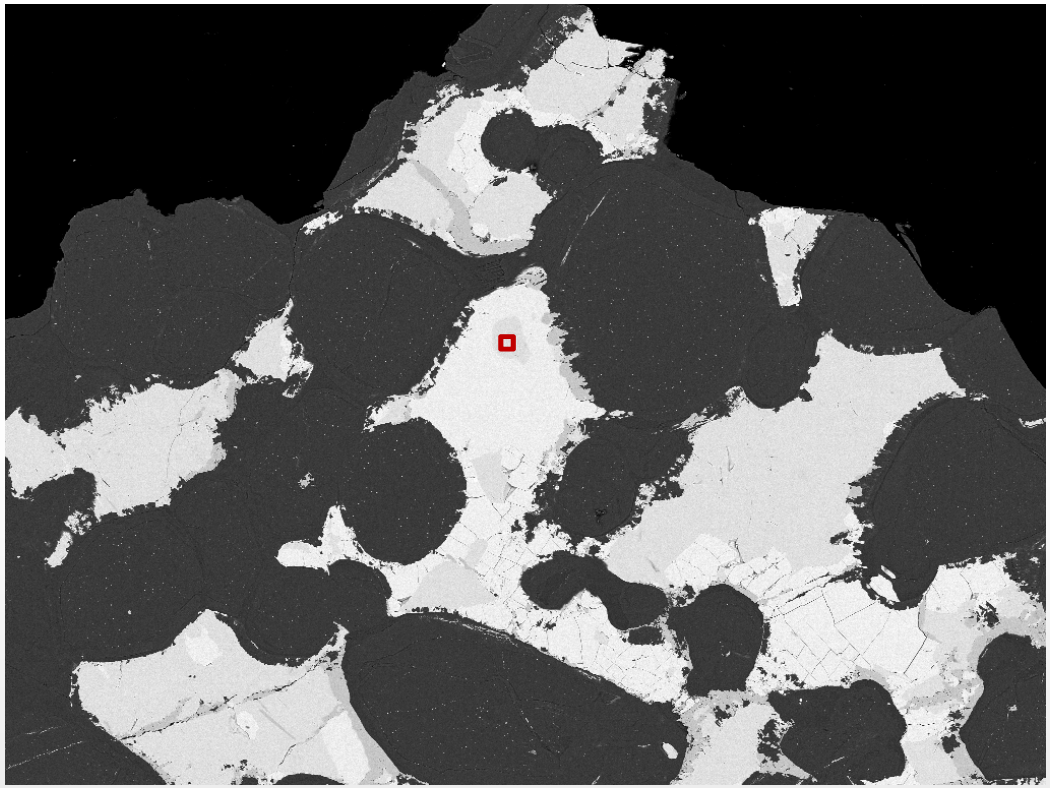
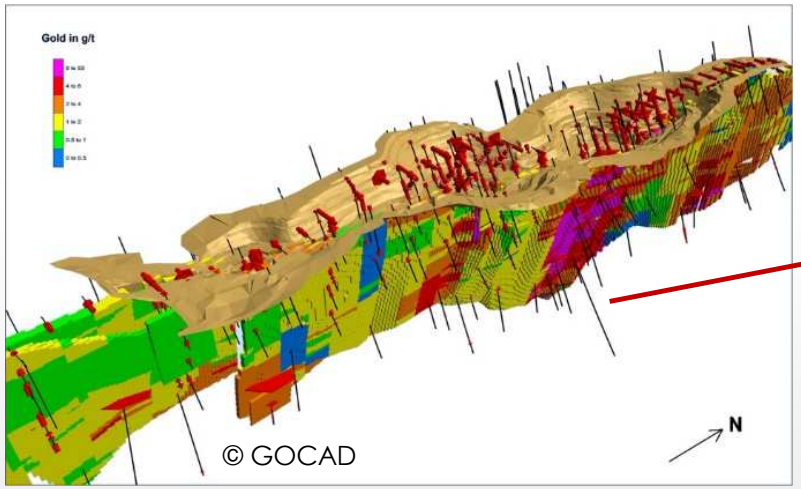
Belgian Surrealism ?

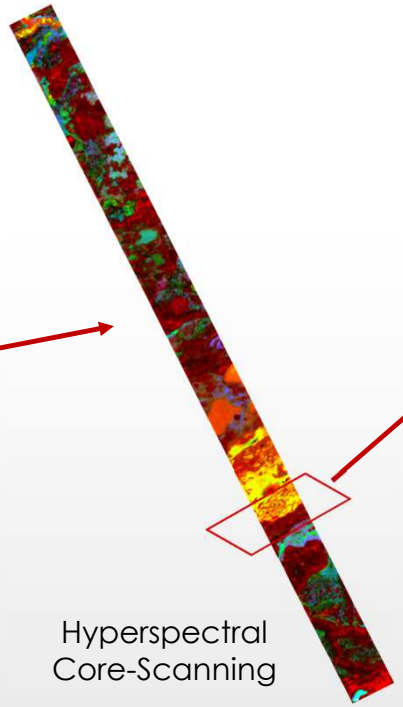


BackScatteredElectrons Image - Raglan (CAN)

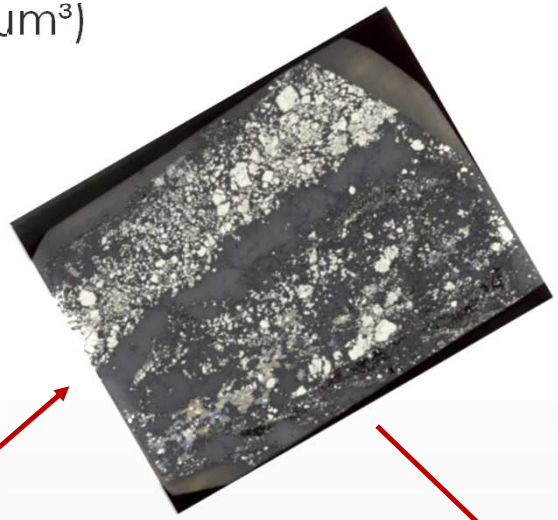
Roxels

- ROXELS are digital twins of orebody elemental volumes (ex. 1 µm³)





Hyperspectral
Core-Scanning



MultiModal
Microscopic Imaging

ROXEL

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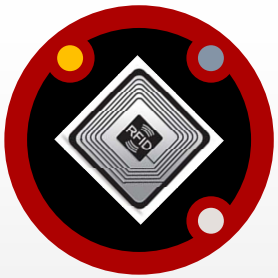
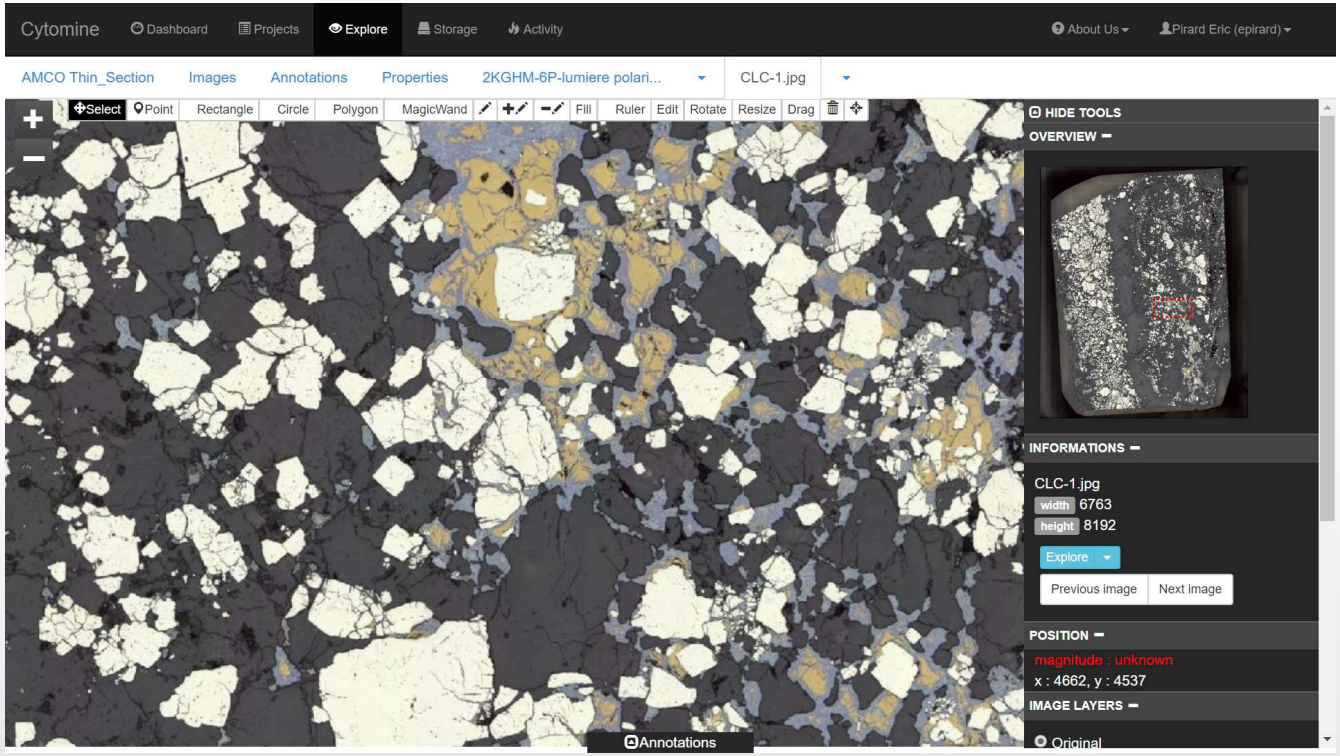
Microscopical Information System

- Deposit(Name type,…)
  - Drill Core (ex. DH1343 Lat/Long/Dip/Azimut/…)
    - Log / Plug (ex. depth/length/…)
      - ✓ Rock_Class (ex. litho type)
        - » *Rock_Compo (ex. modal analysis)*



Polished Block
RFID / metadata
3 point referencing system



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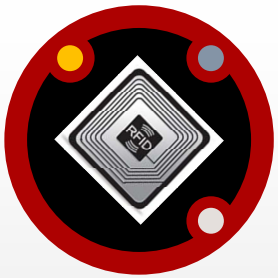
Microscopical Information System

- From roxel to plant
  - ID_Client ID, ID_Plant
  - ID_Time_YY/MM/DD_HH/MM/SS
  - ID_Unit Process
  - ID_In/Out (Conc/Middlings/Tail)
  - ID_Size Fraction
  - ID_Indic_Mineralogy
  - …



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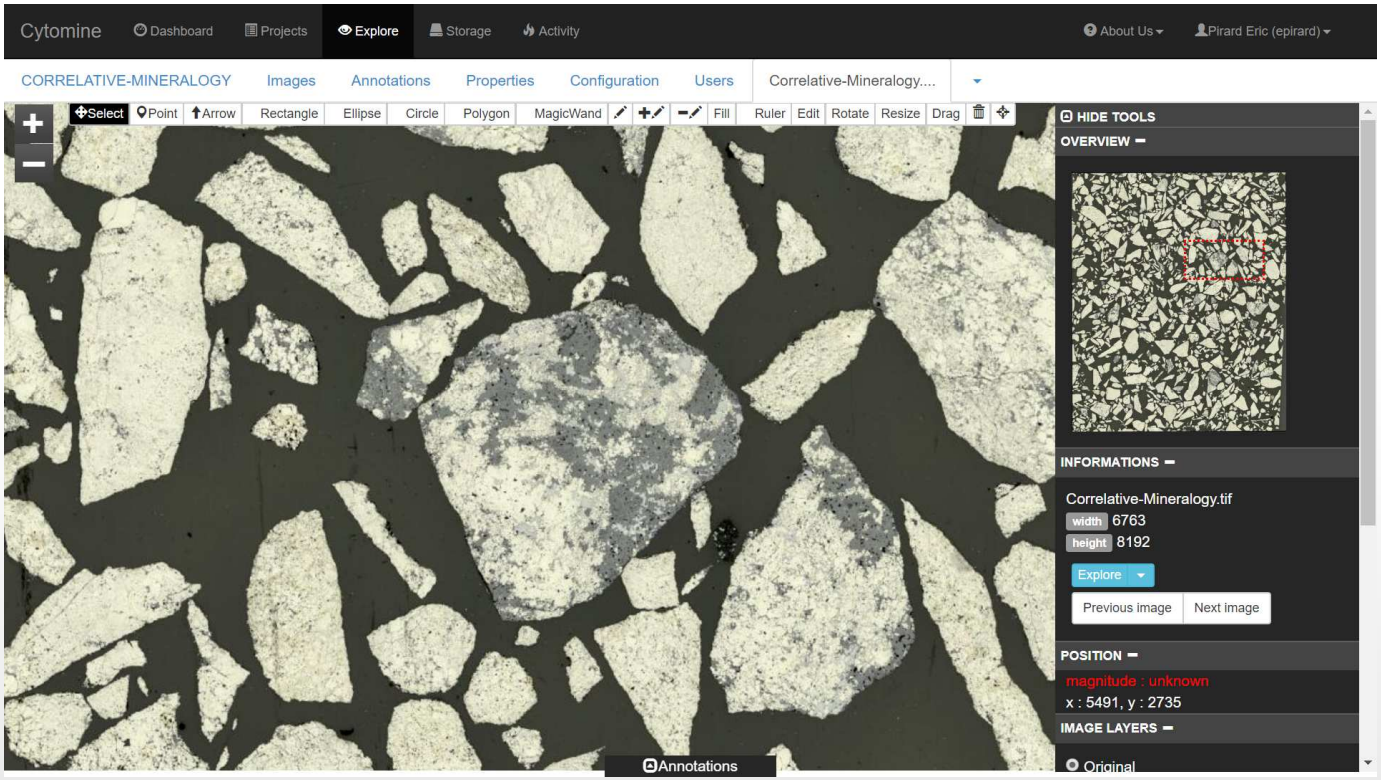

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Sampling & Sample Preparation

Do More Less Well

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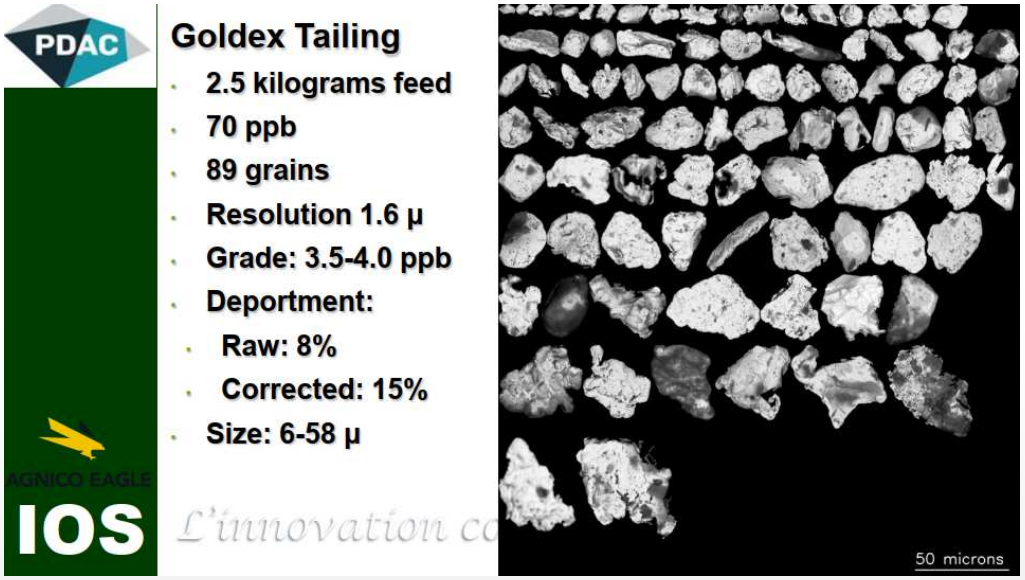
Sample Preparation

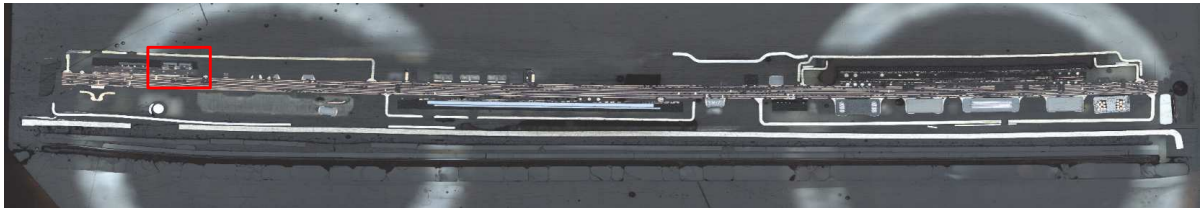
- Subsampling
  - PreConcentration
  - Sieving



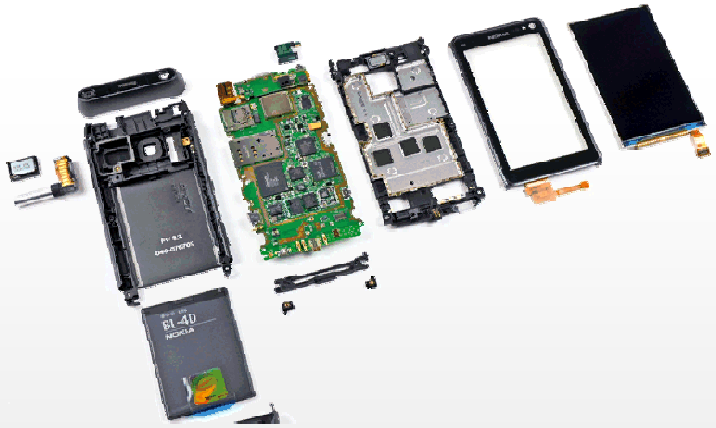
IOS Geoscientifique, R Girard et al., PDAC 2019
Gold deportment in Goldex mine tailings

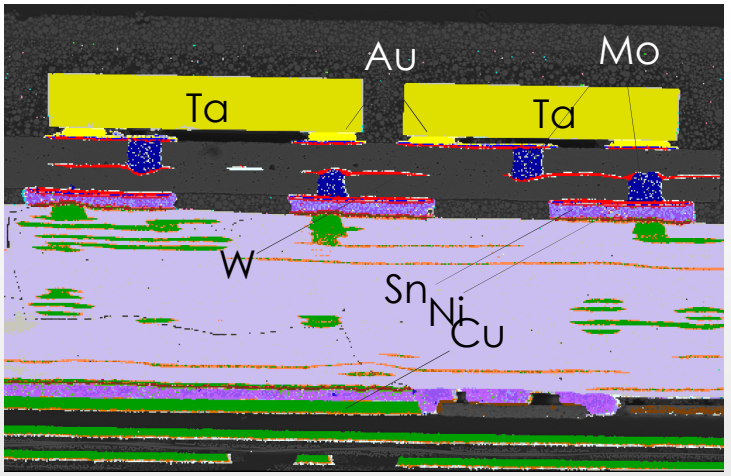
Sample Preparation

- Subsampling
  - PreConcentration
  - Sieving



Reynders et al., Hight-Tech Metals, Cape Town, 2019





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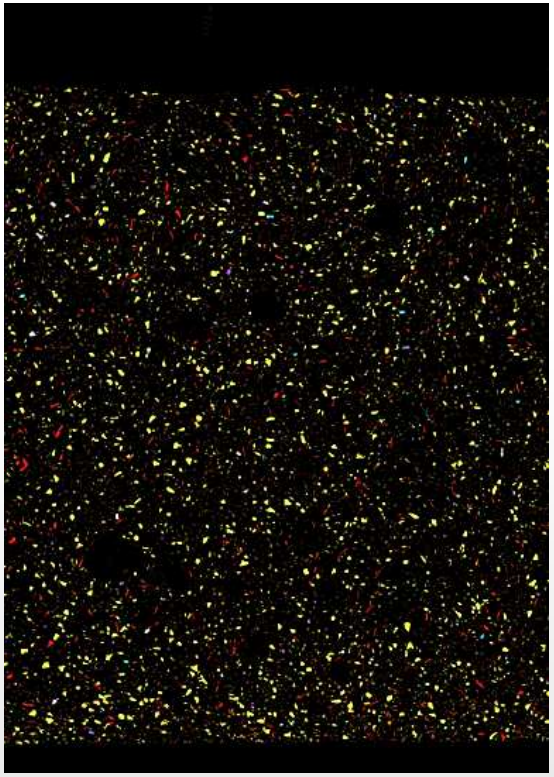
Sample Preparation

- Random Sections
  - Avoid segregation / settling
  - Randomize orientations

Quartz / Molybdenite Mix

Vertical Section

Epoxy only



Epoxy + Carbon Black

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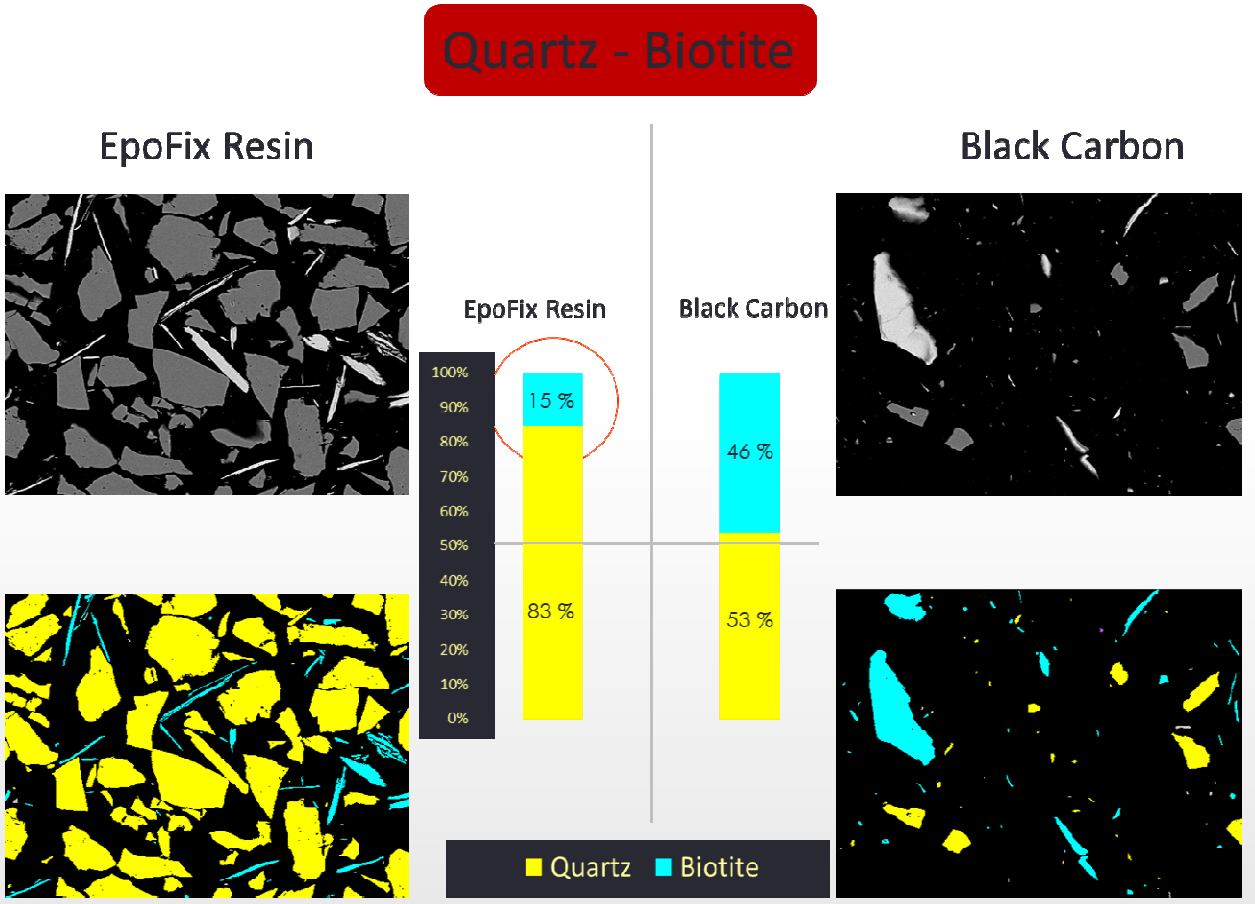
Sample Preparation

- Random Sections
  - Avoid segregation / settling
  - Randomize orientations

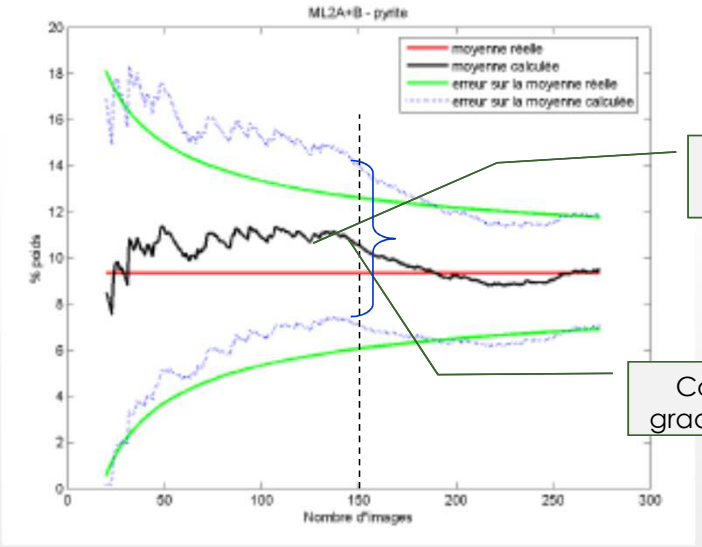


Sample Preparation

- Digital Sampling
  - Gy's stopping criterion
    - Mass (nb particles) to analyze for a given accuracy

$$\sigma_F^2 = \frac{C'.d_{95}^2}{S_E}$$

Pyrite	ML1	ML2	ML3
a_L	0,013295477	0,017914474	0,02573908
$\rho_G(g/cm^3)$	3,03	3,04	3,35
$\rho_A(g/cm^3)$	5	5	5
c	369,12	272,18	187,65
l	1	1	1
f	0,484	0,484	0,484
$d_{95}(\mu m)$	231	231	231
$d_5(\mu m)$	2,28	2,28	2,28
g	0,075	0,075	0,075
C	13,40	9,88	6,81
N_{images}	243	275	270
$S_e(cm^2)$	0,299	0,338	0,332
σ_r	0,11378268	0,091845044	0,07696427
σ	0,001512795	0,001645356	0,00198099



Average pyrite grade after analysing 150 images

Confidence Interval for pyrite grade after analysing 150 images

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The Orebody's DNA

Geometallurgy: what we need

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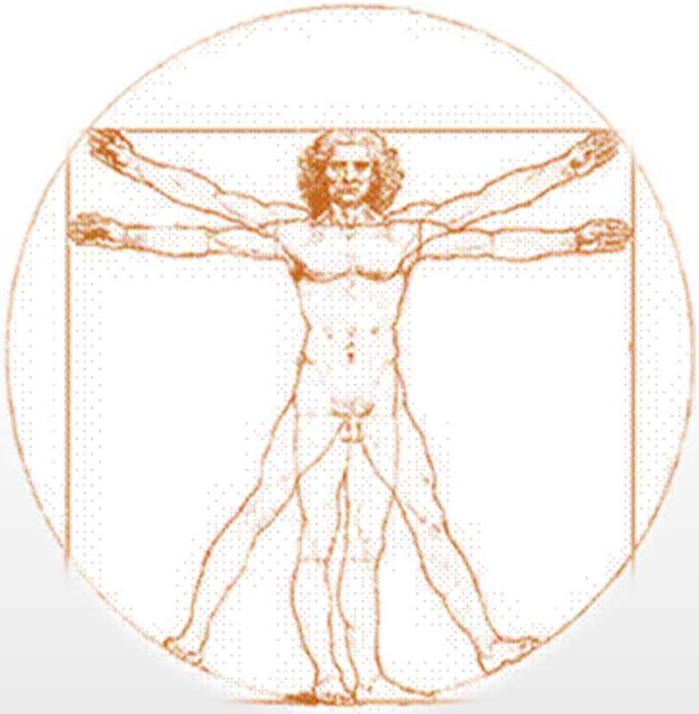
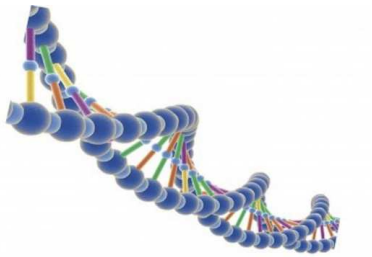
Our body

- What is this ?
  - O 65 %
  - C 18 %
  - H 10 %
  - N 3 %
  - Ca 1,4 %
  - P 1,1 %



Our body

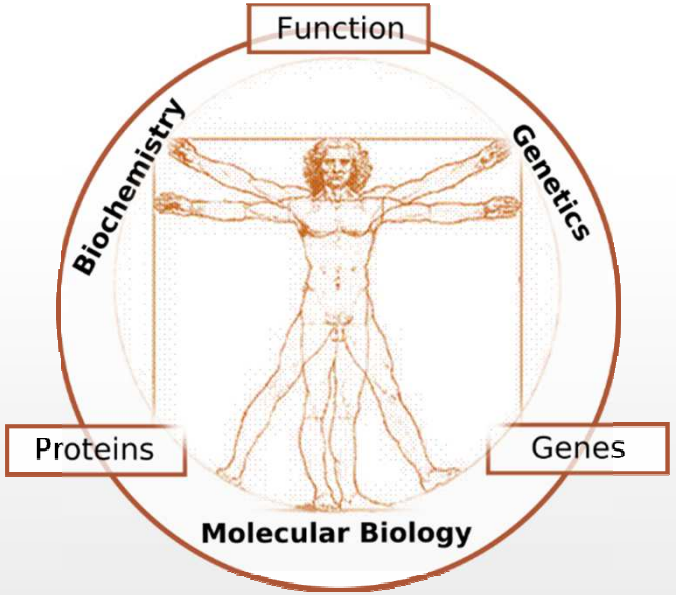
- The molecular base (nucleotides) of our DNA
  - Adenine $C_5H_5N_5$
  - Thymine $C_5H_6N_2O_2$
  - Cytosine $C_4H_5N_3O$
  - Guamine $C_5H_5N_5O$



MOLECULAR BIOLOGY
...not so much a technique as an approach

… with the leading idea of searching below the large-scale manifestations of classical biology…

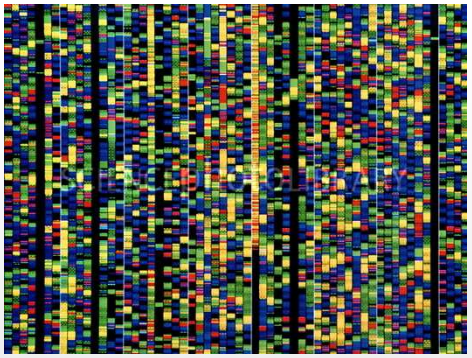
© Wikipedia

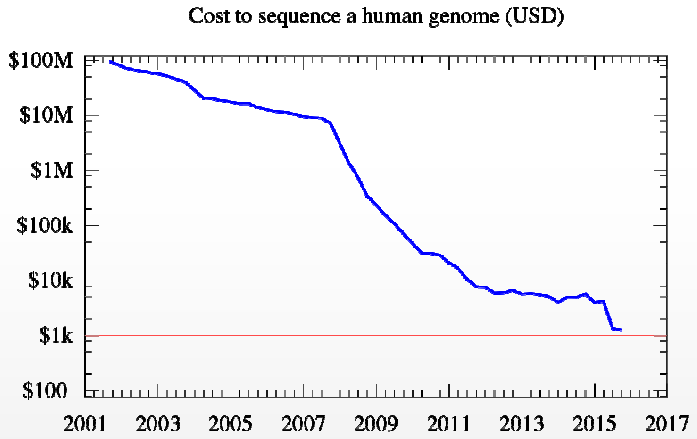


Our body

- The Human Genome
  - 22 000 genes
  - 3,4 billion pairs of nucleotides

DNA sequencing is the process of determining the precise order of nucleotides within a DNA molecule.

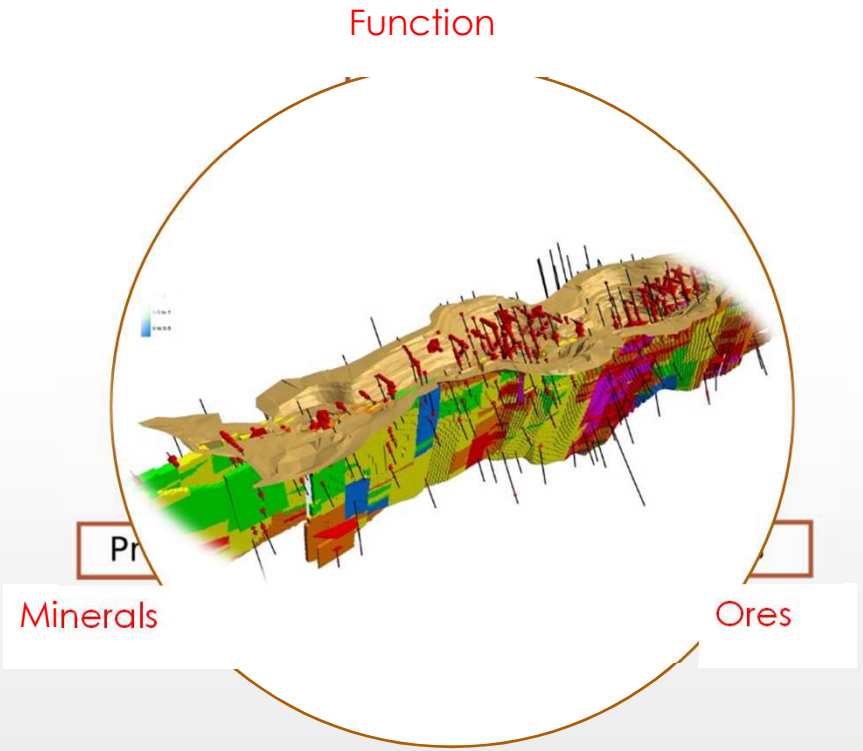




Total cost of sequencing a human genome over time as calculated by the NHGRI

Geometallurgy : what we need

- Molecular Geology
  - Fast and Accurate Mineral Identification
    - Valuable Minerals
    - Gangue Minerals
    - Elemental Deportment
- Sequencing Ores
  - Fully Automated Quantitative Analysis
    - Modal Analysis (% mass)
    - Porosity and fractures
    - Grain/Crystal size
    - Grain shape
    - Microtextures
- Predicting functionality
  - Process Oriented Modelling - Indices
    - ✓ Breakability, Floatability,…
    - ✓ Leachability, Thermal expansion,…



Molecular Geology

Mineral Mapping

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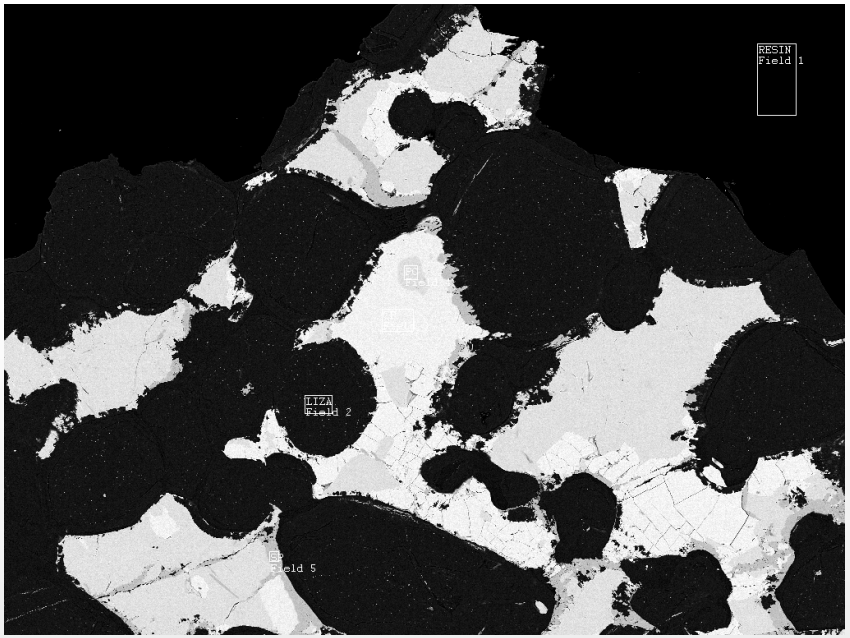
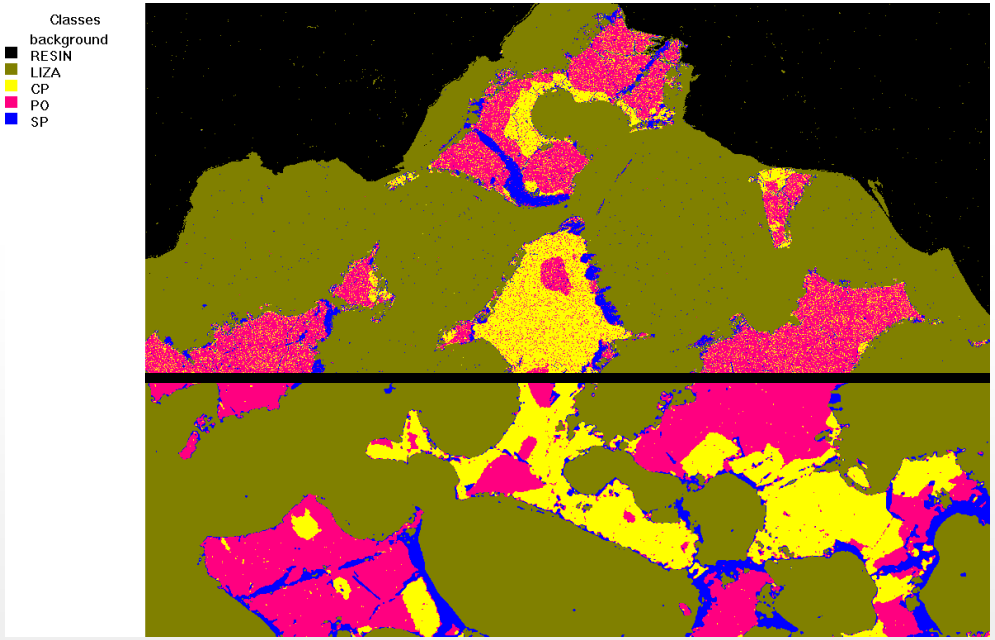
Mineral Mapping

e-beam

- Back Scattered Electron Imaging
  - Maximum Likelihood Classifier vs. Echo Spectral-Spatial





Pentlandite is merged with Chalcopyrite

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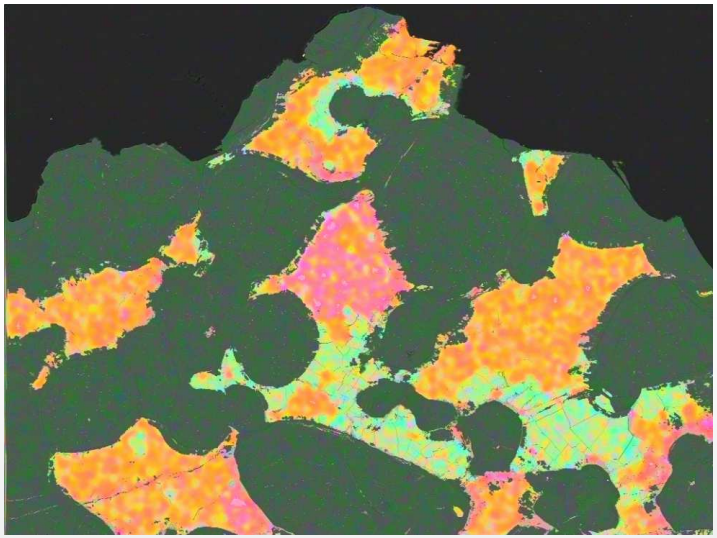
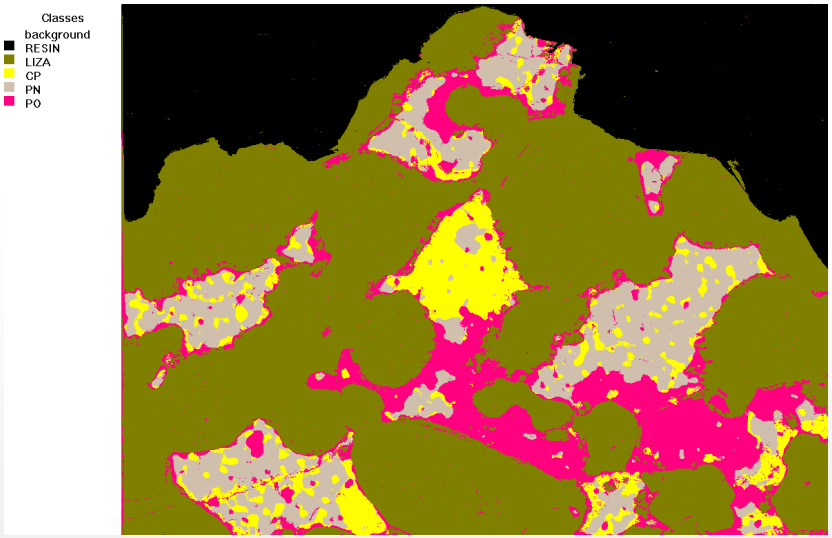
Mineral Mapping

e-beam

- EDX Mapping (fast)
  - 10 secs/image



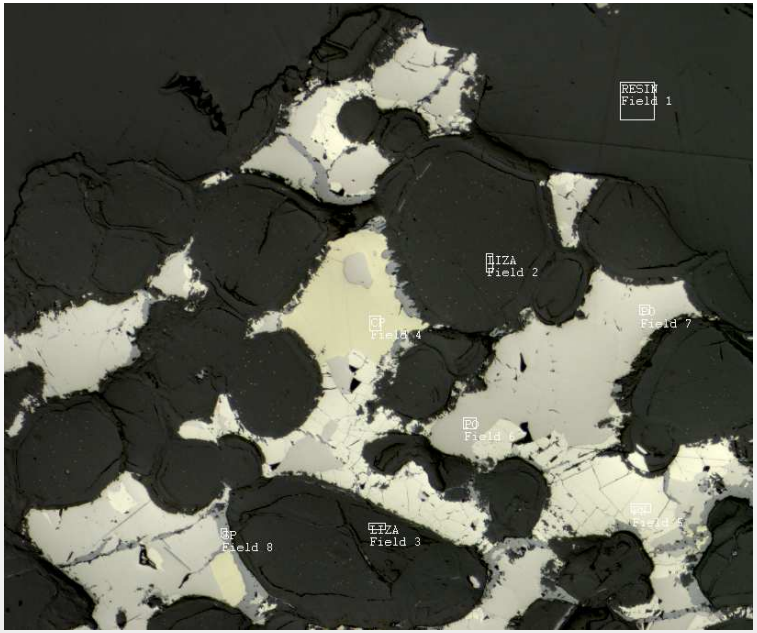


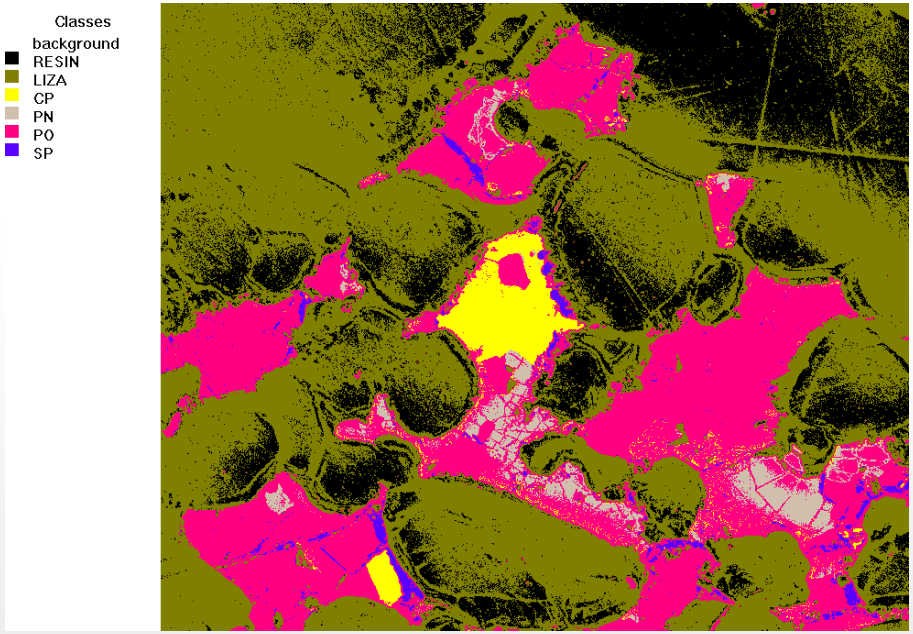
Noisy signals in Pyrrhotite bring confusion with Pentandite

Mineral Mapping

L-beam

- RGB Imaging (Axiocam)
  - Maximum Likelihood Classifier



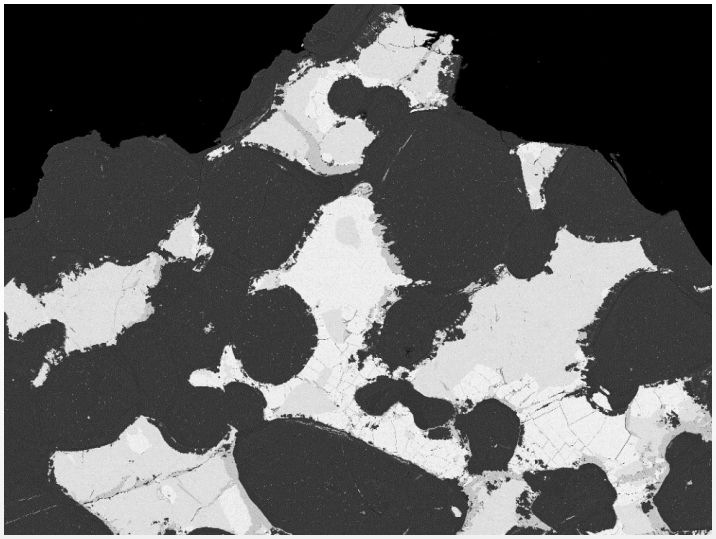
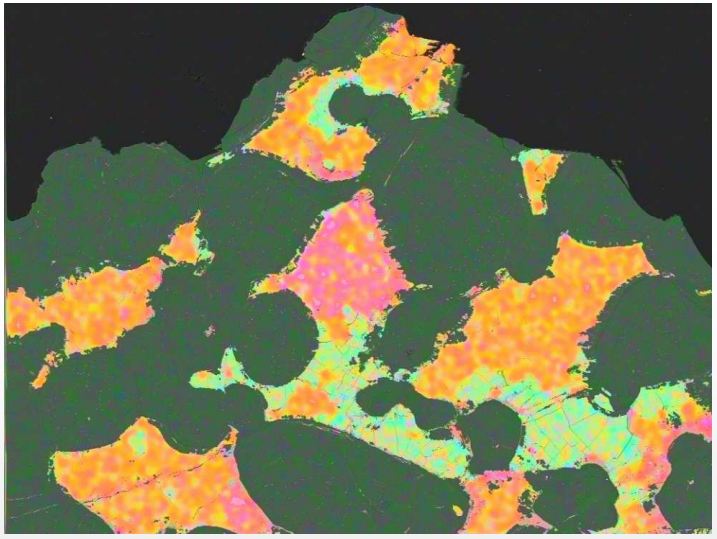
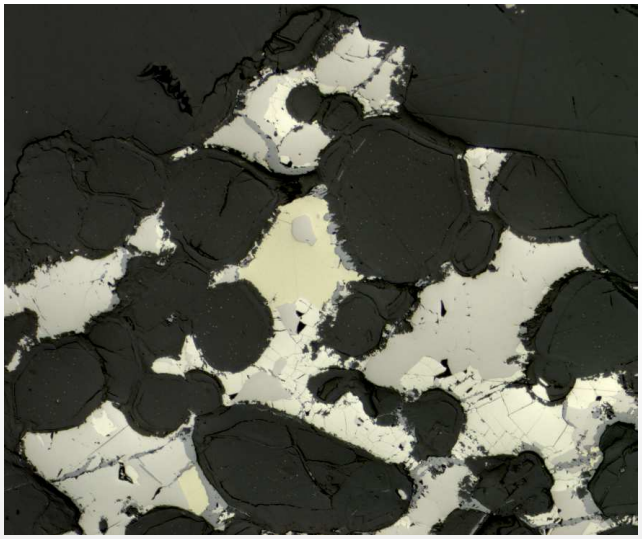


Pyrrhotite bireflectance brings confusion with Pentlandite
Resin and silicates are poorly discriminated

Mineral Mapping

Correlative Microscopy

- Combine Electronic (BSE-EDX) and Photonic (Multispectral)
  - Use advanced classification tools

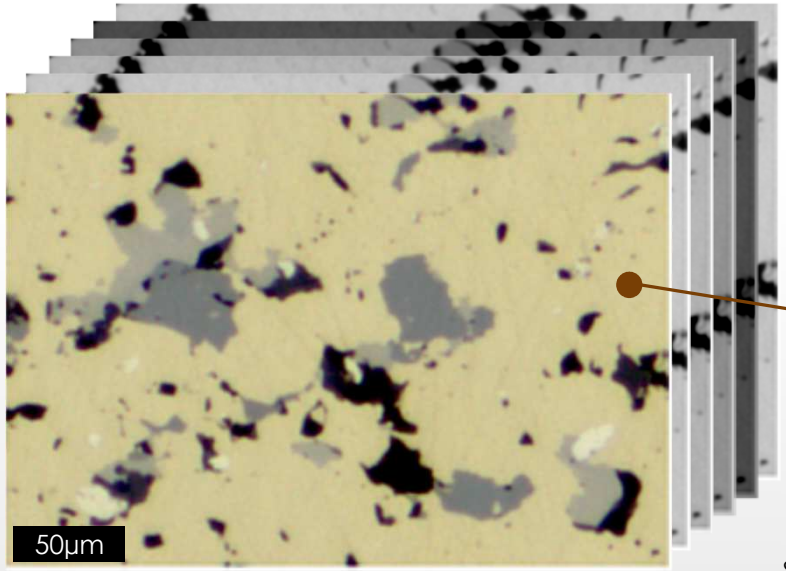




Mineral Mapping

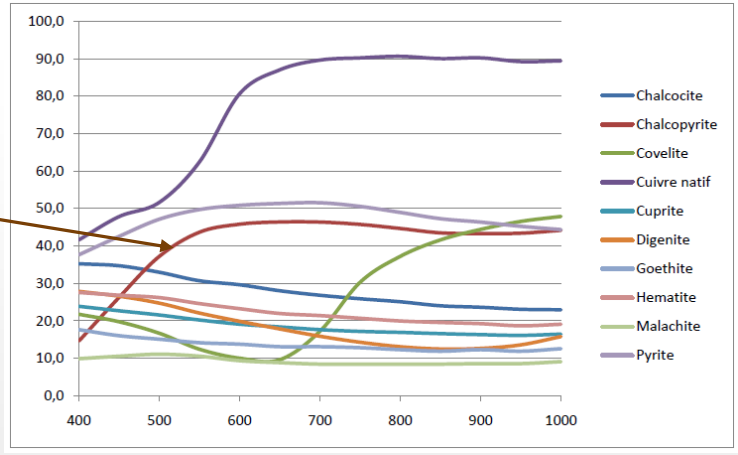
L-beam

- Multispectral Reflected Light Microscopy
  - **AMCO** - *Automated Mineral Characterization of Ores*

UPM Politecnica de Madrid
Université de Liège
TSL Labs
First Quantum (CLC)
KGHM



True colour reflected light microscopy of a copper ore (Neves Corvo, PT)

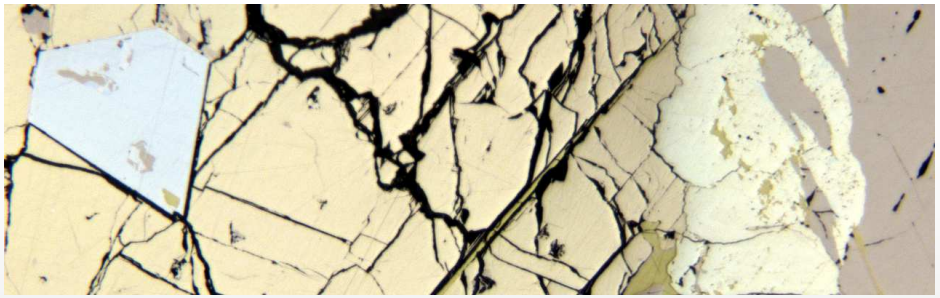


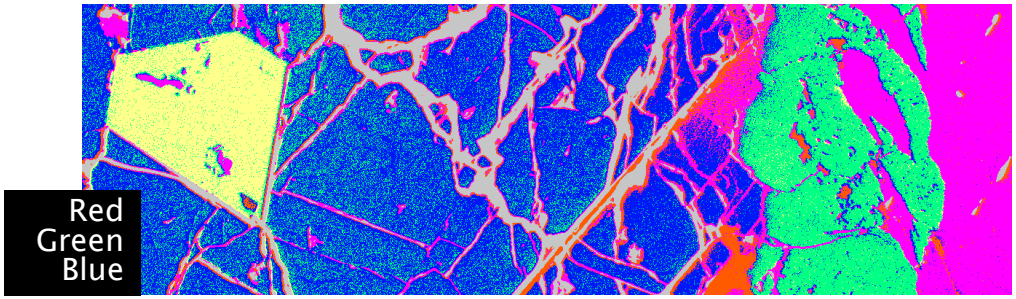
Specular reflectance database of ore minerals (400nm-1000nm)

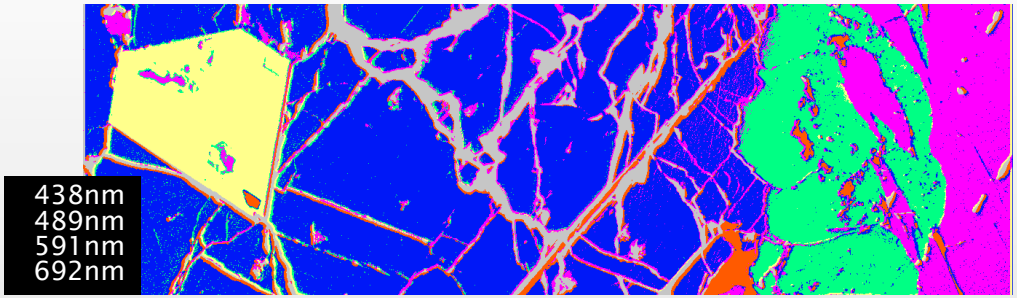
Mineral Mapping

L-beam

- AMCO Multispectral Imaging
  - 400 nm to 1000 nm
  - Calibrated
  - Optimal exposure







Mineral Mapping

e-beam

- MINERALOGIC
  - Strict matching criterion
    - Elemental composition
      - ✓ Limited due to calibration, analytical errors, impurities, etc.

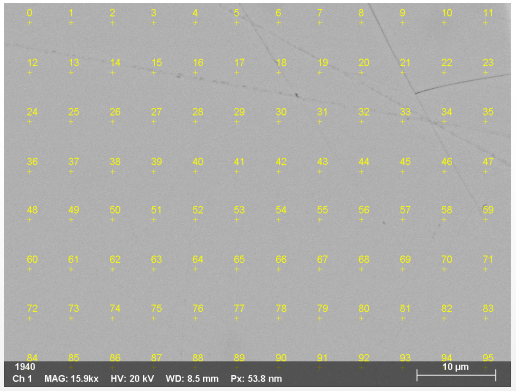
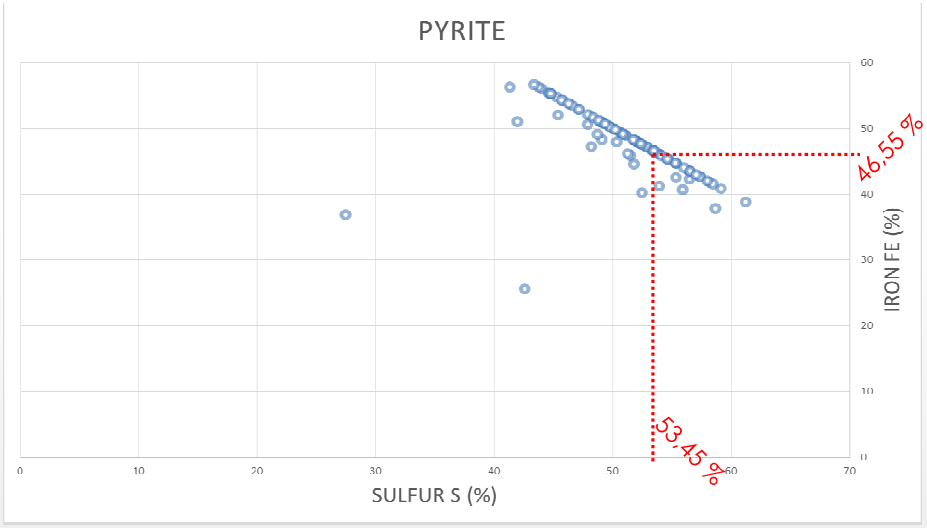


Image of a pyrite crystal with a grid of 96 EDX probes



*Signature of 96 EDX analyses from a Pyrite crystal at **1000cts***
Zeiss FEG Sigma 500 + Bruker 30 mm² + Esprit

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Mineral Mapping

e-beam

- MINERALOGIC
  - Strict matching criterion
    - Elemental composition
      - ✓ Limited due to calibration, analytical errors, impurities, etc.

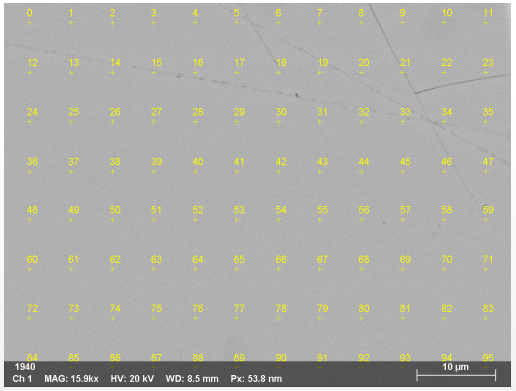
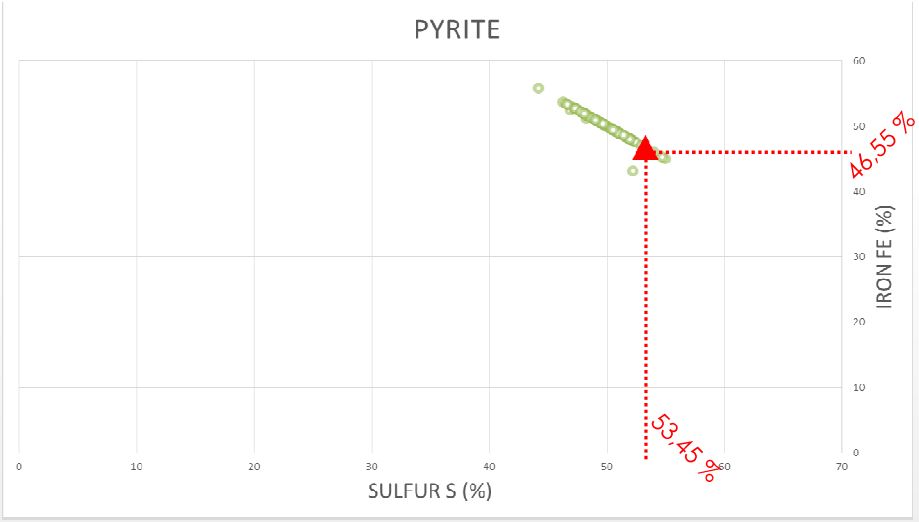


Image of a pyrite crystal with a grid of 96 EDX probes



*Signature of 96 EDX analyses from a Pyrite crystal at **6000cts***
Zeiss FEG Sigma 500 + Bruker 30 mm² + Esprit

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Mineral Mapping

e-beam

- MINERALOGIC
  - Extended matching criterion
    - Elemental ranges (shoebox domains)
      - ✓ Soft fitting (range) to accomodate for impurities, solid solutions, …
      - ✓ Tolerance on composition (« may have » vs. « must have »)

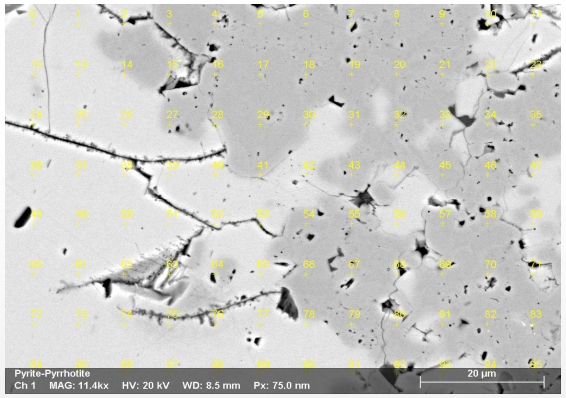
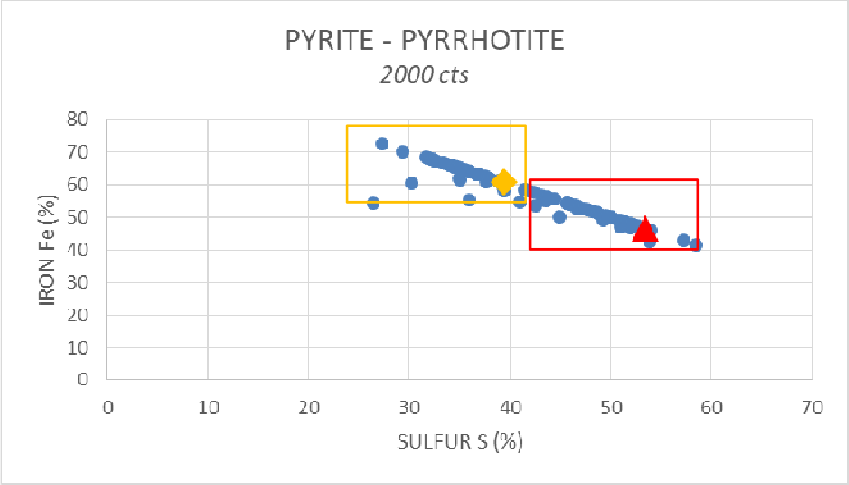


Image of a pyrite-pyrrhotite intergrowth with a grid of 96 EDX probes



*Signature of 96 EDX analyses from a Pyrite-Pyrrhotite at **2000cts***
Zeiss FEG Sigma 500 + Bruker 30 mm² + Esprit

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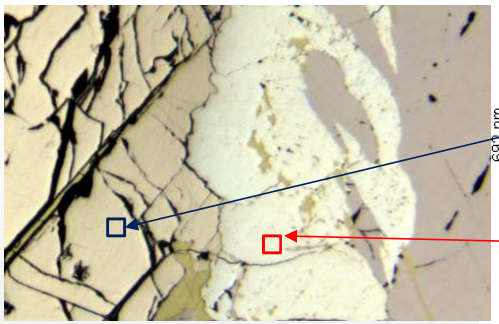
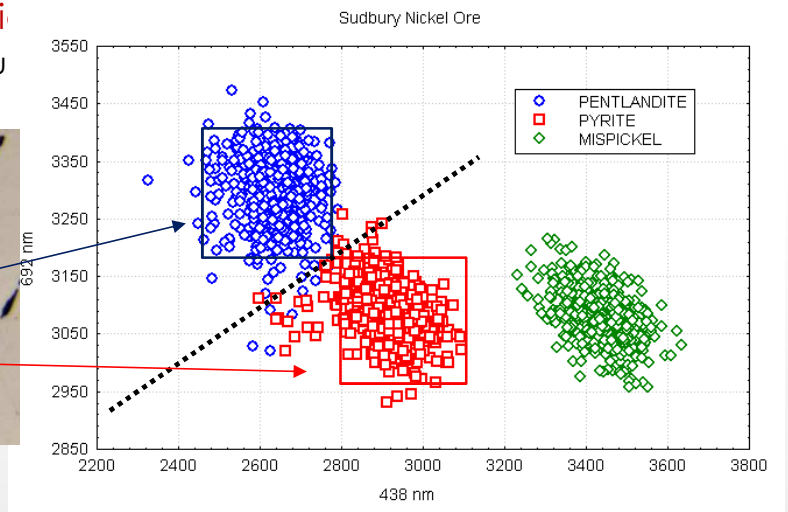
Berrier et al. 1997; Rasband and Bright 1995; Tinkham and Ghent 2005; Tovey and Krinsley 1991; Tovey et al. 1992a
Clarke et al. 2001; Cossio et al. 2002

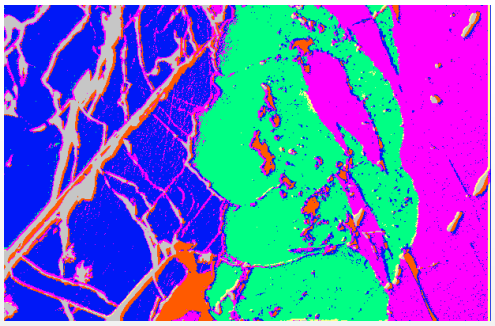
Mineral Mapping

Mineralogic

- Supervised Classification
  - User-selected regions (training sets) to feed a database
  - Adapts to real signatures (incl. minor elts, unknown phases, …)
- Matching criterion
  - Multivariate discriminati
    - MultiGaussian Maximu







Pirard, E, & Bertholet, V. (2000). Segmentation of multispectral images in optical metallography. Revue de Métallurgie - Sciences et Génie des Matériaux, 219-227

Sequencing Ores

Predicting functionality

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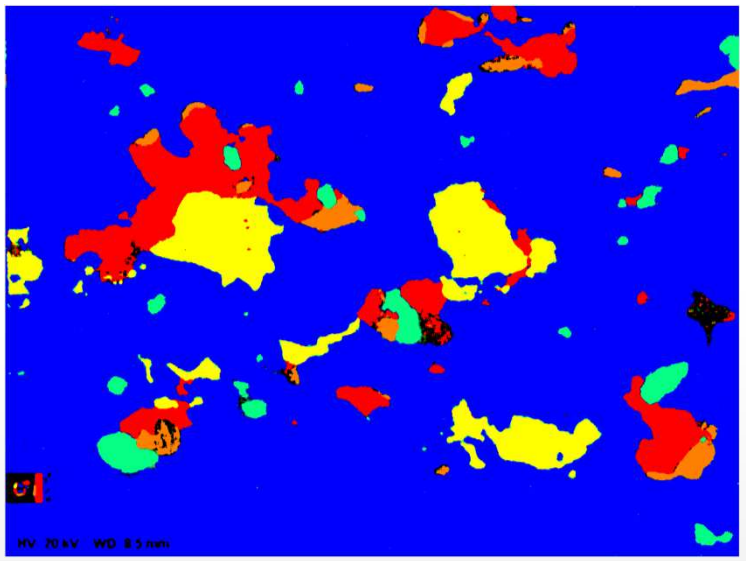
Sequencing Ores

Predicting functionality

- Quantitative Analysis
  - Modal mineralogy
  - Porosity and fractures
  - Crystal / Grain size
  - Grain shape
  - Mineral connexity
- Process Oriented Indices

MINERALOGICAL MAPPING

Chalcopyrite
Stannite
Sphalerite
Pyrite
Quartz
Al-Si



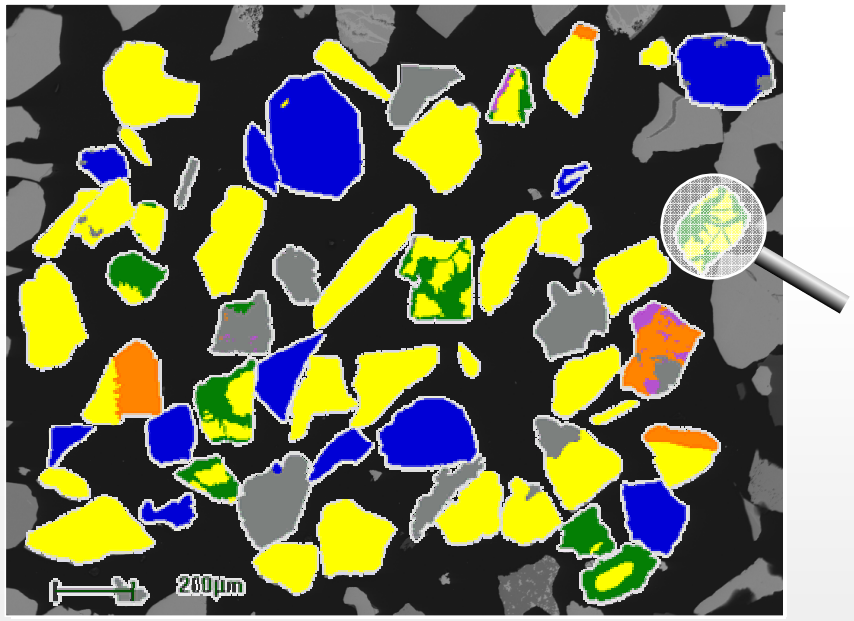
PROGNOSTIC MINERALOGY

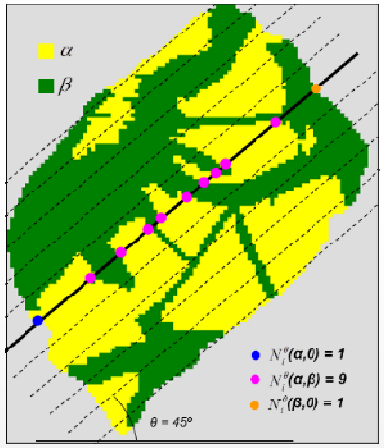
Breakability
Magnetic susceptibility
Floatability
Sinterability
Leachability

Sequencing Ores

Predicting functionality

- Quantitative Microscopy
  - Predictive Indices

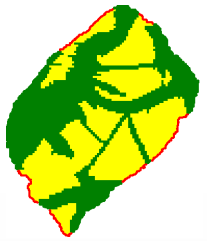




Breakability

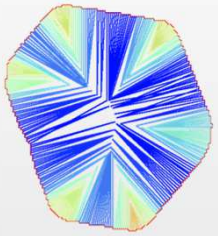
$$S_V(\alpha\beta) = 2 \times \frac{\overline{\sum_{\theta}\sum_{i} N_i^{\theta}(\alpha\beta)}}{\sum_{i} L_i^{\theta}}$$

Floatability

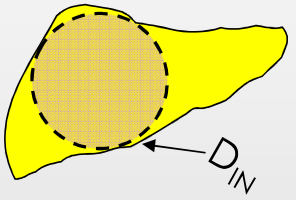


$$B(\alpha,0) = \frac{\pi d}{2} \times \overline{\sum_{\theta}\sum_{i} N_i^{\theta}(\alpha,0)}$$

Abrasivity



Leachability



Pérez Barnuevo, L., Pirard, E., & Castroviejo, R. (2012). Textural descriptors for multiphasic ore particles. Image Analysis and Stereology, 31(3).

Sequencing Ores

Predicting functionality

- Need for databases with physical properties of minerals/phases
  - Density
  - Hardness
  - Magnetic Susceptibility
  - Resistivity
  - Dielectic Constant
  - Hydrophobicity
  - Thermal resistance
  - Mechanical resistance
  - Etc…

Screen shot from a material selection database used by designers © Granta Design

Interactive Visualisation

AMCO WebApp

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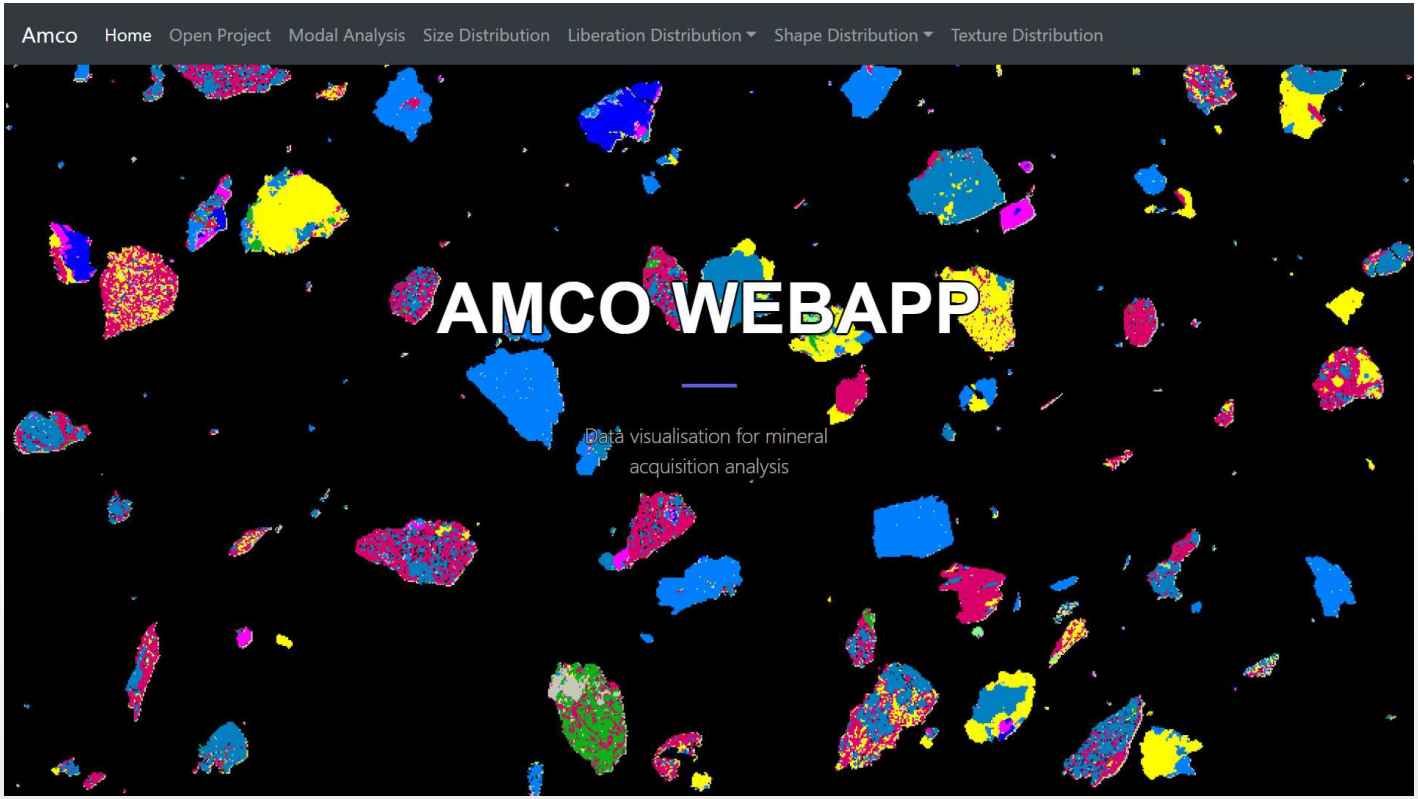
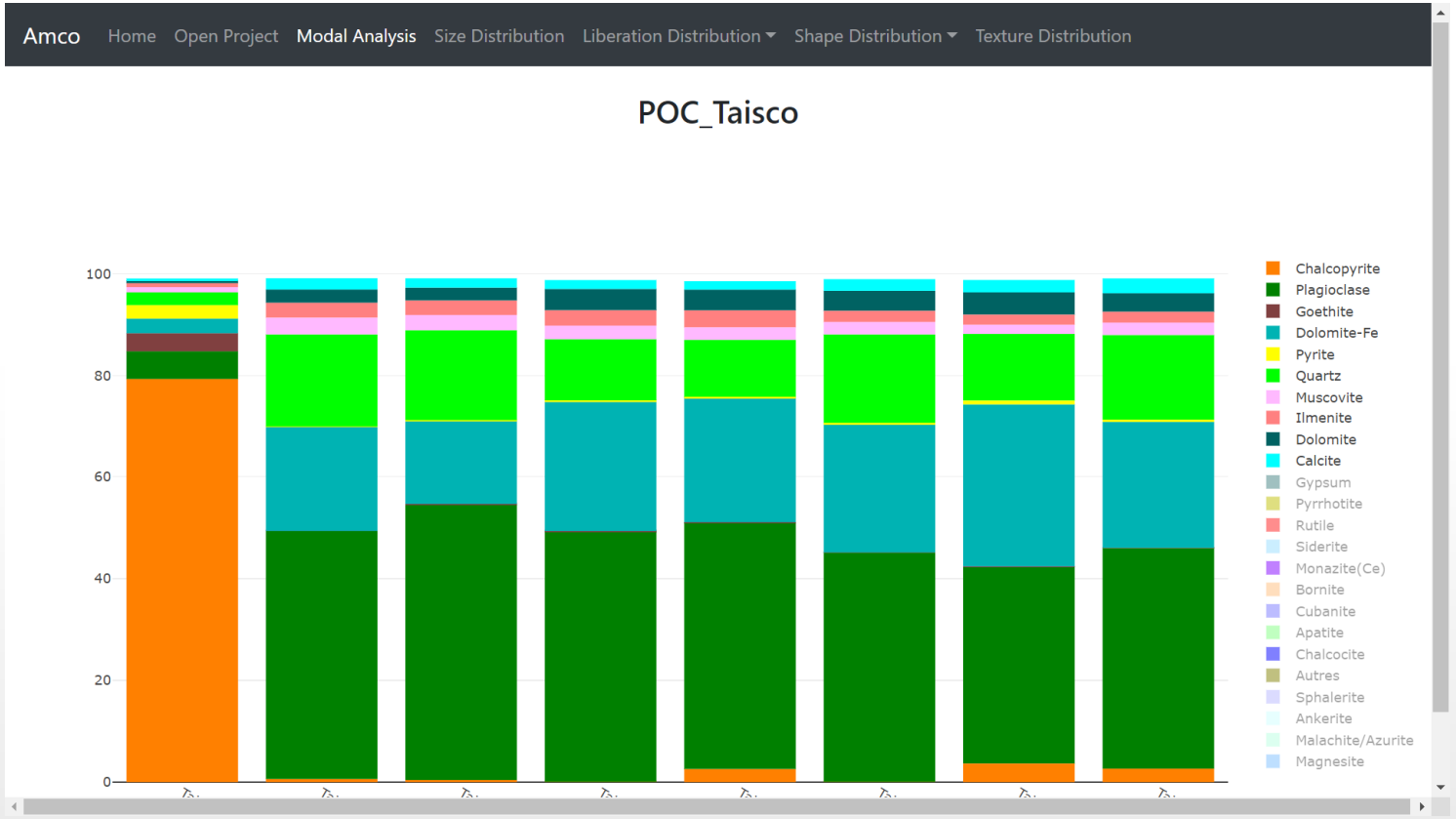
Interactive Visualisation

- Online



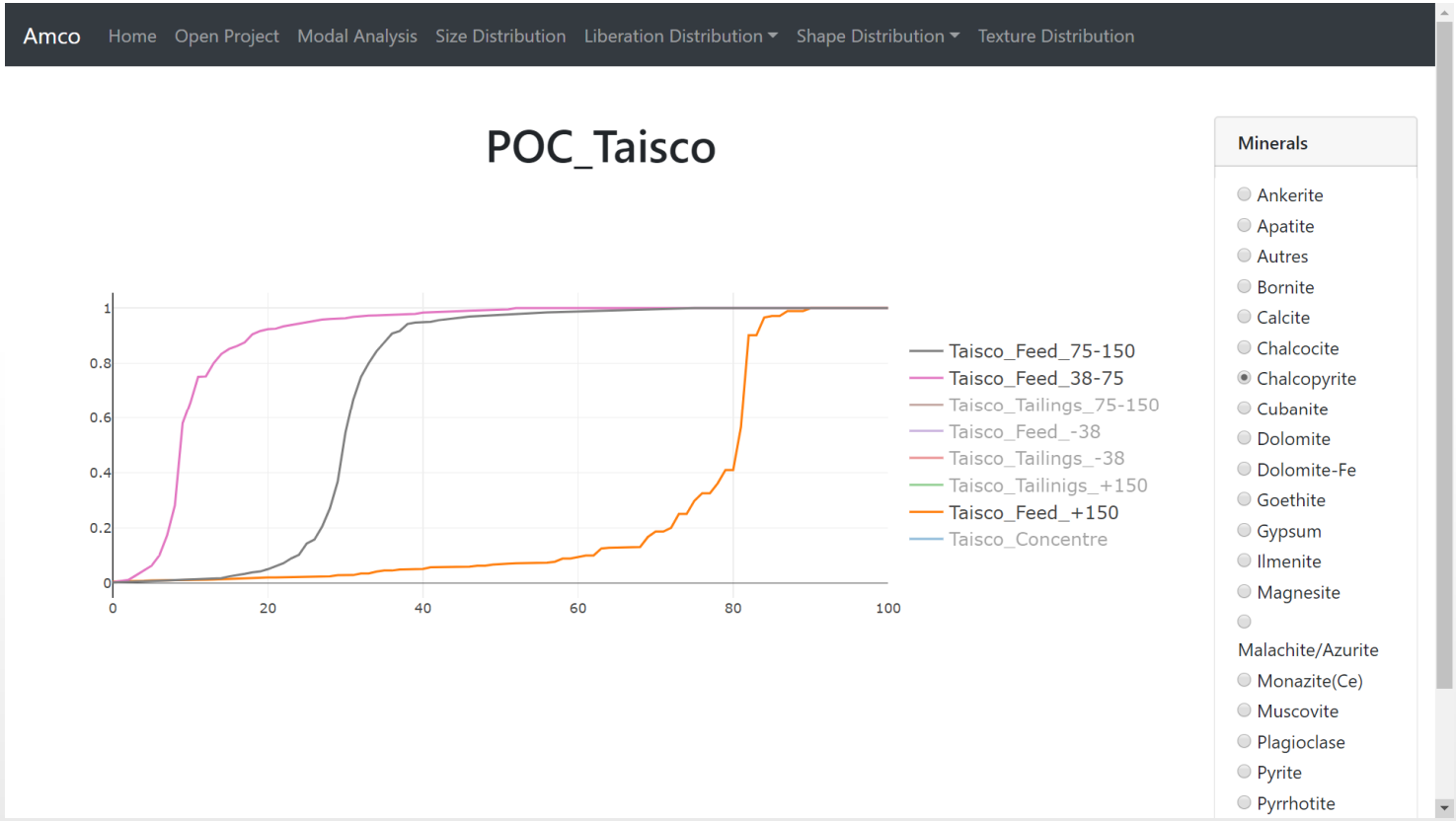
Interactive Visualisation

- Online Graphics



Interactive Visualisation

- Online Graphics

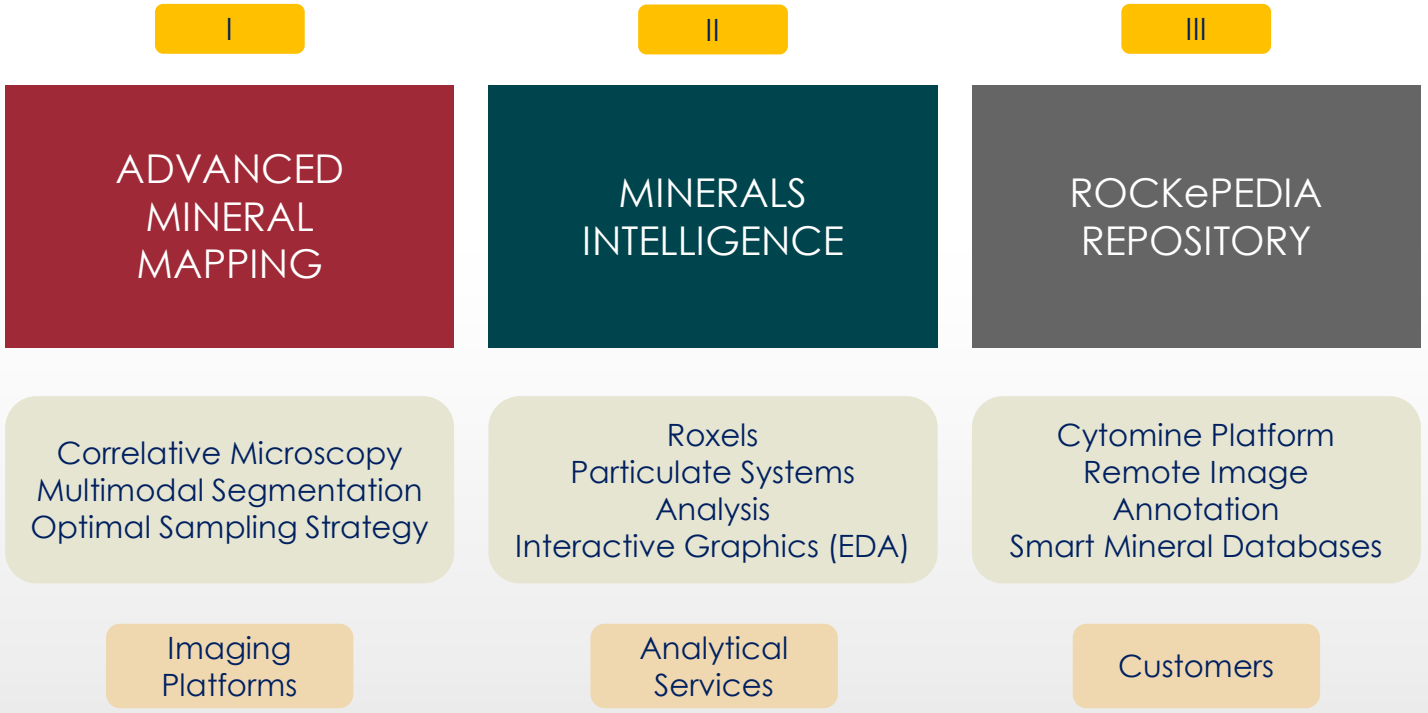


Conclusions

Still a long way to go…

Conclusion

- 3 steps roadmap towards a More Automated Mineralogy



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