The role of Microscopy in a Circular Economy

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Squaring the material circle

TAKE **MAKE** **DISPOSE**

Resource

… Extraction

Product

Lifetime
months

Waste

End-of-Life…

BIC Generation

TAKE **MAKE** **R³CYCLE**

EXTRACTION & CONCENTRATION

Fragmentation/Sorting

PRODUCTION

Materials/Design

GEO-RESOURCES

Exploration/Evaluation

⚒ Mines

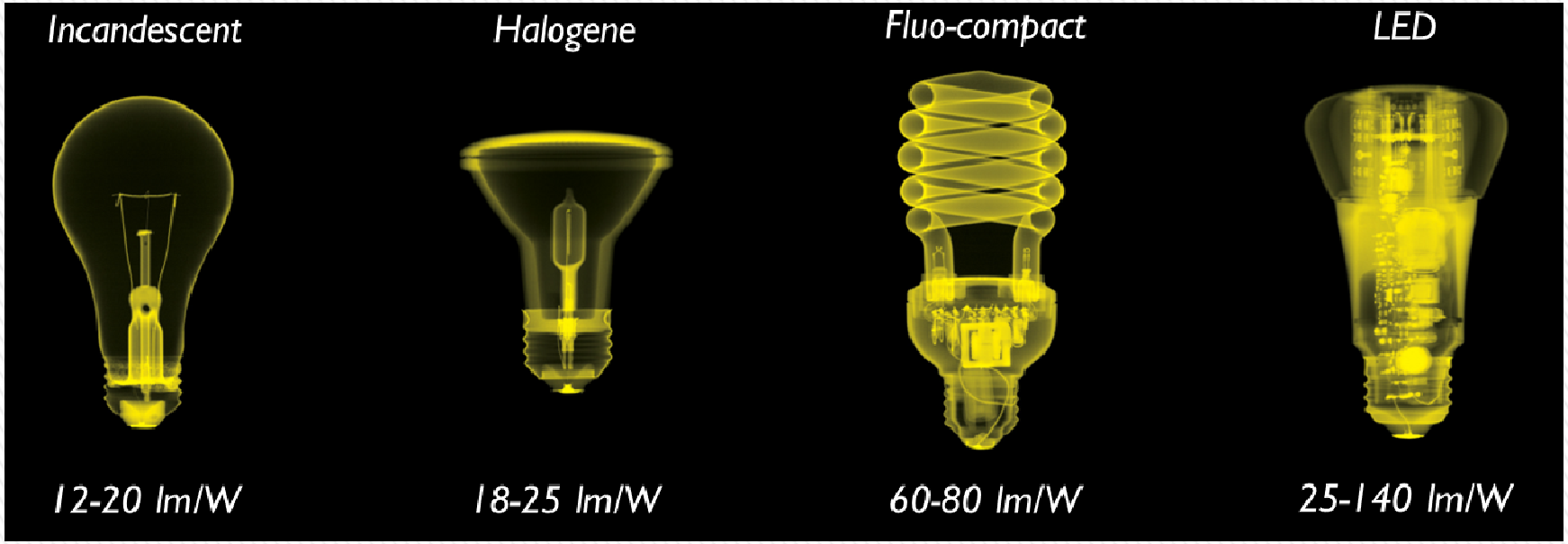
ECO-RESOURCES

Collection/Storage

● Urban Mines

NEXT Generation

A BRILLIANT IDEA ?

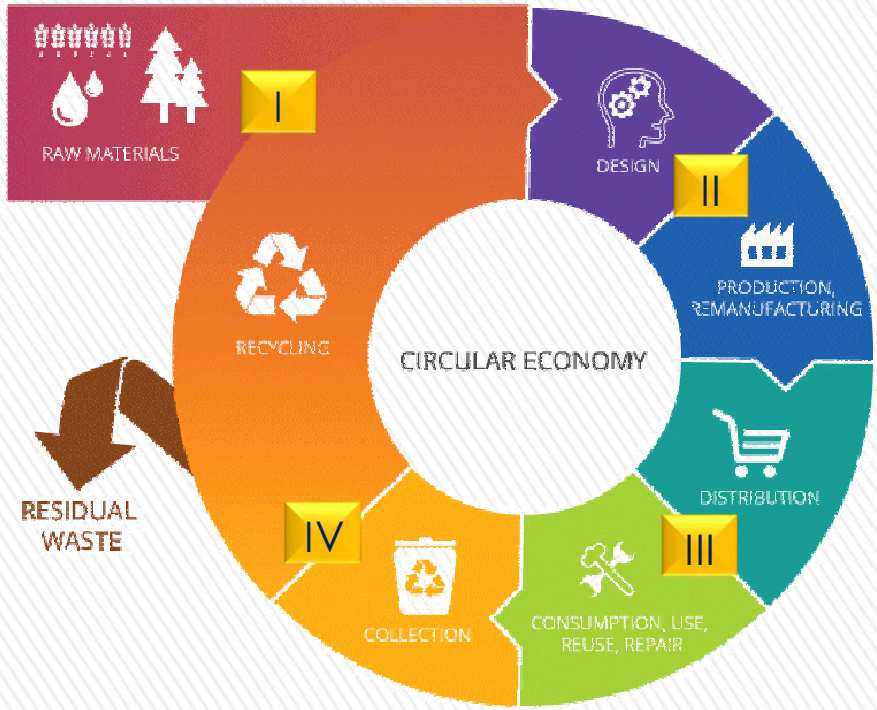


Incandescent	Halogene	Fluo-compact	LED
Tungsten Glass,…	**Tungsten** Iodine, Bromine, … Glass,…	**Tungsten** Mercury, Rare Earths,… Glass, Plastics,…	**Gallium** Indium, Cerium, Yttrium, Copper, Silver, Silicium, … Plastics, …

Future products will not only be optimized with regard to their functionality but also their recyclability and the sustainable availability of resources

LIÈGE université

I. FEED **II. OPTIMIZE** **III. SLOW DOWN** **IV. CLOSE**



4 challenges

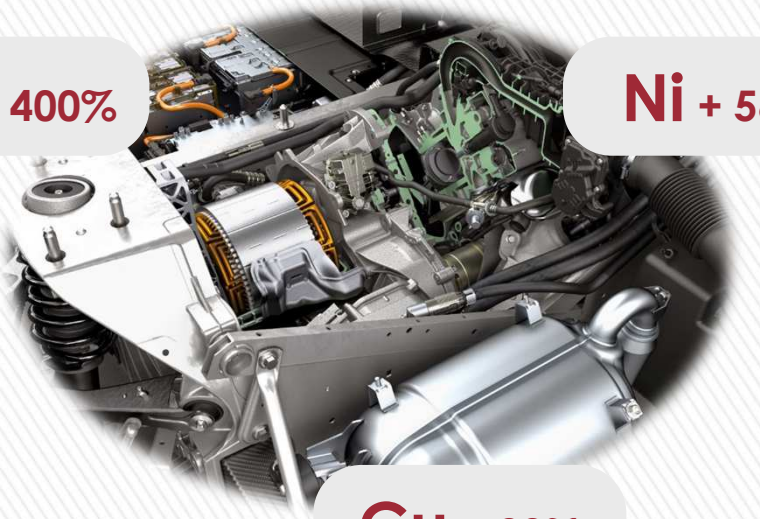
Challenge I

Sourcing Critical Metals

Geometallurgy

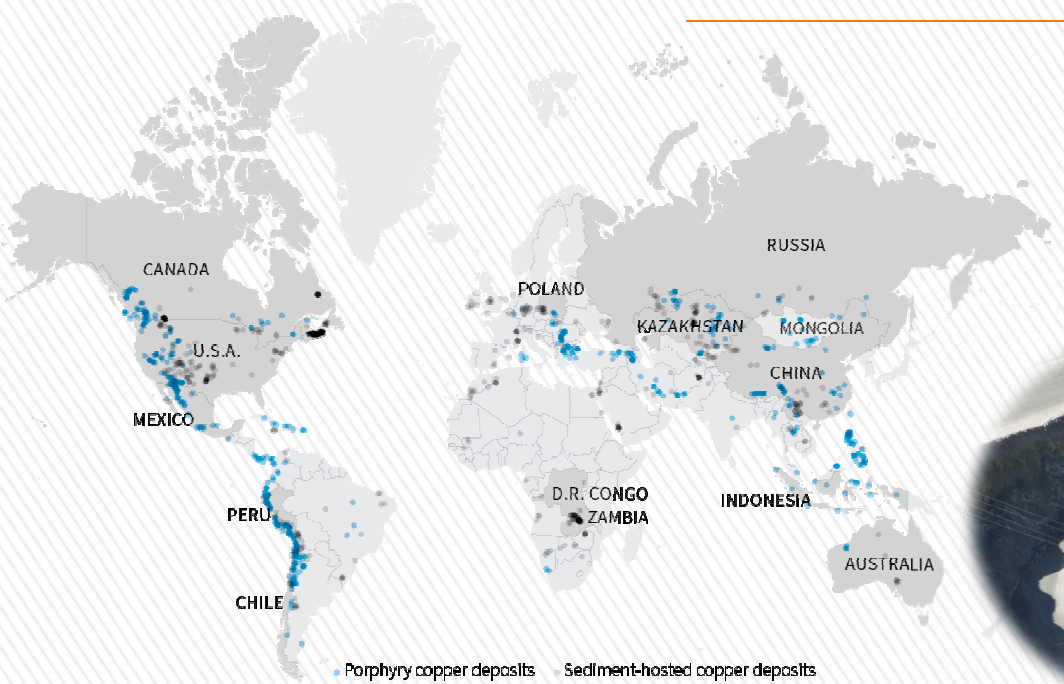
More Metals for e-Mobility

- Perspective 2030*
  - Based on 30% market share of new cars
  - Based on Li-ion MNC Battery Technology
    - NMC : **Li** ($\mathbf{Ni}_{0,5}\mathbf{Mn}_{0,2}\mathbf{Co}_{0,3}$)$O_2$



** Glencore, 2017*

In search for Copper



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TU BERGAKADEMIE FREIBERG

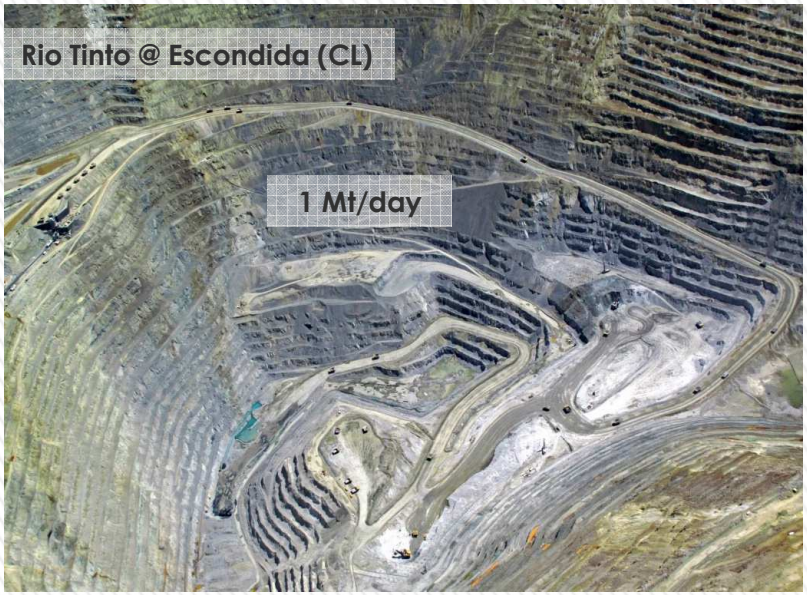
LULEÅ TEKNISKA UNIVERSITET

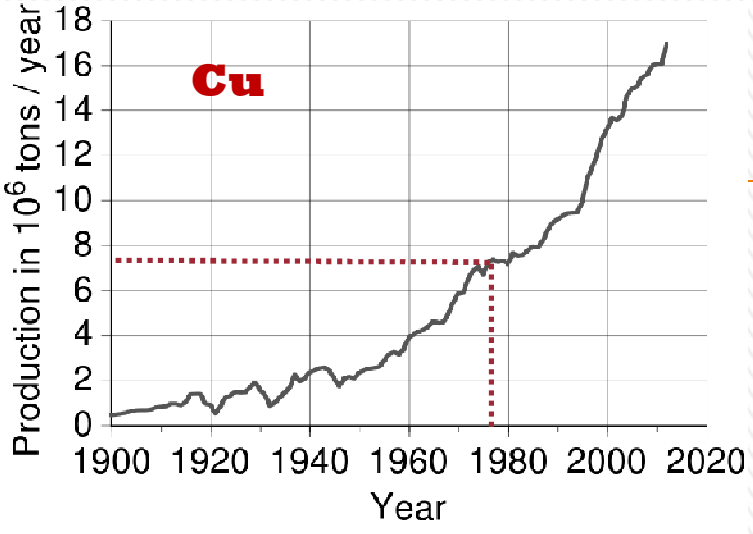
UNIVERSITÉ DE LORRAINE

EMERALD
MASTER IN RESOURCES ENGINEERING

In search for Copper

- Increasingly difficult
  - Lower grades (< 0,1% Cu)
  - More disseminated
  - More complex mineralogy



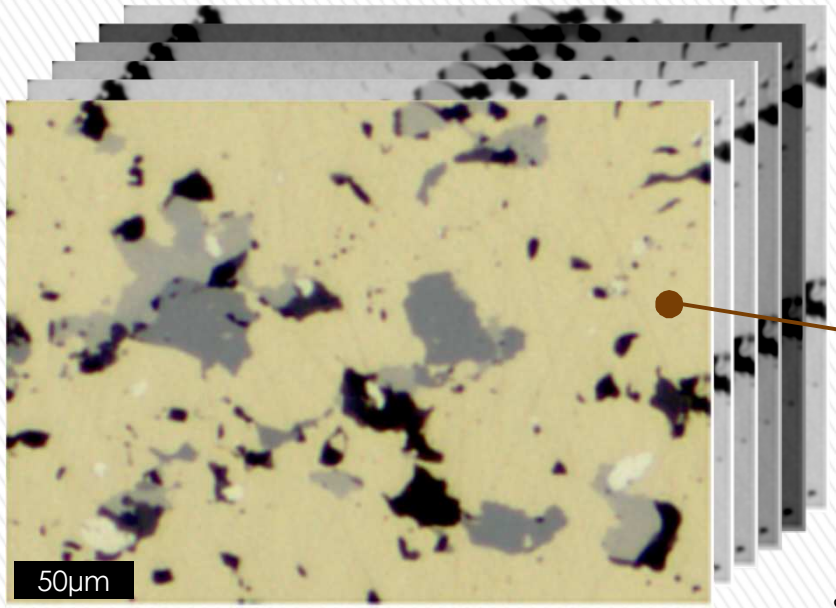


Recycling is not an option

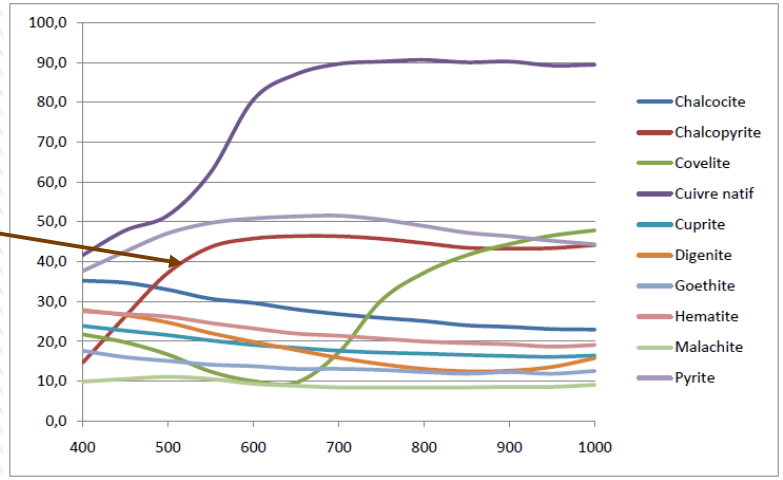
In search for Copper

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

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



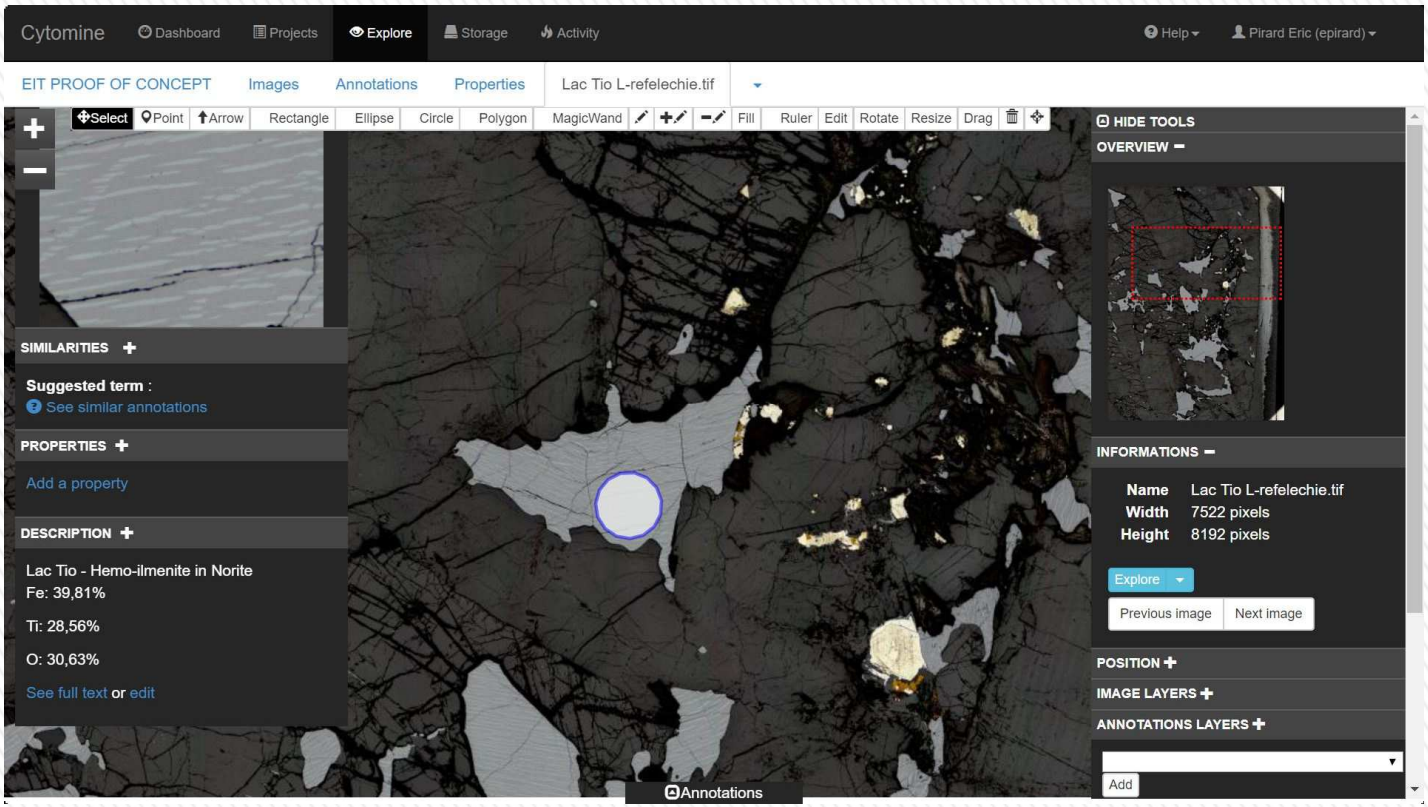
True colour reflected light microscopy of a copper ore (Neves Corvo, PT)



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

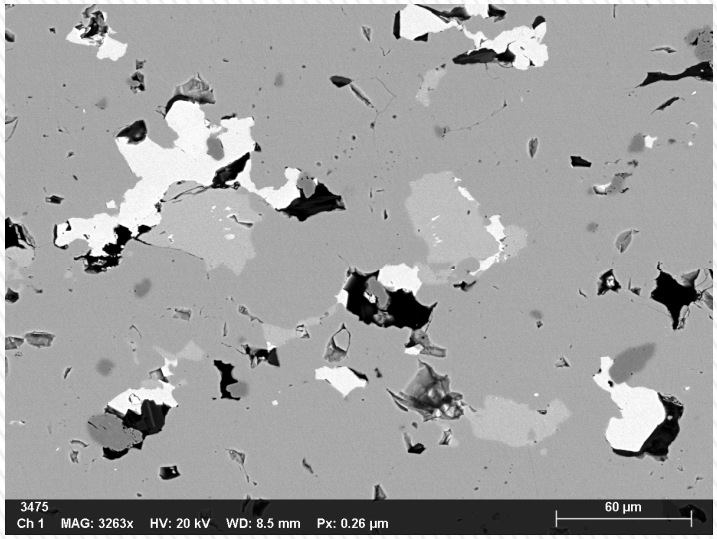
In search for Copper

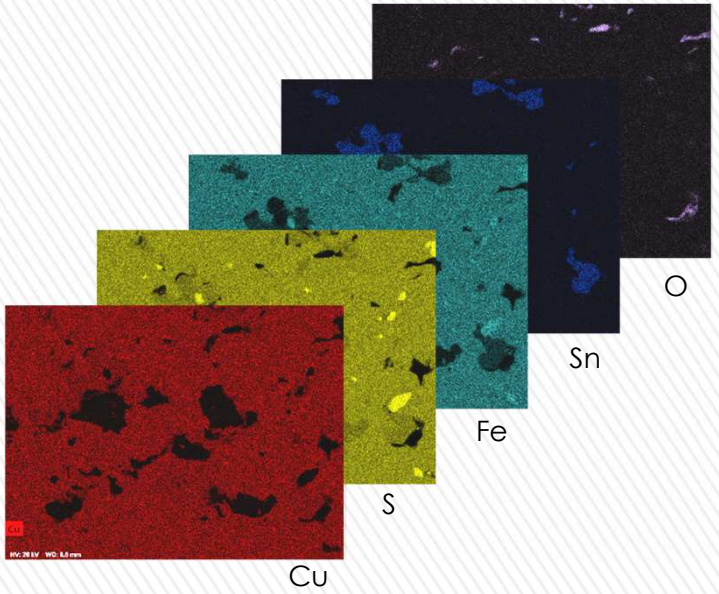
- Web-based Platform
  - Interactive Annotation & Online Analysis for GigaPixels Images



In search for Copper

- High Speed EDX Mapping
  - ZEISS Mineralogic (Sigma300 FEG SEM – 2 x 30mm² Brüker EDX)





In search for Copper

- Towards Automated Mineralogy
  - Mineral Species Identification Protocol
    - From simple thresholds to multivariate classifications

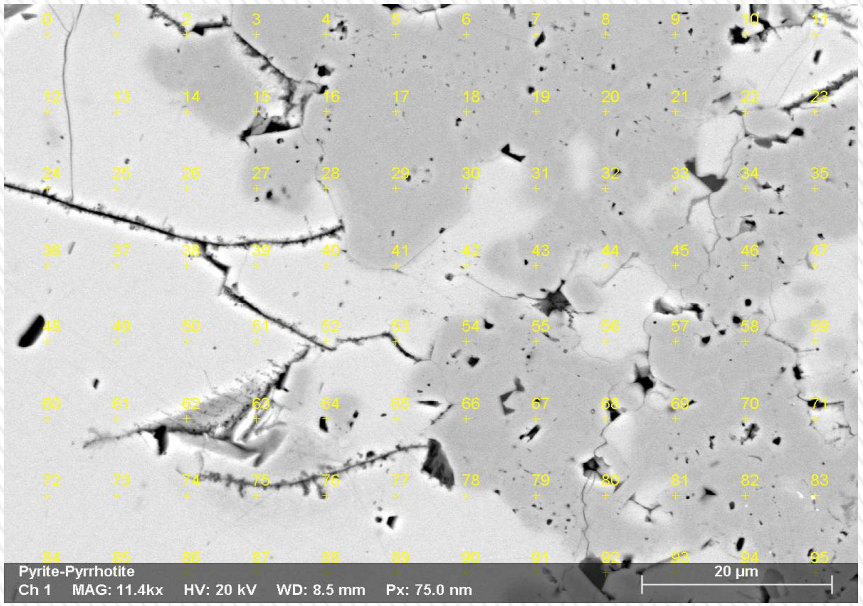
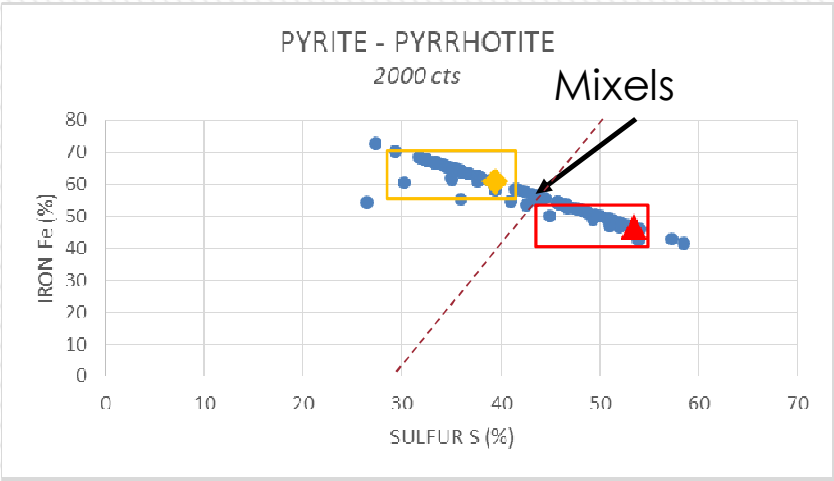


Image of a pyrite-pyrrhotite intergrowth with a grid of 96 EDX probes

Chrysocolla	$(Cu,Al)_2H_2Si_2O_5(OH)_4.nH_2O$
Malachite	$Cu_2(CO_3)(OH)_2$
Cuprite	Cu_2O
Tenorite	CuO
Chalcopyrite	$CuFeS_2$
Bornite	Cu_5FeS_4
Chalcocite	Cu_2S
Covellite	CuS
Enargite	Cu_3AsS_4
Tennantite	$Cu_6[Cu_4(Fe,Zn)_2]As_4S_{13}$



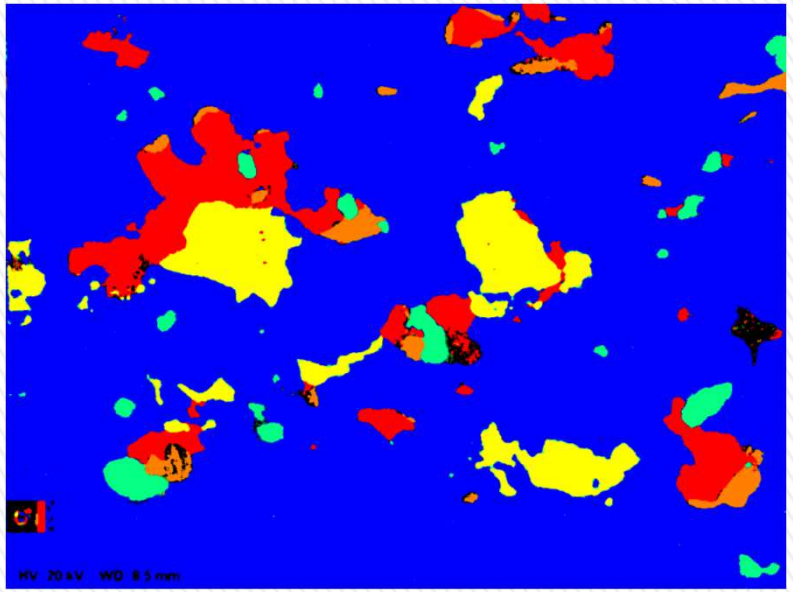
Berrier et al. 1997; Rasband and Bright 1995; Tinkham and Ghent 2005; Tovey and Krinsley 1991; Tovey et al. 1992a Clarke et al. 2001; Cossio et al. 2002

In search for Copper

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

PROCESS ORIENTED MINERALOGICAL MAPPING

Chalcopyrite
Stannite
Sphalerite
Pyrite
Quartz
Al-Si

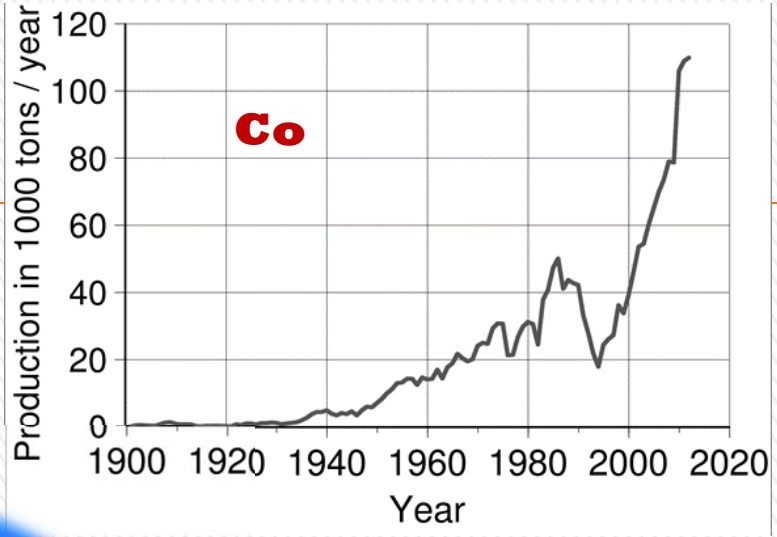


PROGNOSTIC MINERALOGY

Breakability
Magnetic susceptibility
Floatability
Sinterability
Leachability

In search for Cobalt

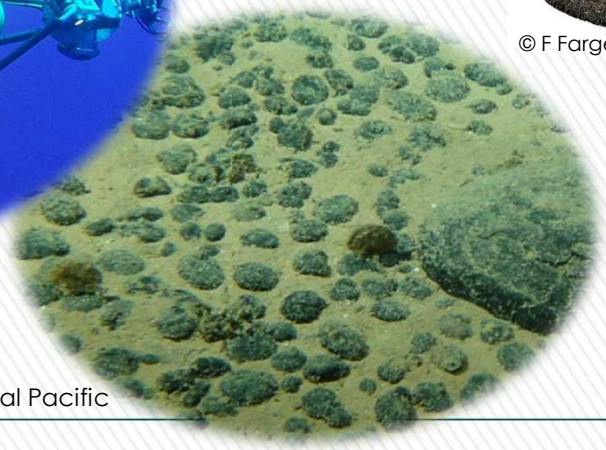
- DR Congo 53 % world production
  - > 50 % world reserves
- Alternative resources ?
  - Laterites
  - Polymetallic Nodules
    - Renewed exploration (GSR 2017)



World mine production of cobalt (USGS)

(GSR (BE) Patania, 2017

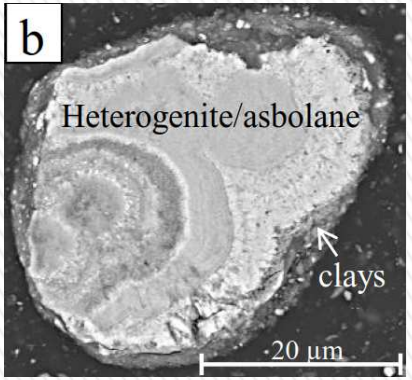
© F Farges (MNHN)

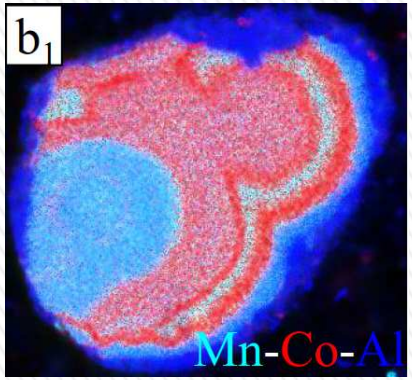


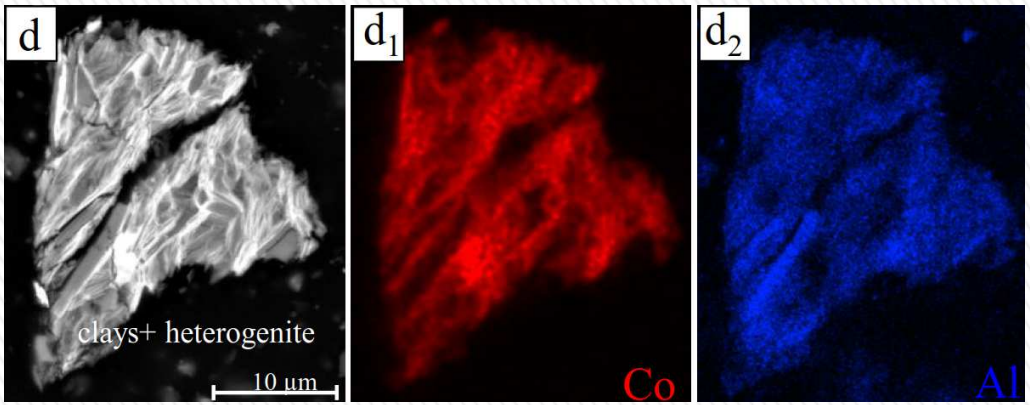
-4500m in East Central Pacific

In search for Cobalt

- Understanding poor recoveries during leaching of Co ores from DR Congo
  - Heterogenite $HCoO_2$
  - Co in Fe-Mn oxides, clay minerals, etc.







Santoro et al., 2018, Mineralogical reconciliation of cobalt recovery from the acid leaching of oxide ores from five deposits in Katanga (DRC), (in press).

Challenge II

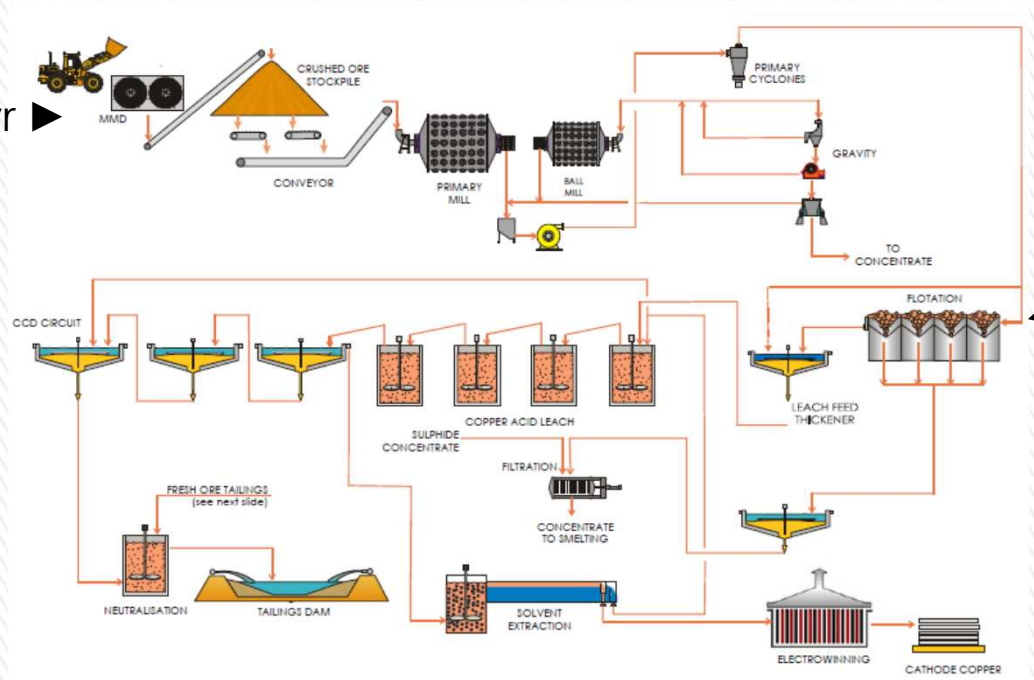
Efficient processing of critical metals

Process Mineralogy

Particle Tracking

- Microscopical Monitoring of plant performance
  - Metal Deportment
  - Material Balance
  - Liberation

25 Mt/yr ►

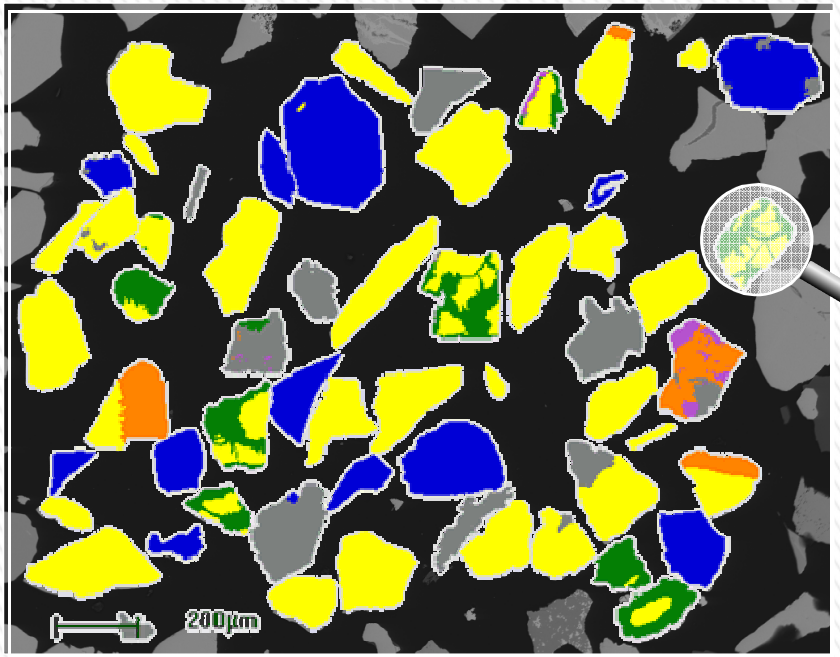


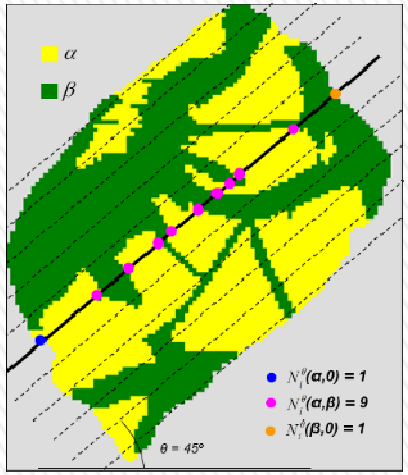
Recleaner Concentrate
75-150µm fraction

Kottgen et al. (2010). Process mineralogy and automated phase identification in mixed copper ores at Kansanshi (Zambia). Process Mineralogy '10, Cape Town, RSA

Particle Tracking

- Quantitative Microscopy
  - Predictive Indices

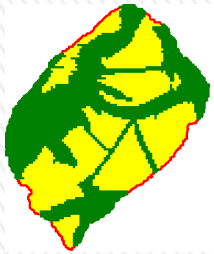




Breakability

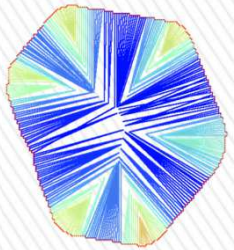
$$S_V(\alpha\beta) = 2 \times \frac{\overline{\sum_\theta \sum_i N_i^\theta(\alpha\beta)}}{\sum_i L_i^\theta}$$

Floatability

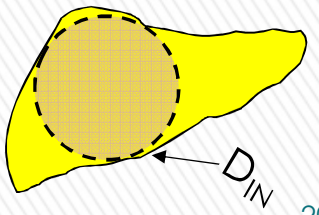


$$B(\alpha,0) = \frac{\pi d}{2} \times \overline{\sum_\theta \sum_i N_i^\theta(\alpha,0)}$$

Abrasivity



Leachability



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

Challenge IV

Recovering Critical Metals from Waste

Urban Mining

Urban Mining

- Metal grades
  - Better than laterite ?

	Smartphone *with Battery*
Polymers	19,2 %
Glass	19,4 %
Cu	10,7 %
Co	8,4 %
Ni	1,2 %
Li	0,8 %
Nd	1935 ppm
Ag	868 ppm
Au	95 ppm

Urban Mining

- Metal tonnages
  - Competing with a mine?

Less than 30% cellphones are currently collected at best

10^9 cellphones (!) needed to equal one year production of a standard gold mine

Urban Mining

- Waste Electric Electronic Equipments (WEEE)
  - ~= 10 kg/pers.yr
    - GB White Goods
    - RS Fridges
    - LMP Discharge Lamps
    - TVM Screens
    - AUT Small Devices, Computers, Cellphones,…
    - DF Smoke Detectors
- Batteries (BAT)
  - ~= 1kg/pers.yr
- End-of-Life Vehicles (ELV)
  - ~= 15 kg/pers.yr

comet traitements

Urban Mining

- Shredding and dismantling
  - Real size testing of a specific car model!

156 Toyota Prius recyclability test

Loading the Shredder (5 ELV/min)

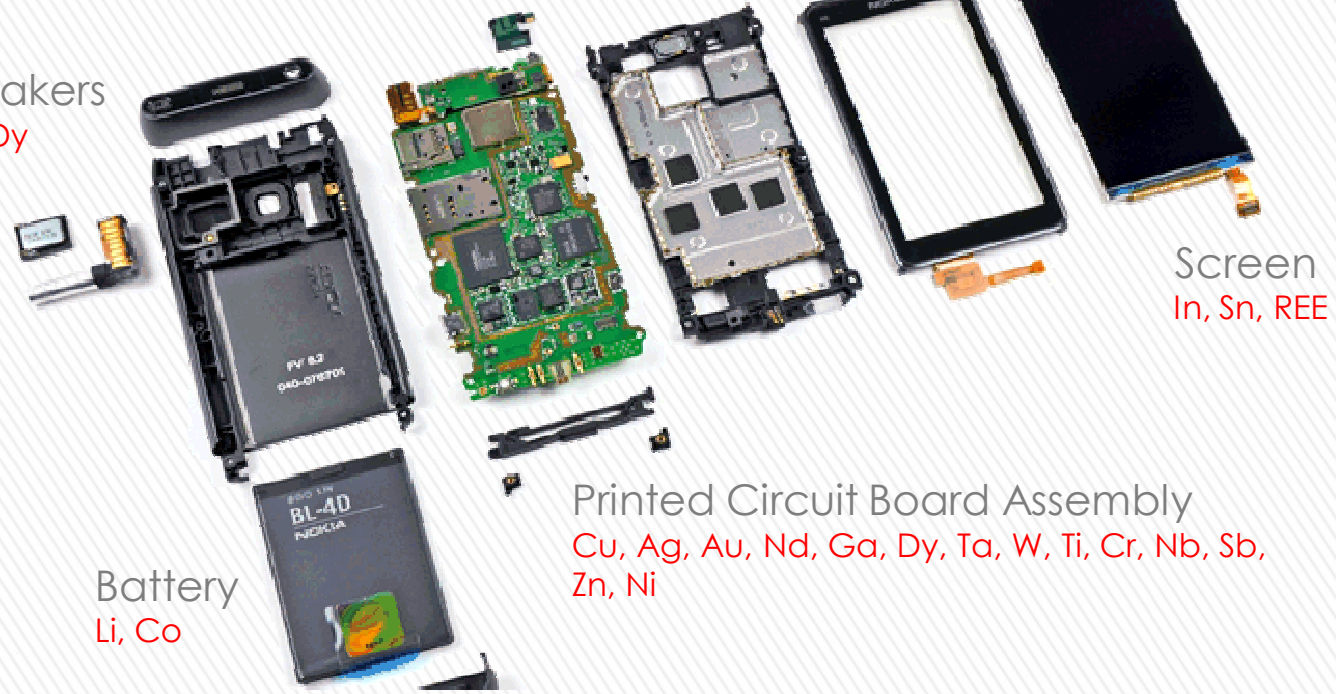
ZORBA Shredded non-ferrous scraps

Urban Mining

- Developing Smart Sorting Technologies
  - PICK IT ® - Multisensor Smart Sorting
    - 3D imaging
    - XRT
    - LIBS
    - Hyperspectral

In search for metals in urban mines

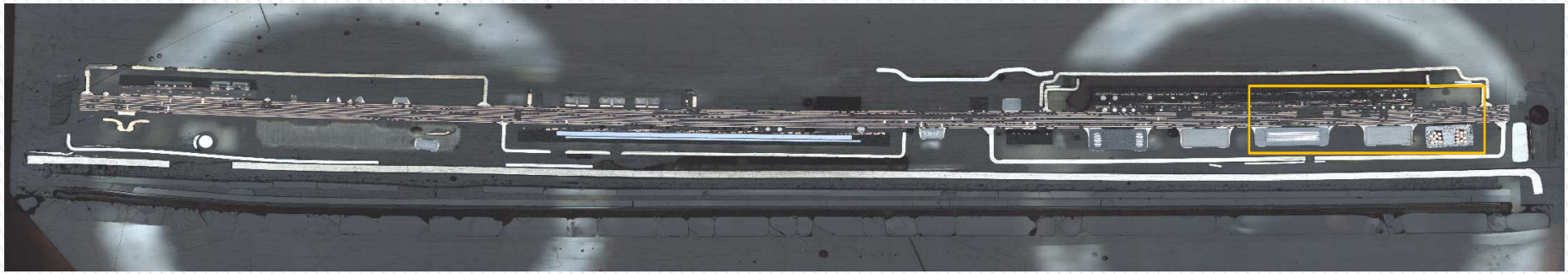
- General knowledge
  - Main components and metal uses

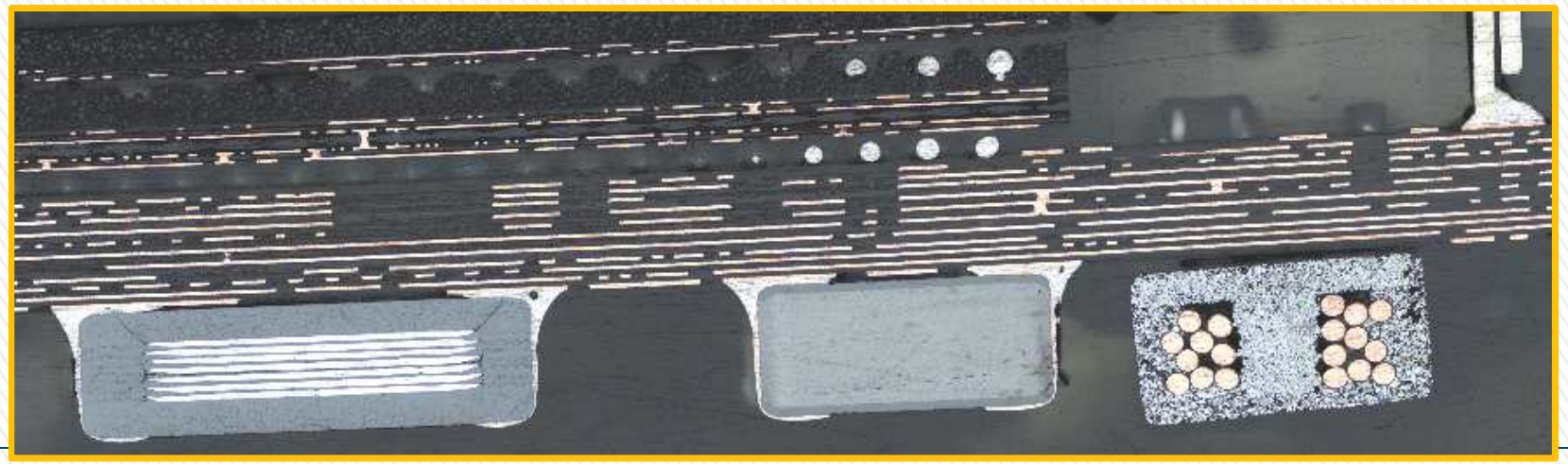


In search for metals in urban mines

- Unknown specific « mineralogy »
  - Unexpected alloys and material assemblages

ZEISS AxioImager M2m (obj. 5x)
10 x 45 images stitched with ZEN 2 core





In search for metals in urban mines

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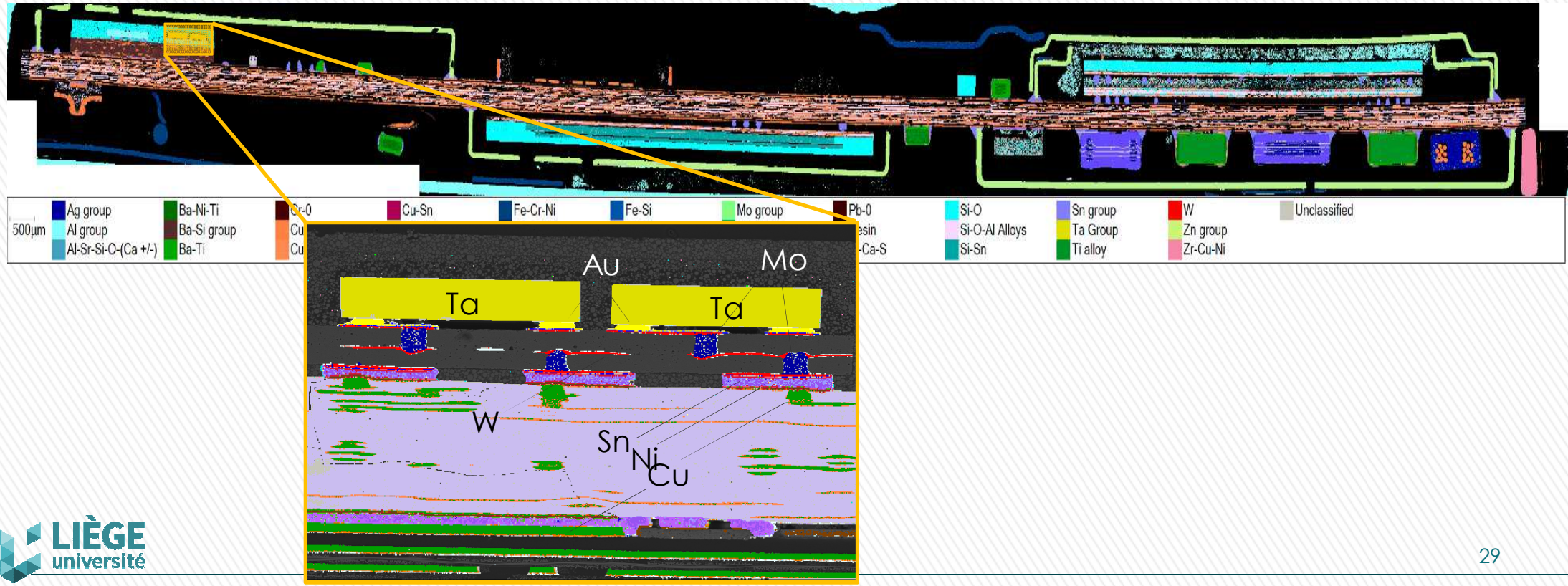

In search for metals in urban mines

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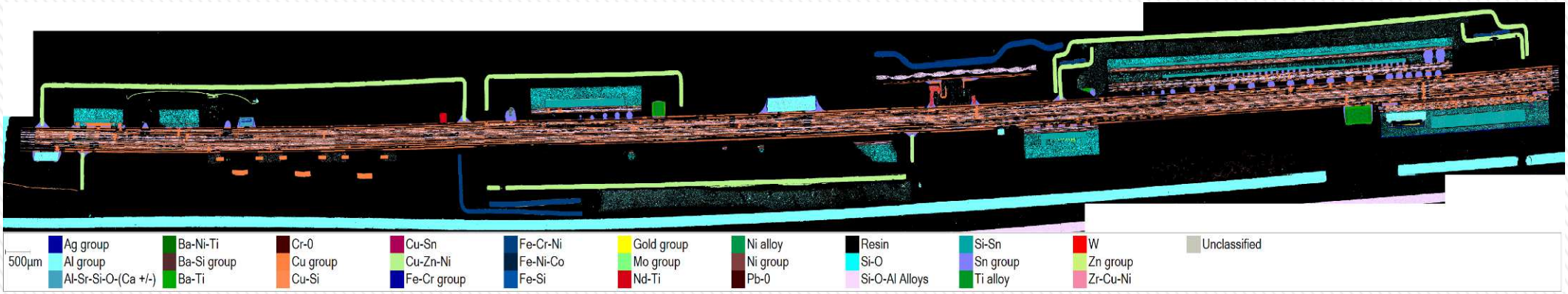
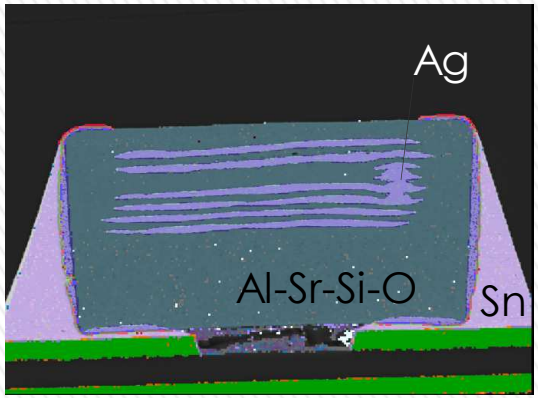
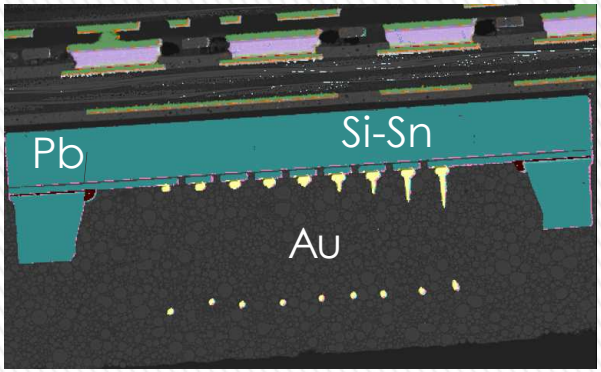
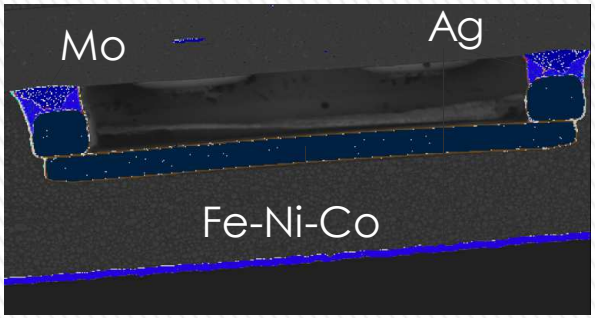






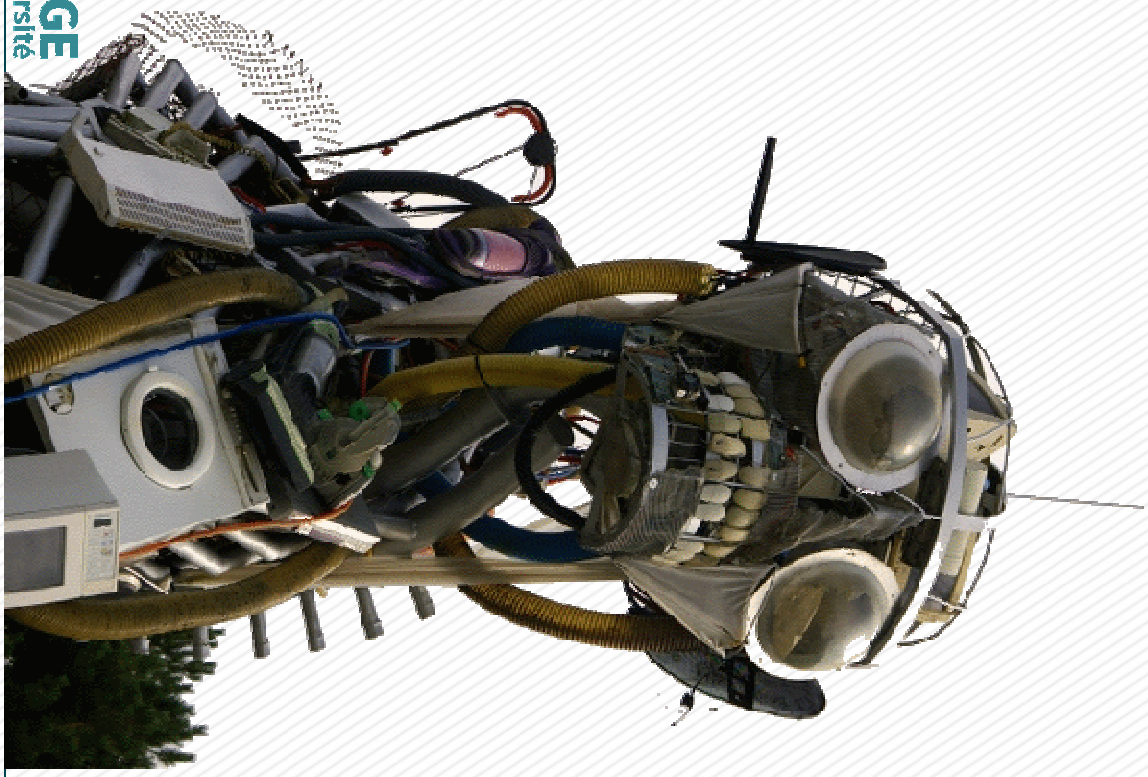


Conclusions

… and dreams!

The ultimate microscopy technique

- Ultrafast sample preparation and scanning
  - Going down from several hours to a few minutes
- 3D particle imaging and tracking
  - Full 3D geometry and composition of particles
- Fully automated identification of minerals / phases
  - Extensive training sets
  - Non-supervised classifications (artificial intelligence)



WEEE sculpture (Eden Project, UK)

Thank You
Merci!

GeMMe
Resourceful Engineers