The role of Microscopy in a Circular Economy

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Squaring the material circle
TAKE

MAKE

DISPOSE

Resource

Product

Waste

... Extraction

Lifetime months

End-of-Life...

BIC Generation
Zeiss – Day of Microscopy, May 16th, 2018

TAKE

MAKE

R³CYCLE

EXTRACTION & CONCENTRATION
Fragmentation/Sorting

GEO-RESOURCES
Exploration/Evaluation

PRODUCTION
Materials/Design

ECO-RESOURCES
Collection/Storage

NEXT Generation

Mines

Urban Mines
Future products will not only be optimized with regard to their functionality but also their recyclability and the sustainable availability of resources.
4 challenges
Sourcing Critical Metals

Geometallurgy

Challenge 1
More Metals for e-Mobility

• Perspective 2030*
  o Based on 30% market share of new cars
  o Based on Li-ion MNC Battery Technology
    • NMC: Li\(_{(\text{Ni}_{0.5}\text{Mn}_{0.2}\text{Co}_{0.3})}\)O\(_2\)

* Glencore, 2017
In search for Copper
In search for Copper

- Increasingly difficult
  - Lower grades (< 0.1% Cu)
  - More disseminated
  - More complex mineralogy

rio Tinto @ Escondida (CL)

Recycling is not an option

0.4 % Cu

1 Mt/day
In search for Copper

- 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
  o Mineral Species Identification Protocol
    • From simple thresholds to multivariate classifications

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chrysocolla</td>
<td>(Cu,Al)$_2$H$_2$Si$_2$O$_5$(OH)$_4$.nH$_2$O</td>
</tr>
<tr>
<td>Malachite</td>
<td>Cu$_2$(CO$_3$)(OH)$_2$</td>
</tr>
<tr>
<td>Cuprite</td>
<td>Cu$_2$O</td>
</tr>
<tr>
<td>Tenorite</td>
<td>CuO</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>CuFeS$_2$</td>
</tr>
<tr>
<td>Bornite</td>
<td>Cu$_5$FeS$_4$</td>
</tr>
<tr>
<td>Chalcocite</td>
<td>Cu$_2$S</td>
</tr>
<tr>
<td>Covellite</td>
<td>CuS</td>
</tr>
<tr>
<td>Enargite</td>
<td>Cu$_3$AsS$_4$</td>
</tr>
<tr>
<td>Tennantite</td>
<td>Cu$_6$[Cu$_4$(Fe,Zn)$_2$]As$<em>4$S$</em>{13}$</td>
</tr>
</tbody>
</table>

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

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

PROGNOSTIC MINERALOGY

- Chalcopyrite
- Stannite
- Sphalerite
- Pyrite
- Quartz
- Al-Si

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)

© F Farges (MNHN)

-GSR (BE) Patania, 2017

4500m in East Central Pacific
In search for Cobalt

- Understanding poor recoveries during leaching of Co ores from DR Congo
  - Heterogenite $\text{HCoO}_2$
  - 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

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

\[ S_{\gamma}(\alpha \beta) = 2 \times \frac{\sum \sum N_{i}^{\gamma}(\alpha \beta)}{\sum L_{r}} \]

\[ B(\alpha, 0) = \frac{m}{2} \times \sum \sum N_{i}^{\alpha}(\alpha, 0) \]

Challenge IV

Recovering Critical Metals from Waste

Urban Mining
Urban Mining

- Metal grades
  - Better than laterite?

<table>
<thead>
<tr>
<th></th>
<th>Smartphone with Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers</td>
<td>19.2 %</td>
</tr>
<tr>
<td>Glass</td>
<td>19.4 %</td>
</tr>
<tr>
<td>Cu</td>
<td>10.7 %</td>
</tr>
<tr>
<td>Co</td>
<td>8.4 %</td>
</tr>
<tr>
<td>Ni</td>
<td>1.2 %</td>
</tr>
<tr>
<td>Li</td>
<td>0.8 %</td>
</tr>
<tr>
<td>Nd</td>
<td>1935 ppm</td>
</tr>
<tr>
<td>Ag</td>
<td>868 ppm</td>
</tr>
<tr>
<td>Au</td>
<td>95 ppm</td>
</tr>
</tbody>
</table>

Residual Value = 1 €
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)
  - ~1 kg/pers.yr

- End-of-Life Vehicles (ELV)
  - ~15 kg/pers.yr
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

  Battery
  Li, Co

  Printed Circuit Board Assembly
  Cu, Ag, Au, Nd, Ga, Dy, Ta, W, Ti, Cr, Nb, Sb, Zn, Ni

  Casing
  Al, Mg, Ni, Plastics...

  Screen
  In, Sn, REE

  Speakers
  Nd, Dy
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

- Unknown specific « mineralogy »
  - Unexpected alloys and material assemblages
In search for metals in urban mines

- Unknown specific « mineralogy »
  - Unexpected alloys and material assemblages
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)
Thank You

Merci!