Mineralogical Constraints for Success (or Failure) in Mineral Processing

by Reimar Seltmann
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Leader of Work Package 2 “Mineral Characterisation” – h2020 FAME

**FAME Overview**

- Increase the competitiveness of European mining enterprises
- Stimulate private engagement and investment in the European mining sector

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**FAME Goals:**

- New flotation reagents for oxidic minerals
- Optimised flotation regimes
- New flotation cells for very fine grain flotation
- Modular equipment supply on Build Own Operate elements

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**WP2**

Economic potential of skarn, pegmatite and greisen ore deposits and requirements for profitable mining. Mineralogical variables significant for process flow design

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**WP3**

Flowsheet and basic engineering of flexible technology for greisen-pegmatitic ore processing; Concentrate upgrading, lithium and metallic by-product recovery

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**WP4**

Flowsheet and basic engineering of flexible technology for skarn ore processing; Concentrate upgrading, by-product recovery and utilization of rejects

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**WP5**

Energy savings in physical mineral liberation + Enhancement of separation contrast for better flotation recovery + Intensification of the processes + (Bio-) Leaching using fine grain activation
Engineering/design at TRL 5 of flexible, modular, economic and environmentally friendly processing of skarn and greisen ores, at TRL 6 (mobile) of pegmatites including recovery of strategic elements

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**WP6**

Smaller socio-ecological footprint for marketing European resources at a global scale, “clean mining” + more raw material awareness and public acceptance

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**WP7**

Dissemination
Exploitation
of Knowledge

**Generation**

Explore and Distribute Marketing Plan

**Dissemination**

Public Awareness
Maximising Impact
Education

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**Project Management Ethics**

- Enhanced pre-processing, fragmentation, sorting
- Viability of bioagglomeration, bioflotation
- Rapid techno-economic appraisals of mineral deposits
- Valorisation of residues, Recovery of strategic elements

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**Performance Increase 10 to 20% ➔ Higher Marketable Concentrate ➔ Stimulating Mining + Attracting Investors**
TARGETING SPECIFIC DEPOSIT TYPES: CRITICAL RAW MATERIAL FOCUS

- Which deposit classes in the EU contain significant “Critical Raw Material” Resources?
  - Skarns
  - Greisens
  - Pegmatites
- Complex mineralogy
- Frequently small resources not economically viable using existing large scale process flow designs

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<th>Sb</th>
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SUMMARY OF AIMS AND OBJECTIVES

• To describe the economic potential of skarn, pegmatite and greisen ore deposits and requirements for profitable mining in a European context (Task 2.1)

• To verify chosen reference sites and to study selected sites and materials through mineralogical, textural and chemical characterisation of ore and associated gangue (Task 2.2)

• To achieve geochemical modelling of initial ore assemblage to define its stability field and of residues to test the yield of the process
An appropriate understanding of the mineralogical and chemical variation within the European deposits underpins all subsequent mineral processing test work.

Essentially this work package delivers:

• Assessment of economic potential of skarns, greisens and pegmatites in Europe

• Detailed mineralogical and chemical characterisation of reference ores
  • SEM/light microscopy – NHM
  • QEMSCAN – CSM

• Characterisation of processing products/residues
**European Sn-W (Li, In, ...) potential**

<table>
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<tr>
<th>Deposit</th>
<th>EU</th>
<th>Carrier metal</th>
<th>Grade, %</th>
<th>By-products</th>
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<td>In, Ga, Ge, Zn, Cu,</td>
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<td>Pöhla-Globenstein</td>
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The most important remaining EU28 Sn/by-product deposits (data courtesy of FAME project proposal, 2015)

World ranking of Tellerhäuser deposit (red) regarding its Indium by-product potential
40 descriptive deposit passports including geometallurgy implications

5 ACKNOWLEDGEMENTS

The selected descriptive deposit passports were compiled by the following authors:

UK: Jens Andersen (CSM, University of Exeter), Barrie O’Connell (WAI)
France: Guillaume Bertrand (BRGM)
Portugal: Fernando Noronha (UP), Mario Machado Leite, Daniel Oliveira, Carlos Inverno (all LNEG), Luis Martins (Co turnover Resources), Filipe Pinto, Romeu Vieira, Alfredo Franco (all Panasqueira Mine)
Spain: Fernando Noronha (UP), Paul Ferras (Almonty Resources), Mario Machado Leite (LNEG)
Germany: Mirko Martin, Kersten Kühn, André Baumann (all GEOS), Reimar Seltsmann (NHM)
Czech Republic: Pavel Reichl (GROMET)
Finland: Aki Manninen, Esa Sandberg, Jarmo Finnilä (all Keiiber Oy)
Austria: Reimar Seltsmann (NHM)
Serbia: Robin Armstrong (NHM)

Editing and design:
Reimar Seltsmann (NHM), Robin Armstrong (NHM), Karen Oliver (WAI) and Chris Broadbent (WAI)
TASK 2.1 RESULTS

• Passports generated for 40 key deposits containing the elements Li, Sn, W & geometallurgy profile
TASK 2.2. REFERENCE SITES

Original Site List
- **Greisen** Cinovec (GeoMet)
- **Pegmatite** Goncalo
- **Skarn** Tabuaco (ECT)
- **Pegmatite** Keliber (KBO)
- **Skarn** Pöhla-Globenstein (SME)
- **Greisen** Redmore

Revised Site List
- Cinovec (CNV)
- Goncalo (GON)
- Tabuaco (TAB)
- Keliber (KEL)
- Pöhla-Hämmerlein = Tellerhäuser (POH) (Saxore)

Potentially in future:
- ? Hemerdon (HEM)
### Location of Greisen Deposits

#### Map

![Map of Europe highlighting Greisen deposits](image)

#### Table: Greisen Deposits in Europe

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LOCATION OF PEGMATITE DEPOSITS

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LOCATION OF SEDIMENT HOSTED DEPOSITS

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<td>Jadar</td>
<td>Sediment Hosted</td>
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</table>
• Characterise the total mineralogical diversity and residency of specific elements and materials of interest within the differing ore types
  The “Good” vs the “Bad”

• Understand the spatial characteristics of that mineralogy
  Grain size, morphologies, modal quantities, the spatial distribution within the ore bodies
SAMPLING IN PORTUGAL
UNDERGROUND AT TELLERHÄUSER
TASK 2.2. WORK FLOW

Sampling
- Observable mineral diversity
- Understanding sample context within the deposit
- Initial macro mineralogical & textural observation

Capturing Textural Information
- Macro imaging
- Optical Microscopy
- Analytical SEM (QEM Scan)
- CT-Scanning

Capturing Mineralogical Information
- Optical Microscopy
- E-beam techniques
- XRD

Elemental residency
- E-Beam techniques (SEM, EPMA)
- WR-Chemistry
- LA-ICP-MS

F. Noronha (UoP)
C. Stanley (NHM)
TASK 2.2 CLASSICAL OPTICS (NHM, UNEXE, UOP)

- Cost effective method to establish both ore and gangue mineralogy
- Requisite for the targeting of Electron-beam based instruments and LA ICP-MS
- Generates textural data
Photo (Chris Stanley, NHM): Scheelite (blue), malayaite (green) and garnet (black) from Tabuaço (thin section under short-wave UV in plane polarised light)
Sample from Cinovec in false coloured map from EVO SEM (NHM):
Sn – red (cassiterite), Ce – blue (monazite), Zr – green (zircon)
**TASK 2.2 – QEMSCAN® WORKFLOW (UNEXE)**

1. **Sample preparation**
   - Carbon coated thin sections

2. **QEMSCAN® analysis**
   - X-ray spectra & BSE collected every 10 µm

3. **Data processing**
   - X-ray spectra & BSE data are compared to a database of known minerals. A false colour image is produced.

4. **Optical / EPMA verification**
   - The false colour image is verified using optical microscopy and EPMA. Minerals with similar chemistry can overlap in the QEMSCAN® database.

5. **Classification adjustments**
   - The original mineral list is edited to remove overlaps. Each deposit has ≥1 mineral list. Modal abundance and mineral association data produced providing information to WP3-5. The new deposit-specific mineral lists are to be used for processing products from WP3-5.

Example of data verification and adjustment of mineral databases:

- Mixed classification
- 1st classification
- Thin section
- BSE image
- Final classification

Fe amphibole
Sphalerite
INITIAL QEM SCAN RESULTS (FROM CSM)

Mineral Name
- Background
- Quartz
- K-Feldspar
- Plagioclase feldspar
- Dioctahedral mica
- trioctahedral mica
- Chlorite
- Tourmaline
- Kaolinite
- Topaz
- Zircon
- Fe-Ox/CO3
- Cassiterite
- Rutile
- Wolframite
- Scheelite
- Columbite
- REE minerals
- Uraninite
- Pyrite
- Chalcopyrite
- Cu arsenides
- Sphalerite
- Galena
- Bismuthinite
- Cobaltite
- Calcite
- Fluorite
- Apatite
- Others

CNV-007 Mineralogical Analysis BSE
TASK 2.2. COMPUTED TOMOGRAPHY (NHM)

- Method allows the 3D imaging of material
- Ideal for assessing distribution of ore minerals within the rock mass
- Able to quantify size distributions
- Requires integration with information from other methods

CT animation of half-core: heavy vs light fraction (SnW ore & LiFe mica vs quartz & fsp)
The construction of a Raman spectra database of lithium-bearing minerals (namely of lepidolite, spodumene, petalite, lithiophilite, amblygonite, montebrasite and cookeite) is being constructed, since Li is not detected under SEM.

Additional work will be conducted at NHM using LA-ICP-MS analysis to develop methods to allow the direct measurement of Li.
RAMAN SPECTROSCOPY APPLICATION

• Raman analysis is possible without previous preparation of hand samples.

White fibrous mineral identified as petalite.

Lepidolite in a pegmatite.
RAMAN SPECTROSCOPY APPLICATION

• Raman analyses on thin-sections

Lpd – lepidolite; Tpz – topaz; Mnt – montebrasite; Zr – zircon
Raman analyses performed on lepidolites from both aplitic (spectrum A) and pegmatitic facies (spectrum P) from Gonçalo reveal distinct Raman features. The Raman spectrum of lepidolite from the aplitic facies shows similar features to lepidolite + albite.

Lepidolite with very-fine (< 0.06 mm) grain size
Pöhla skarn ore (amphibole-sphalerite skarn): POHS-17-1b

- Background
- Quartz
- Plagioclase feldspar
- Trioctahedral mica
- Epidote group
- Actinolite
- Fe-amphibole
- Chlorite
- Talc
- Diopside
- Zircon
- Fe oxides
- Malayaite
- Cassiterite
- Titanite
- Calcite
- Fluorite
- Apatite
- Pyrite
- Sphalerite
- Chalcopyrite
- Galena
- Gypsum
- Zincite
- Others

Inclusions of pyrite and chalcopyrite in sphalerite.

Fe amphibole intergrown with sphalerite.
MINERALOGY OF PÖHLA SCHIST ORE (1)
### MINERALOGY OF PÖHLA SCHIST ORE (2)

#### Table

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<th>Mo</th>
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<td>-0.133</td>
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<td>-0.073</td>
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<td>-0.03</td>
<td>-0.038</td>
<td>0.186</td>
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<td>78.759</td>
<td>-0.003</td>
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<td>-0.105</td>
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<td>-0.008</td>
<td>0.006</td>
<td>0.36</td>
<td>0.004</td>
<td>78.538</td>
<td>0.024</td>
<td>-0.074</td>
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<td>0.092</td>
<td>0.016</td>
<td>0.042</td>
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</table>
MINERALOGY OF PÖHLA SCHIST ORE (3)

Gonçalo: GON6

Mineral Name
- Background
- Quartz
- Plagioclase feldspar
- Triorthohedral mica
- Lepidolite
- Chlorite
- Tourmaline
- Kaolinite
- Topaz
- Al silicates
- Zircon
- Fe-Ox/CO3
- Mn oxides
- Cassiterite
- Rutile
- Ilmenite
- Columbite
- REE minerals
- Amblygonite-Montebrasite
- Uraninite
- Fluorite
- Apatite
- Secondary phosphates
- Others

Gonçalo: GON12

Amblygonite-montebrasite altered to secondary phosphates, intergrown with muscovite and plagioclase.

Biotite intergrown with apatite, rutile and alkali feldspar.
Cross-polarised light optical photo and QEMSCAN mineral map of comb-textured quartz (Qz) vein with coarse **cassiterite** (Cst) and a core of fluorite (Fl), chlorite (Chl) and K-feldspar (Ksp). The vein follows the fabric of the host quartz + K-feldspar + muscovite (Ms) schist at Pöhla-Tellerhäuser, Germany (UNEXE)
### Simplified empiric overview of mineral deportment of elements in the Tellerhäuser Sn-W (In) complex deposit (for mineralogical and geochemical proof of concept case study)

<table>
<thead>
<tr>
<th>Main elements of W Erzgebirge complex deposit:</th>
<th>Actual by-product suite in the focus of our work:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn    cassiterite, malayaite, garnet, sulphides</td>
<td>In   roquesite (&amp; Cu, Zn, As, Fe sulphides)</td>
</tr>
<tr>
<td>W     wolframite, scheelite, arsenopyrite</td>
<td>Ga   arsenopyrite</td>
</tr>
<tr>
<td>Zn    sphalerite</td>
<td>Ge   sphalerite, topaz</td>
</tr>
<tr>
<td>Cu    chalcopyrite, bornite</td>
<td>Sc   wolframite, sphalerite</td>
</tr>
<tr>
<td>Fe    magnetite, pyrite, pyrrhotite</td>
<td>Nb   cassiterite, Fe,Ti-minerale, columbite</td>
</tr>
<tr>
<td></td>
<td>Ta   cassiterite, Fe,Ti-minerale, tantalite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact from veins of 5-element-formation:</th>
<th>Penalty by-product elements (economic value):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi    Bi-sulphides, sulphosalts, arsenopyrite</td>
<td>Cd    sphalerite</td>
</tr>
<tr>
<td>Ag    sulphosalts, sulphides, arsenides, native Ag</td>
<td>As    arsenopyrite, loellingite</td>
</tr>
<tr>
<td>Ni    Ni-sulphides, pyroxene, garnet, amphibole</td>
<td>P     apatite, phosphate xx in magnetite</td>
</tr>
</tbody>
</table>
CONCLUSIONS FROM BULK ORE STUDY

Hämmerlein bulk samples – Conclusion for WP 3/WP 4 work

- all samples contain more or less lumps of barren material / rimrock
- valuable components are ± concentrated in specific sections (veins, Bands...)
  → pre-concentration is an important issue (HMS, XRT, optical sorting)
- components have different comminution behaviour
  → gentle grinding is required
  → gradual comminution with removal of free material at each stage
- skarn ore has the expected complex characteristics
  → multistage processing required: combination of
    - magnetic, gravity, flotation
    - multistage flotation (at least cassiterite – sulphides)
- environmental issues (waste reduction, ± marked arsenic contents, cadmium)

Zlaty Kopec ore

Tin is contained as pseudomorphoses of schoenfliesite + magnetite after hulsite (product of hydrothermal alteration)

bulk ore composition:

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Fe</td>
<td>36,7%</td>
<td>%</td>
</tr>
<tr>
<td>S</td>
<td>5,4%</td>
<td>%</td>
</tr>
<tr>
<td>As</td>
<td>0,1%</td>
<td>%</td>
</tr>
<tr>
<td>Sn</td>
<td>5,1%</td>
<td>%</td>
</tr>
<tr>
<td>Zn</td>
<td>8,8%</td>
<td>%</td>
</tr>
<tr>
<td>B</td>
<td>2537 ppm</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>542 ppm</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>36,5 ppm</td>
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</tbody>
</table>
Li-bearing minerals pose analytical challenges
Development of the Raman library and the LA-ICP-MS analytical run will address this
MAJOR ISSUES WITH ANALYSIS OF LITHIUM

• Light Metal
• Under-reported in SEM/Laser techniques

FAME ores are rich in Lithium, hence need to be able to characterise Li content accurately

FAME (LNEG/UP working with NHM & CSM) has built up a RAMAN database for Lithium bearing minerals

* Potential to be used for accurate Li-determination

SERENDIPITY – Not envisaged at proposal stage BUT may establish the basis for ‘exploitable’ results.
FAME CONSORTIUM DRIVEN BY INDUSTRY

• COLT RESOURCES – PORTUGAL
  FAME helping to deliver business plan

• GEOMET – CZECH REPUBLIC
  FAME R&D shortens time to BFS & reopening, unlock by-products

• SAXORE - GERMANY
  FAME R&D to improve by-product recovery & exploitation route

• WOLF - UK
  FAME help to reduce operating costs / to improve recovery?
Thank you for your attention!