MINING WASTE MANAGEMENT IN CHILE: EXPERIENCE, CHALLENGES AND OPPORTUNITIES

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WORKSHOP ON BEST PRACTICES ON MINING POLICIES AND TECHNOLOGIES
Thematic session 2 - Mining waste management and mine rehabilitation

BREY Building, European Commission
15-16 / 10 / 2015, Brussels, Belgium
AGENDA

1. Mining production in Chile
2. Environmental regulations
3. Waste generation from copper processing
4. Waste management and metals recovery
5. Final Remarks
Today, Chile is the largest producer of copper in the world and a globally significant supplier of Mo, Re, Ag, Au, and industrial minerals, like nitrate, lithium and iodine, among others.

### 2014 Production (*)

<table>
<thead>
<tr>
<th>Main Metals &amp; minerals</th>
<th>Volume</th>
<th>Global ranking</th>
<th>Global share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (Mton)</td>
<td>5.8</td>
<td>1º</td>
<td>31%</td>
</tr>
<tr>
<td>Molybdenum (kton)</td>
<td>48.8</td>
<td>3º</td>
<td>16%</td>
</tr>
<tr>
<td>Gold (ton)</td>
<td>46</td>
<td>18º</td>
<td>1.6%</td>
</tr>
<tr>
<td>Silver (ton)</td>
<td>1,572</td>
<td>5º</td>
<td>6.0%</td>
</tr>
<tr>
<td>Iron ore (Mton)</td>
<td>18.9</td>
<td>14º</td>
<td>0.6%</td>
</tr>
<tr>
<td>Nitrates (Mton)</td>
<td>0.7</td>
<td>1º</td>
<td>100%</td>
</tr>
<tr>
<td>Iodine (kton)</td>
<td>19</td>
<td>1º</td>
<td>60%</td>
</tr>
</tbody>
</table>

(*) 50% of rhenium world production, obtained as a by-product from roasted Mo concentrates

2025

<table>
<thead>
<tr>
<th>Potencial Volume (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
</tr>
<tr>
<td>96</td>
</tr>
<tr>
<td>81</td>
</tr>
<tr>
<td>3,067</td>
</tr>
<tr>
<td>33</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>31</td>
</tr>
</tbody>
</table>

(**) According to Cochilco’s forecast (2015): US$ 77 billion with 42 projects

Note: by 2018, first TiO₂ production in Chile: 200 kt/y as concentrate (95% TiO₂)
1. Mining production (2/3)

a. Growth in copper production from 1990 to 2014

<table>
<thead>
<tr>
<th>Final product</th>
<th>Production (metric ton)</th>
<th>World share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine (total)</td>
<td>1,588,400 5,750,000</td>
<td>31.1 (1)</td>
</tr>
<tr>
<td>Concentrate</td>
<td>259.9 2,549,800</td>
<td>18.9 (1)</td>
</tr>
<tr>
<td>Cathode SX-EW</td>
<td>122.1 1,844,000</td>
<td>48.0 (1)</td>
</tr>
<tr>
<td>Cathode E-R</td>
<td>955.6 885.4</td>
<td>9.0 (3)</td>
</tr>
<tr>
<td>Blister and other (*)</td>
<td>250.8 470.8</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

(*) blister and fire refined; N.A.: not available

b. Main copper producers, 2014

<table>
<thead>
<tr>
<th>Operation</th>
<th>Main Owners</th>
<th>Production (kton)</th>
<th>% total</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 operations (*)</td>
<td>Codelco (100%)</td>
<td>1,841</td>
<td>32.0%</td>
</tr>
<tr>
<td>Escondida</td>
<td>BHP-Billiton (57.5%), Rio Tinto (30%)</td>
<td>1,165</td>
<td>20.3%</td>
</tr>
<tr>
<td>Collahuasi</td>
<td>Anglo American (44%), Glencore (44%)</td>
<td>470</td>
<td>8.1%</td>
</tr>
<tr>
<td>Los Bronces</td>
<td>Anglo American (50.1%), Codelco (24.5%)</td>
<td>437</td>
<td>7.6%</td>
</tr>
<tr>
<td>Los Pelambres</td>
<td>Antofagasta Minerals (60%), Japanese investors (40%)</td>
<td>405</td>
<td>7.0%</td>
</tr>
<tr>
<td>Centinela (**)</td>
<td>Antofagasta Minerals (70%), Japanese co.</td>
<td>278</td>
<td>4.5%</td>
</tr>
<tr>
<td>Pampa Norte (***)</td>
<td>BHP-Billiton (100%)</td>
<td>256</td>
<td>4.5%</td>
</tr>
<tr>
<td>El Abra</td>
<td>Freeport McMoRan (51%), Codelco (49%)</td>
<td>166</td>
<td>2.9%</td>
</tr>
<tr>
<td>Candelaria</td>
<td>Lundin Mining (100%)</td>
<td>135</td>
<td>1.7%</td>
</tr>
<tr>
<td>Zaldivar</td>
<td>Barrick (50%), Antofagasta Minerals (50%)</td>
<td>100</td>
<td>2.2%</td>
</tr>
<tr>
<td>Others</td>
<td>Over 20 medium size mines and small operations</td>
<td>492</td>
<td>9.7%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5,745</td>
<td>100%</td>
</tr>
</tbody>
</table>

(*) Chuquicamata, Radomiro Tomic, Ministro Hales, Gabriela Mistral, Salvador, Andina and El Teniente
(**) El Tesoro and Esperanza mines
(***) Cerro Colorado and Spence mines

Source: Cochilco, 2015 Yearbook and Report on Mining Investment for Copper and Gold; Analysis AL Prospecta
By 2026: >90% of new Cu production will be in the form of concentrate

Concentrate exports:
- 2014: 2.55 Mton (65.3% of the total production)
- 2026: 4.4 Mton (73.6% of the total production)
AGENDA

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2. Environmental regulations

a) Regulations affecting mining operations and copper smelters

- **Environmental Law 19,300**: 1991
- **D.S. 90**: Discharges of industrial wastes into water: 1999
- **DS 148**: Sanitary Regulation on Handling of Dangerous Wastes: 2003
- **Law 20,551**: Mine Closure (*): 2012

Decontamination plans to reduce SO₂, MP and As emissions from smelters:
- Ventanas (1992)
- Chuquicamata (1993)
- Paipote (1995)
- Potrerrillos (1998)
- Caletones (1998)

- **DS 165/99**: As emission standard for smelters: 1999
- **D.S. 248**: Tailing Management: 2007
- **D.S. 28**: Air emission standard for smelters: As and SO₂: 2013

Next environmental regulations?

Source: AL Prospecta’s analysis using data from Ministry of Environment, CONAMA, EcoMetales Limited

(*) Including technical, safety and financial obligations for large, medium and small scale operations
b) SO$_2$ and As emissions from Cu smelters, the present standard, and future standard to be reached between 2016 and 2018

<table>
<thead>
<tr>
<th>Smelter</th>
<th>Sulphur dioxide emissions (t/y)</th>
<th>Arsenic emissions (t/y)</th>
<th>Source: AL Prospecta's analysis using data from Ministry of Environment, CONAMA, Chilean Copper Commission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chuquicamata</td>
<td>56,600</td>
<td>92,104</td>
<td>49,700</td>
</tr>
<tr>
<td>Caletones</td>
<td>230,000</td>
<td>118,642</td>
<td>47,680</td>
</tr>
<tr>
<td>Potrerillos</td>
<td>100,000</td>
<td>82,258</td>
<td>24,400</td>
</tr>
<tr>
<td>Altonorte</td>
<td>24,000</td>
<td>44,251</td>
<td>24,000</td>
</tr>
<tr>
<td>Ventanas</td>
<td>90,000</td>
<td>18,820</td>
<td>14,650</td>
</tr>
<tr>
<td>Chagres</td>
<td>14,400</td>
<td>13,437</td>
<td>13,950</td>
</tr>
<tr>
<td>Hernán Videla Lira</td>
<td>40,000</td>
<td>23,021</td>
<td>12,880</td>
</tr>
<tr>
<td>Ministro Hales (*)</td>
<td>-</td>
<td>-</td>
<td>548</td>
</tr>
</tbody>
</table>
| **Note:** (*): Roasting plant starting operation by 2014.

- Investment to reach new standard (95% S capture): US$ 2 billion, mainly from State’s smelters: Codelco and ENAMI facilities
- In process: review quality standard for SO$_2$ – by 2020
c) Law 20,551: mine closure for mining and metallurgical operations

**Main objectives:**
- To protect life, health and safety of people and the environment.
- To mitigate the negative effects of the mining industry.
- To avoid “new” abandoned mining operations and plants.
- To ensure the physical and chemical stability of mining facilities (i.e. tailings dam)
- To establish a financial guarantees covering mine closure costs.
- To create a post-closure fund for monitoring closed mining operations

**Main characteristics:**
- To submit a mine closure plan to the National Geological Service
- Different requirements, according exploitation or processing rate (10 kt/month)
- working plan and related activities based on risk assessment + economic evaluation
- Proposal of financial guarantees + payment schedule related to mine life

**Result (to Dec 2014):**
- 134 plans were submitted with a total value of US$ 12 billion

Source: AL Prospecta’s analysis using data from National Geological Service (SERNAGEOMIN)
1. Mining production in Chile
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5. Final Remarks
3. Waste generation (1/4)

**a) Concentrator plants**

- 15 large-size operations (> 50 kton/y Cu production)
- +10 operations of medium-size

**Tailings generation (Mton/y):**
- 2014: 511 (1.4 Mt/d)
- 2026: 1,078

Source: AL Prospecta’s analysis using data from mining companies, SERNAGEOMIN; Cochilco
3. Waste generation (2/4)

a) Concentrator plants: tailings dams

<table>
<thead>
<tr>
<th>Type</th>
<th>Total</th>
<th>Main regions - location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N°</td>
<td>%</td>
</tr>
<tr>
<td>Active</td>
<td>161</td>
<td>24.5% Copyapó, Coquimbo, Valparaíso</td>
</tr>
<tr>
<td>No active</td>
<td>364</td>
<td>55.3% Copyimbo, Copyapó, Valparaíso</td>
</tr>
<tr>
<td>Abandoned</td>
<td>94</td>
<td>14.3% Copyimbo, Antofagasta, Copyapó</td>
</tr>
<tr>
<td>Without information</td>
<td>39</td>
<td>5.9% Copyapó, Copyimbo</td>
</tr>
<tr>
<td>Total</td>
<td>658</td>
<td>100%</td>
</tr>
</tbody>
</table>

Source of tailings dam – metal processed:

- Copper: 50%
- Gold: 30%
- Without info: 18%
- Other: (*) 02%

Additionally, over 400 abandoned processing plants

(*) iron ore, molybdenum, zinc, silver, industrial minerals.

Source: AL Prospecta’s analysis using data from mining companies and SERNAGEOMIN
3. Waste generation (3/4)

b) Hydrometallurgical plants

- 13 large-size operations (> 50 kton/y Cu)
- Several operations of medium-size

\[ \approx 270 \text{ Mton/year} \]

Source: AL Prospecta’s analysis using data from mining companies
3. Waste generation (4/4)

**c) Smelters**

- Smelters using Flash, Teniente or Noranda technology
- Blister production: 100 to 580 kton/y copper

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**Chile**

- Altonorte (Glencore)
- Chacabuco
- Chuquicamata (CODELCO), *
- Conception
- Copiapó (CODELCO), *
- Curanto
- Osorno
- Puerto Montt
- Puerto Williams
- Valparaíso
- Valdivia
- Tocopilla

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**(*) with refinery**

**Source:** AL Prospecta’s analysis using data from mining companies
AGENDA

1. Mining production in Chile
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4. Waste management and metals recovery

**Operations**

- **Smelter flue dusts (2007):**
  - EcoMétales Limited (Codelco)
  - Cu in solution sent to SX-EW facilities

- **Cu flotation tailings (2008):**
  - CMP magnetite plant (CAP)
  - Iron ore concentrate

- **Acid drainage (1984):**
  - Underground mine El Teniente (Codelco)
  - 3-4 kton/y Cu cathodes

- **Smelter flue dust (1982):**
  - Caletones smelter (Codelco)
  - Cu in solution sent to SX-EW facilities

- **Cu flotation tailings (1992):**
  - Minera Valle Central (Amerigo Res.)
  - Cu-Mo concentrate from fresh and old tailings

- **Mining waste (year startup):**
  - Plant’s name – owner
  - Metal recovery or waste generation

**Projects & R+D**

- **Anodic slimes (under construction):**
  - SpA Metals Recovery Plant (LS-Nikko Copper, 66% - Codelco, 34%)
  - 4k/y processing plant to recover Cu, Au and Ag and PGM’s (Pt, Pd, Rh), Te, Se, etc.

- **Roasting plant flue dusts (under study):**
  - Ministro Hales plant (Codelco) – EcoMétales
  - Waste generation: > 20 kt/y containing Cu, Ag, Bi and As

- **Old flotation tailings – Chañaral beach (feasibility study):**
  - Playa verde Project (Copper Bay) to process 5 Mt/y during 10 years
  - Concentrate (Cu, Au) and Cu cathodes

- **Cu slags:**
  - Several smelters testing in road construction
  - Some R+D to recover metals

- **Flotation tailings:**
  - Several owners
  - Lab testing to recover some rare earths, Ge, Ga, Te, Se, etc.

Source: AL Prospecta’s analysis using data from mining companies
4. Waste management and metals recovery

a) Cu and Mo concentrate from tailings

- Minera Valle Central has rights to process Codelco El Teniente’s tailings to Dec 2037:
  - Fresh: 135 kt/d (0.12% Cu)
  - Colihues (1977-1986): 40 kt/d (0.2-0.23% Cu)
  - Cauquenes (1936-1977): 338 Mt (0.37% Cu) processing 60 kt/d

4. Waste management and metals recovery

b) Iron ore from copper flotation tailings

Typical chemical analysis for a tailings generated from a copper flotation process.

<table>
<thead>
<tr>
<th>% Solid</th>
<th>Fe Total (%)</th>
<th>Fe Mag (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>SiO₂ (%)</th>
<th>CaO (%)</th>
<th>MgO (%)</th>
<th>Al₂O₃ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>18 - 22</td>
<td>10 - 13</td>
<td>0.2 – 0.4</td>
<td>1 - 4</td>
<td>40</td>
<td>3.5 – 4.0</td>
<td>3.5</td>
<td>8 - 9</td>
</tr>
</tbody>
</table>

CMP magnetite plant (iron ore operator)

- Since 2008, this plant treats tailings (10% mag Fe and 1% S) from a flotation plant (a copper operation) located in Atacama region.
- About US$ 70 in investment to produce about 3.5 Mton/y of iron ore concentrate (> 68% Fe)
- Process includes: magnetic concentration (Rougher), Milling, magnetic concentration (Cleaner), Flotation (Inverse pneumatic).

- Challenges: access to port (iron ore exports), high S level in copper tailings

4. Waste management and metals recovery

c) Copper slag: research to recover value metals

- Chemical analysis: 30-40% Fe, 35-40% Silica, 10% calcium oxide, 1% Cu, 0.3% Mo, as well as Zn and precious metals, among others)

Research and flowsheet proposals:
- Target: recovery of Cu, Mo, Fe.
- Hydro and pyrometallurgical routes have been proposed, including a roasting-leaching, IX (Mo) and SX-EW flowsheet.
- However, no pilot plant yet, and more research is required to solve remaining challenges, such as proper separation of Mo-Fe, and high acid consumption

- Now, testing slag as material for road construction.

Source: Propuesta recuperación Mo desde escorias, Proyecto FONDEF D02 I 1159, Univ. De Concepción, Chile, 2006
d) Treatment of smelter flue dusts

• Since 2007, EcoMetales treats smelter flue dusts, mainly generated from Codelco smelters:

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>As</th>
<th>S%</th>
<th>Bi</th>
<th>Cd</th>
<th>Pb</th>
<th>Sb</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-30%</td>
<td>1-17%</td>
<td>0.8-13%</td>
<td>0.1-0.9%</td>
<td>0.2-20%</td>
<td>0.5-12%</td>
<td>0.1-1.5%</td>
<td>Ge, Mo, Ag, etc.</td>
</tr>
</tbody>
</table>

• Main achievements:
  ✓ >350 kton of dusts and >500,000 m$^3$ of refinery effluent
  ✓ >67 kton of Cu recovery, contained in a PLS solution
  ✓ Up to 10 kt/y of As is precipitated and disposed of as Scodorite (crystalline ferric arsenate).
  ✓ Precipitation also includes Sb and Cd, meeting D.S. 148 requirements.

New focus: Recovery of Mo, Re, Ge, Pb, Ag, and other metals from PLS and leached residue.

EcoMetales plant at Codelco Norte`s facilities, Chile

**4. Waste management and metals recovery**

**e) Chemical characterization of old tailings (*)**

<table>
<thead>
<tr>
<th>Chemical element</th>
<th>Minimum [gr/ton]</th>
<th>Maximum [gr/ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>800</td>
<td>18,880</td>
</tr>
<tr>
<td>Ti</td>
<td>107</td>
<td>4,000</td>
</tr>
<tr>
<td>V</td>
<td>27.5</td>
<td>206</td>
</tr>
<tr>
<td>Mn</td>
<td>113</td>
<td>37,660</td>
</tr>
<tr>
<td>Fe</td>
<td>10.100</td>
<td>183,450</td>
</tr>
<tr>
<td>Co</td>
<td>6.0</td>
<td>199</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2</td>
<td>19,300</td>
</tr>
<tr>
<td>Mo</td>
<td>8.5</td>
<td>200</td>
</tr>
<tr>
<td>Zn</td>
<td>0.3</td>
<td>16,290</td>
</tr>
<tr>
<td>Ga</td>
<td>2.1</td>
<td>35</td>
</tr>
<tr>
<td>Ge</td>
<td>1.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Se</td>
<td>0.6</td>
<td>2,202</td>
</tr>
<tr>
<td>Sr</td>
<td>72.4</td>
<td>1,138</td>
</tr>
<tr>
<td>Sb</td>
<td>2.1</td>
<td>581</td>
</tr>
<tr>
<td>Ba</td>
<td>1.0</td>
<td>70,576</td>
</tr>
<tr>
<td>W</td>
<td>5.0</td>
<td>52</td>
</tr>
<tr>
<td>Te</td>
<td>6.4</td>
<td>8.6</td>
</tr>
</tbody>
</table>

• Lab testing to recover some rare earths, Ge, Ga, Te, Se, Sr, V, etc.

(*) from medium copper mining companies sites
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5. Final remarks

a) What is Chile doing to stay competitive?

Roadmap

Source: Chilean Copper Commission
b) Mining Waste: New source of metals and materials

MINING AND METALLURGICAL OPERATIONS

Mineral Resources

Main gas, liquid and solid wastes
- Mining and processing
  ✓ Acid drainage
  ✓ OTR Tyres, oil (mining trucks)
  ✓ Flotation tailings
- Smelting and Refining
  ✓ SO₂, arsenic and PM emissions.
  ✓ Slags
  ✓ Flue dust
  ✓ Refinery effluent
- Hydrometallurgical plants
  ✓ Waste rock
  ✓ Leached ore
  ✓ Raffinate effluent

Inputs
- Water
- Energy
- Chemicals
- Oil
- Tyres
- Steel, etc.

Metals and mining products
 ✓ to final users or additional processing

5. Final remarks

- Market Access
- International and local regulations
- Waste management and treatment
- Technologies for metals recovery
<table>
<thead>
<tr>
<th>Monday 25</th>
<th>Tuesday 26</th>
<th>Wednesday 27</th>
<th>Thursday 28</th>
<th>Friday 29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening Ceremony EXPOMIN Congress:</td>
<td>2nd Seminar: “Mining Procurement”</td>
<td>4th Workshop: “Technological Development in Mining” - Codelco</td>
<td>2nd Seminar: “Smelting - Refining”</td>
<td>2nd Round Table: “Labor and Human Resources Challenges in Mining”</td>
</tr>
<tr>
<td>“CEO Summit” Round Table</td>
<td>3rd Seminar: “Sustainable Trends”</td>
<td>4th Workshop: “Metal Recovery from Mining Waste” (full-day)</td>
<td>Seminar: “Challenges in Mining Exploration”</td>
<td></td>
</tr>
<tr>
<td>VII Seminar: Mining Competitiveness in the Americas (hosted by National Society of Mining)</td>
<td>2nd Seminar: “Sea Water for Mining”</td>
<td>Seminar: “Productivity in Mining”</td>
<td>2nd Seminar: “Energy Challenges in Mining”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seminar: “Public Policy in the Mining Sector”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(hosted by Ministry of Mining)</td>
<td></td>
<td></td>
<td>1° seminar: Environmental issues in mining</td>
<td></td>
</tr>
</tbody>
</table>

Organiza y Produce:

- AL PROSPECTA Consultores: Technical coordination
5. Final remarks

4th INTERNATIONAL WORKSHOP
“METAL RECOVERY FROM MINING WASTE”

Preliminary program:

- Regulatory and market trends for waste management:
  - European Commission, China, Australia and Chile

- Impurities: Waste or resources?:
  - Market trends
  - Management, neutralization, disposal or production

- Industrial Practices (projects and operations):
  - Chile, South Korea, Australia, Canada

Looking forward for proposals!!!!
MINING WASTE MANAGEMENT IN CHILE: EXPERIENCE, CHALLENGES AND OPPORTUNITIES

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WORKSHOP ON BEST PRACTICES ON MINING POLICIES AND TECHNOLOGIES
Thematic session 2 - Mining waste management and mine rehabilitation

BREY Building, European Commission
15-16 / 10 / 2015, Brussels, Belgium

Many thanks for your attention!!!