Circularity of REE, Critical Metals and Bulk Metals

The case for valorization of mine tailings and end of life streams

Kiril Mugerman – REE Conference – October 2024

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Outline

1. Introduction
2. Case studies
3. Final remarks

Introduction

Introduction

We develop **clean technologies** to extract **critical & strategic metals**

Sourcing from primary ores, mine tailings and industrial waste

Geomega in numbers:

Founded in **2008**

> $23M investments in R&D since 2015

5 patented and patent-pending technologies

A strong team of technical professionals (researchers, engineers, technologists, technicians)

Well-equipped analytical laboratories and piloting facilities

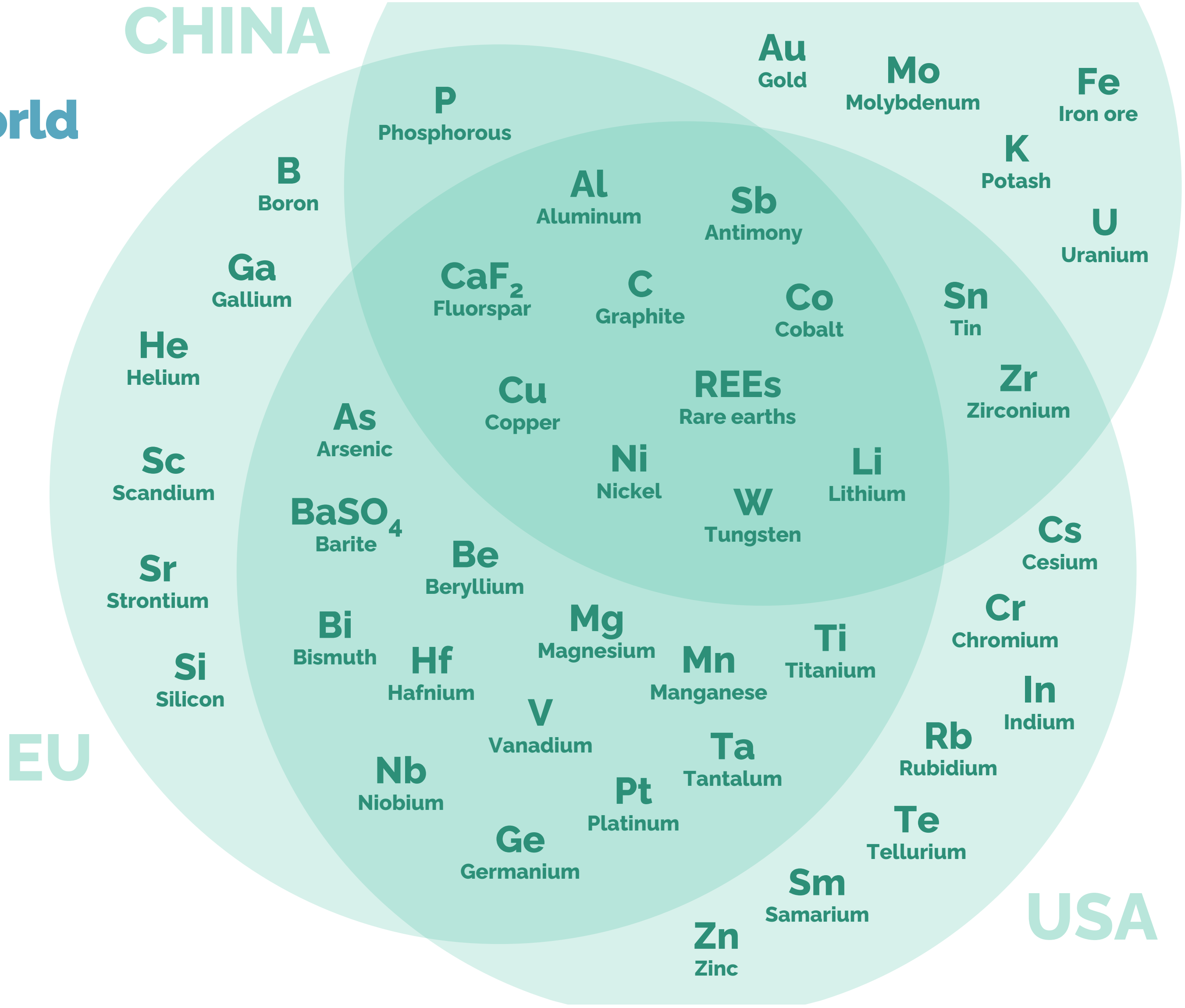
Demonstration plant in construction

Lab and pilot facility expansion planned for 2025

Critical and strategic elements

A growing problem in an evolving world

- Secure and sustainable supply is on every nation's mind
- It changes according to evolving technologies and geopolitics
- Developing mines takes time and is not feasible in every region



Adapted from: IRENA, US. Department of Energy. Diagram by Visual Capitalist, Sept-23.

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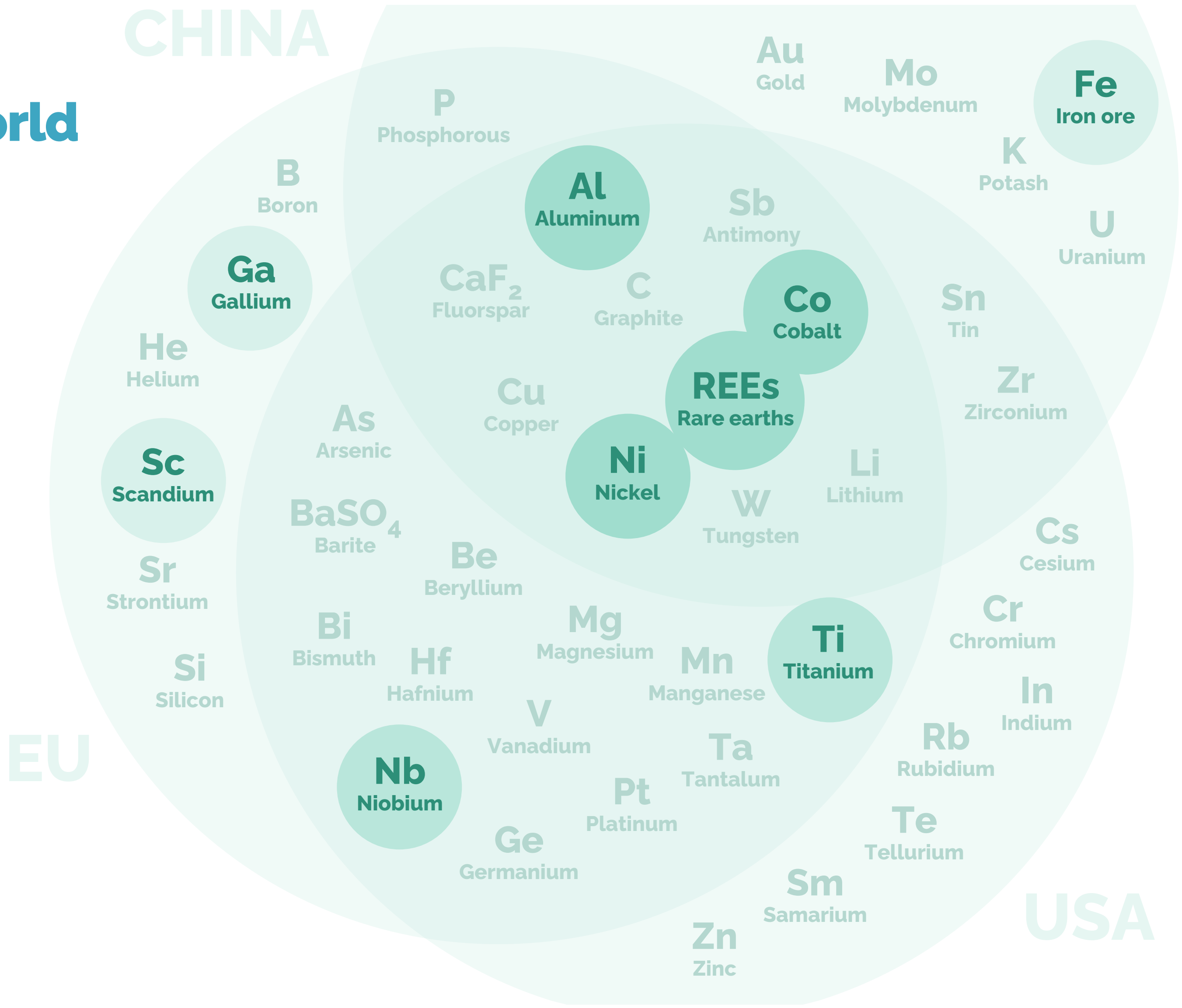

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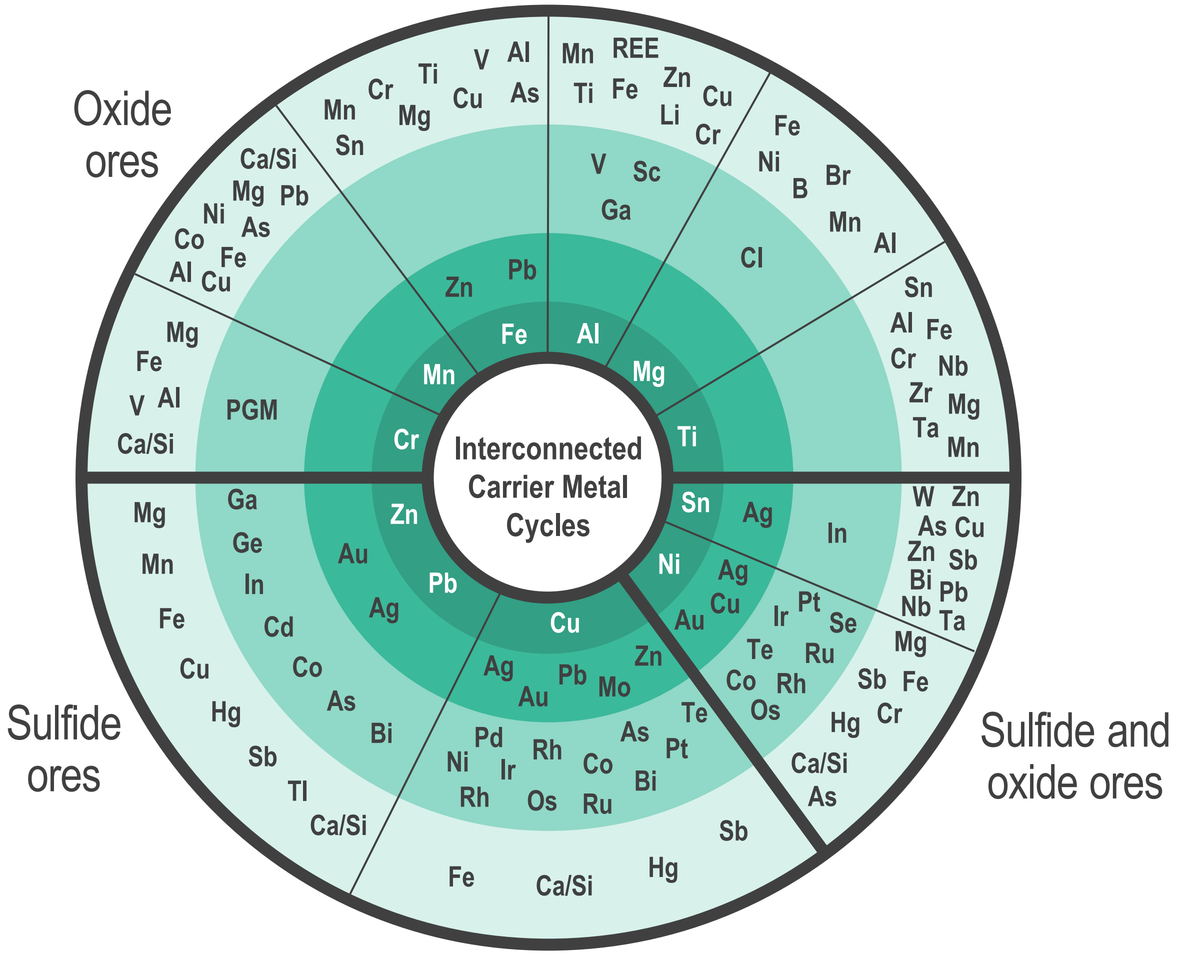
Metal extraction associations

- Critical metals are present in association with other minerals in various deposits
- Grades not high enough to have justified extraction in the original mine design
- Innovative & disruptive methods could allow extraction in certain cases
- Secondary sources such as mine tailings become an important source



Companion metals that end up as residue
Lacking or limited production infrastructure
Broad production infrastructure
Carrier metals

Source: Mulder, 2006. Sustainability Made in Delft

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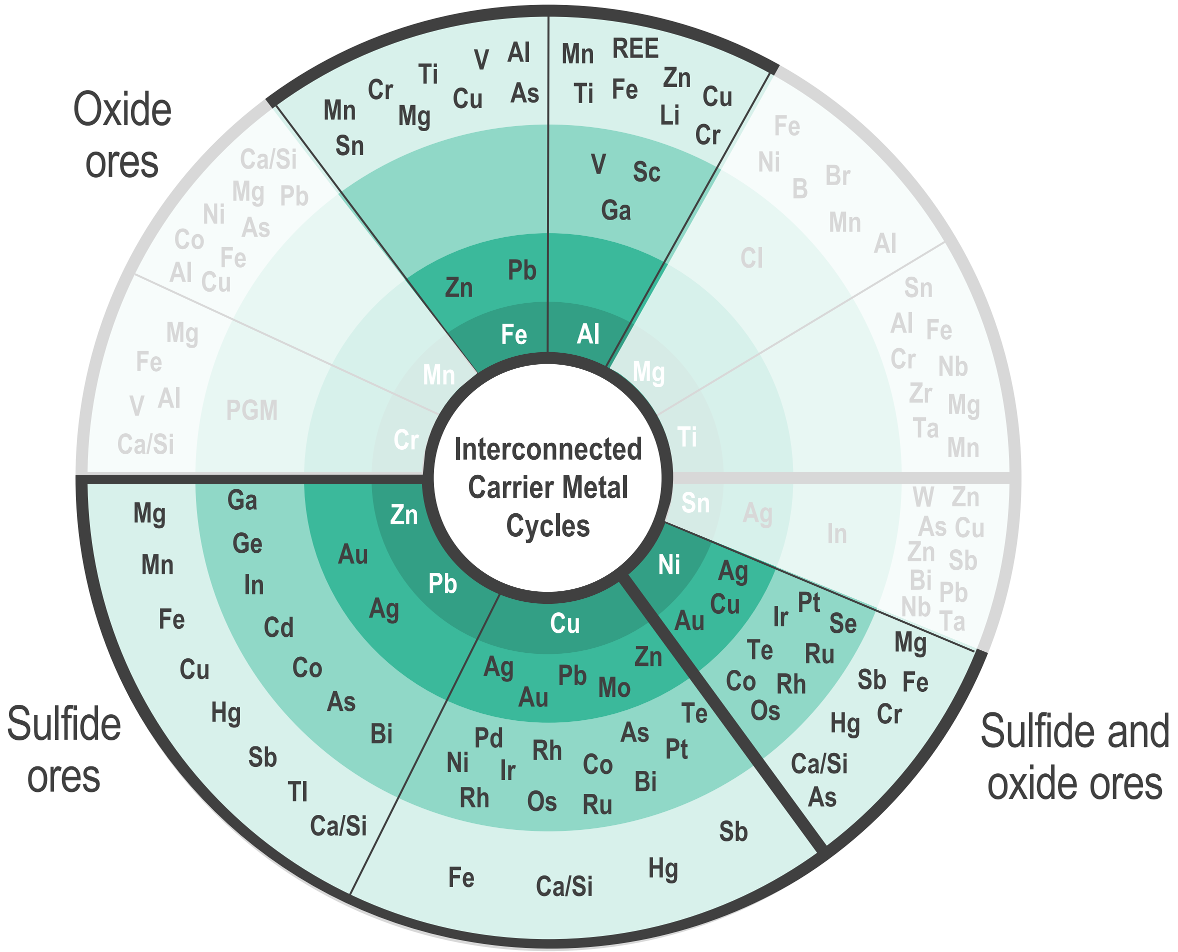


Companion metals that end up as residue
Lacking or limited production infrastructure
Broad production infrastructure
Carrier metals

Source: Mulder, 2006. Sustainability Made in Delft

Why process innovation?

The drivers

- Demand for critical minerals
- Declining ore quality
- Sustainability targets
- Competitivity

Our goals

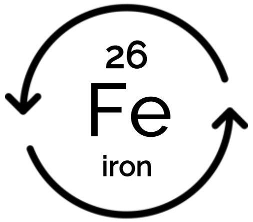
- Tailings and industrial waste valorization
- Processing unconventional ores
- Resource circularity
- Energy efficiency improvement
- GHG reduction

Our approach

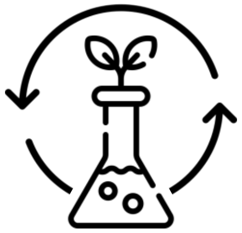
- Recover the bulk metals (Fe, Ca, …)
- Extract the critical metals (REE, Nb, ….)
- Recycle the reagents
- Recover the waste energy

Core technologies

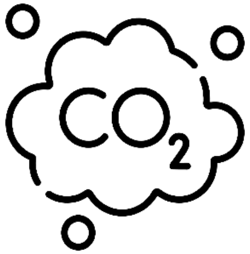
Critical Metals
Extraction & Refining



Iron Recovery
& Valorization

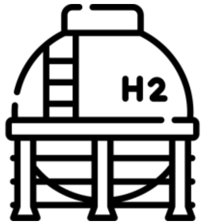


Reagent
Recycling



CO_2 Utilization
& Storage

Process Heat
Recovery



H_2 Production

Value recovery from tailings

Key drivers:

- Need to develop more sustainable production of metals
- Provides secure resources and a diversified supply chain
- Distributes the environmental impact of the project over a wide range of products

Strategy:

- Target bulk minerals and metals with strong established markets to decrease tailings volume
- Leads to grade enrichment for the critical metals present
- Recyclability of reagents allows for a near zero waste operations

Benefits of value recovery from tailings

Social and environmental:

Decreasing social and environmental risks of untreated tailings.

Avoiding the impacts of expanding tailings sites.

Avoiding the costs, delays, risks and impacts of opening new mines.

Cutting complexity, costs and delays to reclaim tailings.

Operational and financial:

Large resource potential.

Simpler access to already fine material.

Use of already available infrastructure.

Case studies

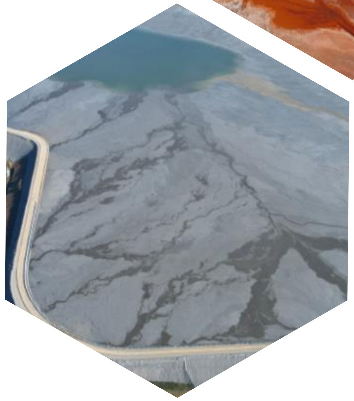
Processing secondary feeds

End-of-life

NdFeB magnet scraps

Industrial

Bauxite residues



Mining

Sulphide tailings

Processing secondary feeds

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NdFeB magnet scraps

Industrial
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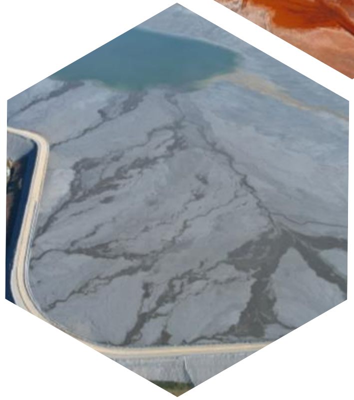


Mining
Sulphide tailings

Reuse vs. elemental recycling

NdFeB magnet reuse:

- Pulverization of the NdFeB alloy (e.g. H_2 decrepitation), then sintering or re-bonding.
- Magnetic coercivity is adjusted by doping the alloy with fresh materials.

Pros

- Simplified chemical treatment
- Less process units and steps required

Cons

- Alloy downgrade (loss of remanence)
- Extra REE required
- Not suitable for all forms of scrap

Elemental recycling:

- Chemical breakdown of NdFeB alloy to the elemental level.
- Enables new magnet formulations.
- Enables new uses for the recycled elements.
- Diversified routes (chlorination, bioleaching, electrochemical) in R&D stage.

Lower environmental footprint achieved with Geomega's process technology.

Geomega's process overview

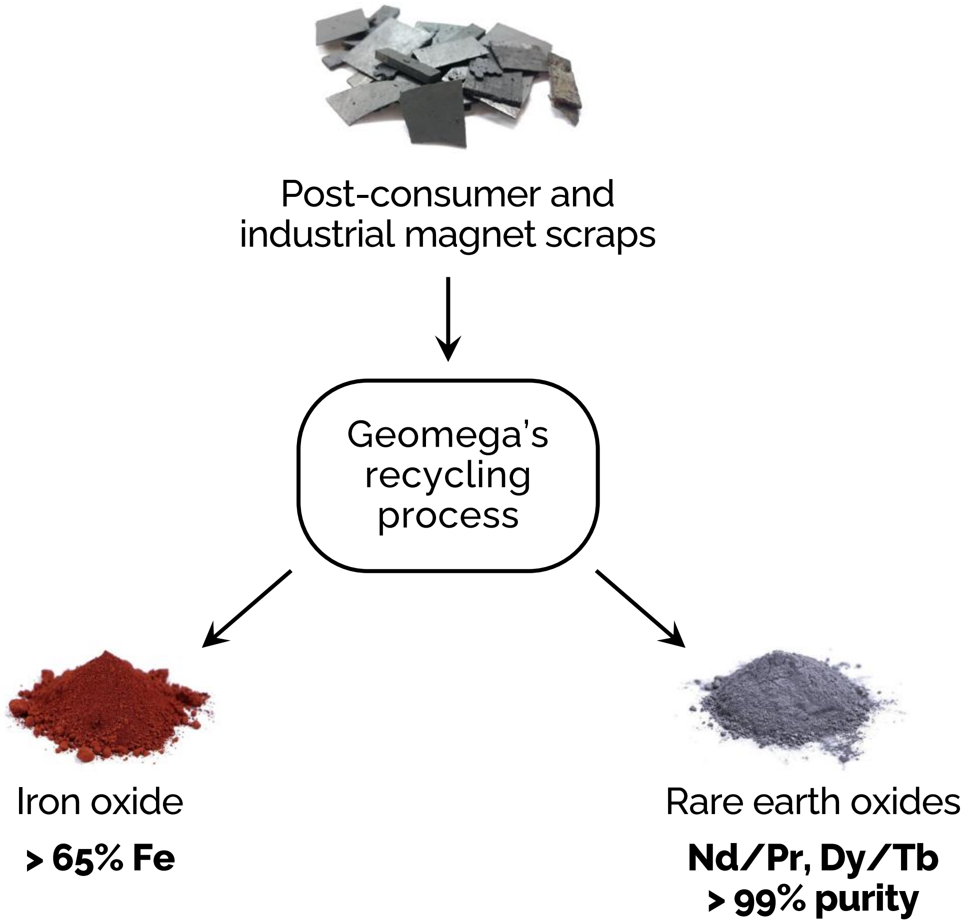
Competitive edge

versus other magnet recycling approaches:

Process chemistry and design:

- ✓ Readily available, non-aggressive main reagent
- ✓ Closed-loop reagent recycling
- ✓ Feed agnostic (coated scrap, swarf, etc.)
- ✓ Use of standard equipment
- ✓ Over 90% REE recovery

Cryogrinding H_2 decrepitation



Geomega's process overview

Competitive edge

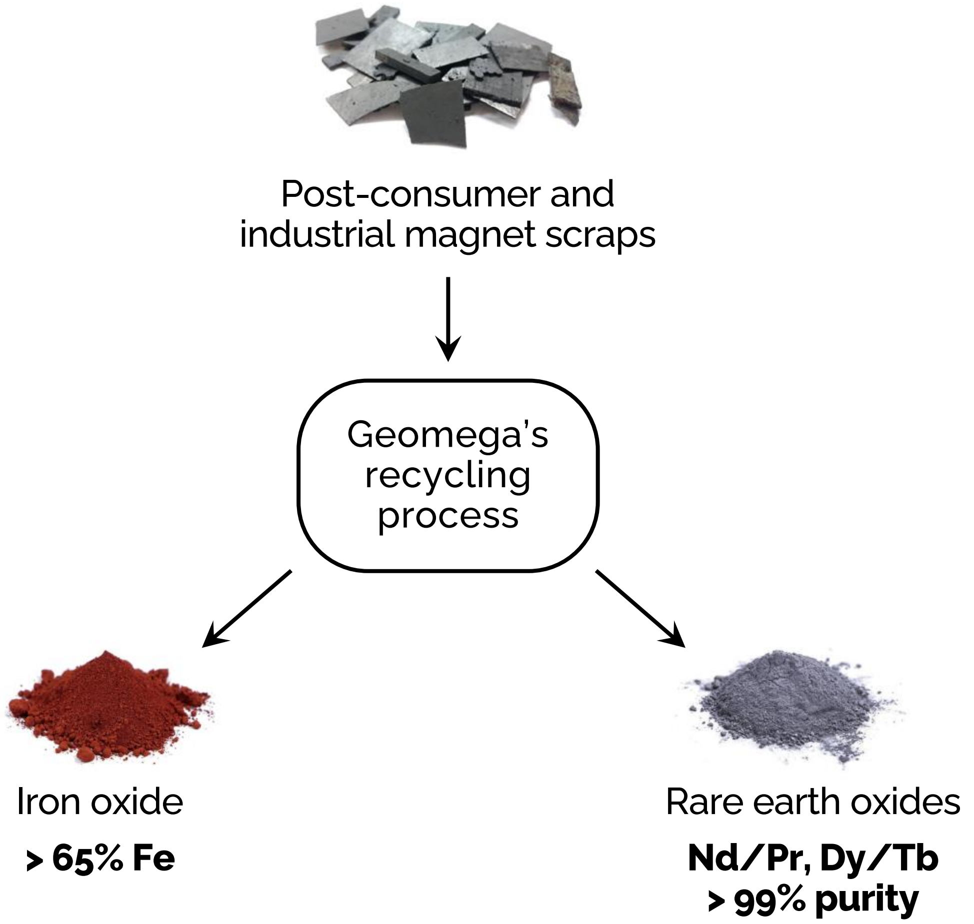
versus other magnet recycling approaches:

Environmental footprint mitigation:

- ✓ Limited effluents and solid waste
- ✓ Recovery of iron in a sellable form
- ✓ Much lower carbon footprint vs. conventional production

Carbon footprint, including Scope 3:

11 kg CO_2/kg REO
46% of conventional production



Project development

- Technology Readiness Level (TRL) 7
- Demonstration plant project ongoing
- Patent pending (provisional PCT application)
- Full ownership of intellectual property by Geomega.

Capacity:
1.5 tonnes of magnet/day

Location:
Saint-Hubert, QC, Canada

Financing from several organisms:

$3M — TECHNO CLIMAT, Québec

$3M — Natural Resources Canada / Ressources naturelles Canada, Canada

$2M — NGen

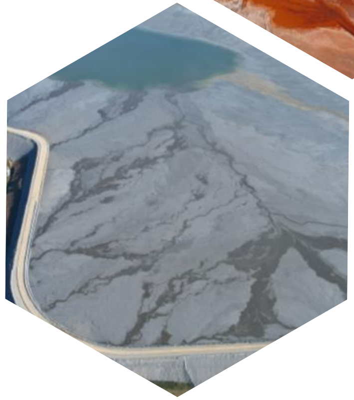
Processing secondary feeds

End-of-life

NdFeB magnet scraps

Industrial

Bauxite residues



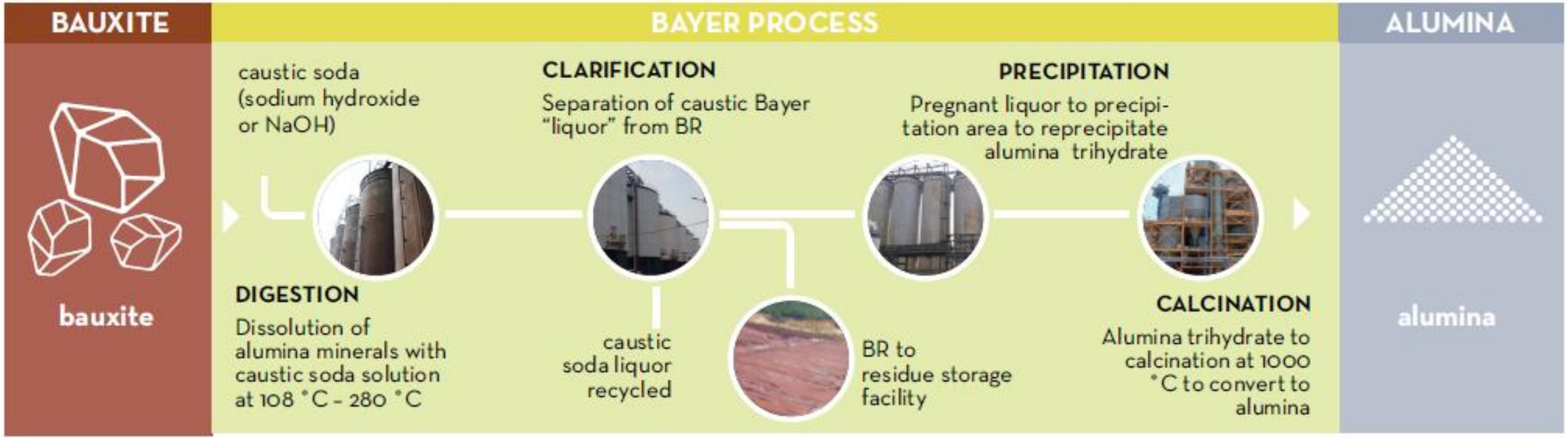
Mining

Sulphide tailings

About bauxite residues

Bauxite residue is a mineral waste resulting from alumina refining via the Bayer Process.

Every new tonne of aluminum metal results in about 4 to 5 tonnes of bauxite residue[1].



Schematic from the International Aluminium Institute, 2022.

1 International Aluminium Institute, 2022. Sustainable bauxite residue management guidance.
2 USGS Mineral Summaries 2024. Available online.

Valorization of bauxite residues

The opportunity

- Global stockpile: over 4 billion tonnes
- Global production: 170 Mt per year
- Finely ground material
- Potential to liberate large areas for other developments
- Large tonnage and high value of critical metals untapped

Geomega's solution

- Recovery of bulk and critical metals
- Resource circularity & waste prevention
- Products of commercial interest
- Addressing clean-tech markets

[1]Source: International Aluminium Institute, 2022. Sustainable bauxite residue management guidance.

Element resources of bauxite residues

Bulk minerals:

Component	Fe_2O_3	Al_2O_3	TiO_2	CaO	SiO_2	Na_2O
Typical range [1] (%)	5-60	5-30	0.3-15	2-14	3-50	1-10

Critical minerals:

- **High total REE**
  - Greece: 1,040 ppm • Jamaica: 1,500-2,500 ppm • China, Russia, Suriname, and others [2,3]

  All REE from bauxite reports to the residue, enrichment factor of two

- **Particularly rich in scandium**
  - Greece: 130 ppm • Jamaica: 390 ppm • Suriname: 1700 ppm • Russia 135 ppm [2]

- **Vanadium, gallium** and other critical metals at extractable concentrations

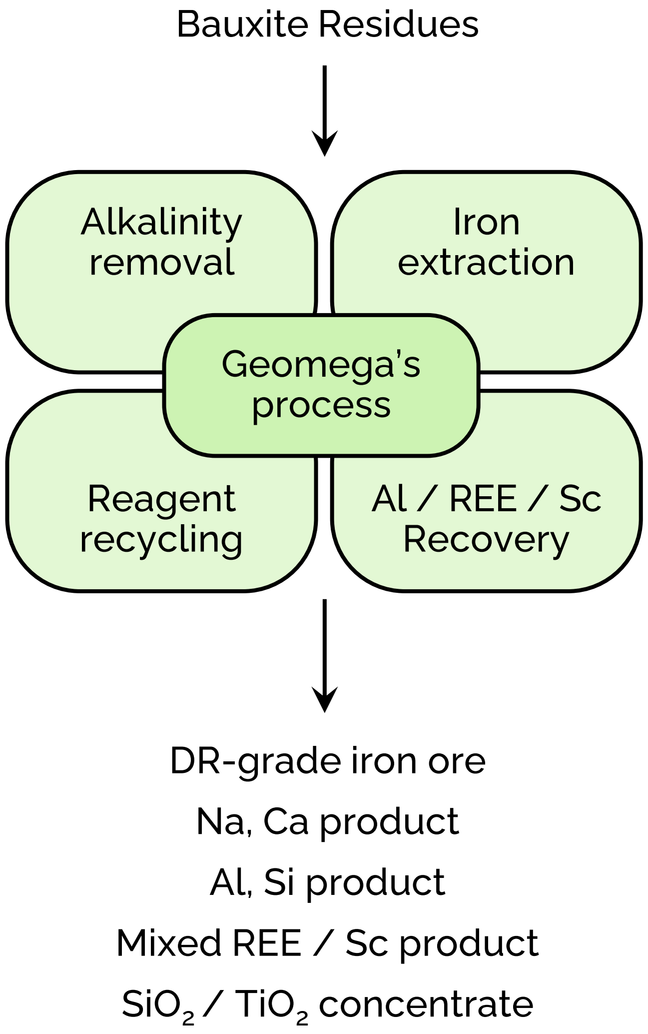
1 International Aluminium Institute, 2022. Sustainable bauxite residue management guidance.
2 Binnemans et al., 2015. Towards zero-waste valorization of rare-earth-containing industrial process residues: a critical review. Journal of Cleaner Production 99, pp 17-38.
3 https://www.lightmetalage.com/news/industry-news/smelting/article-addressing-the-challenge-of-bauxite-residue/

Geomega's process

Three treatment modules to maximize resource recovery

Flexible commercial strategies adopting one, two or three modules in sequence

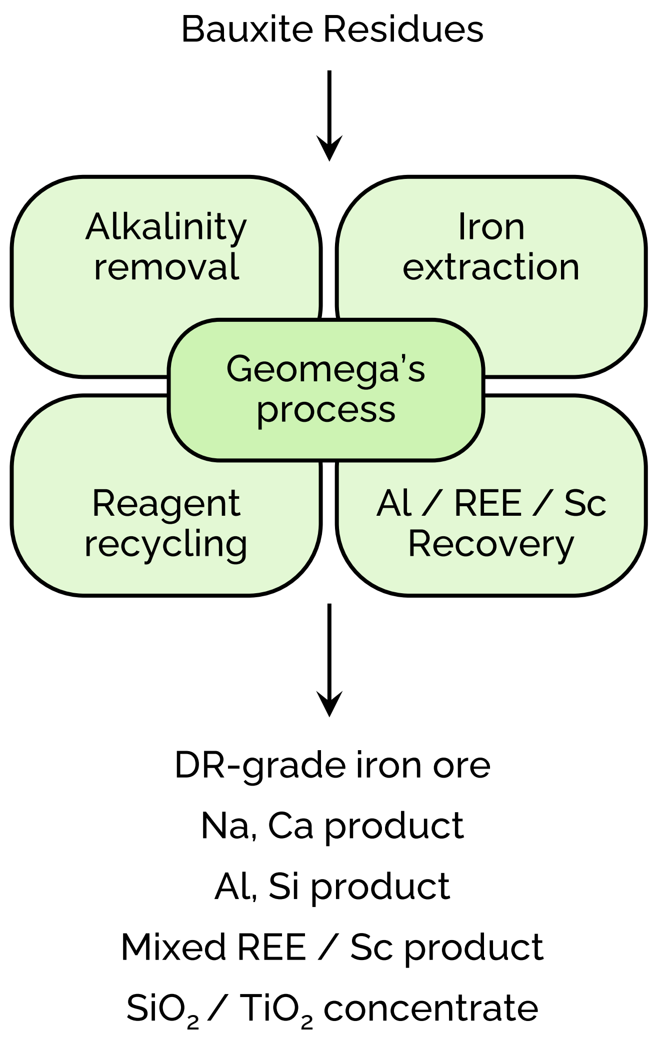
- ✓ Volume reduction potential up to 85%
- ✓ Revenues from various product streams
- ✓ Main reagent recycling at all stages
- ✓ Minimal effluents
- ✓ No hazardous waste
- ✓ No net direct CO_2 emissions



Geomega's process

Addressing key success criteria that has been challenging to prior approaches:

- ✓ Versatility to treat residue from different origins
- ✓ Neutralization with no reagent consumption
- ✓ Higher selectivity for iron than magnetic separation
- ✓ Products for growing market demands
- ✓ Direct recovery of critical metals



GEOMEGA
Rare Earths · Refining · Recycling

Project development

- Technical Readiness Level (TRL) 5-6
- Patent pending (provisional PCT application)
- Full ownership of intellectual property by Geomega.

Timeline

2020
Initial bench-scale experiments

2021
R&D development co-financed by

NGen

2022
$4M piloting and $1M iron valorization projects launched, co-financed by

RioTinto

SUSTAINABLE DEVELOPMENT TECHNOLOGY CANADA
TECHNOLOGIES DU DEVELOPPEMENT DURABLE CANADA

Québec

2023

2024
Ongoing pilot test work

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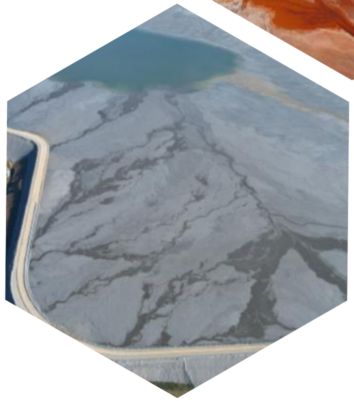


Mining

Sulphide tailings

Implications of sulfide tailings

Land and water impacts:

- One of the most globally predominant and problematic types of tailings
- Risks of acid mine drainage and environmental contamination of harmful metals
- Limited technoeconomic potential reached by prior processing techniques

Case example: pyrrhotite tailings

Resource extraction potential [1,2] :

- Over 100 Mt of material stockpiled worldwide
- Nickel inclusions and lattice substitution in pyrrhotite
- Entrained pentlandite and chalcopyrite
- Other non-ferrous metals (Cu, Co, Au, Ag, PGM)
- Non-sulphide minerals (mafic and felsic silicates, magnetite, etc.)

Duffy, D. et al., 2015. Mineralogical characterization of Sudbury pyrrhotite tailings: evaluating the bioleaching potential. 54th Annual Conference of Metallurgists, Toronto.
Peek, E., et al, 2011. Nickeliferous pyrrhotite – "Waste or resource?" Minerals Engineering 24, pp 625-637.

Objectives for a zero-waste valorization

Iron
High extraction rate and selectivity to obtain low-Ni, DRI-grade iron ore

Nickel
Upgraded nickel concentrate (> 6% Ni) with high recovery rate

Sulfur
Commercial processes to obtain H_2SO_4 or S, flexible commercial strategies

Silicates
Potential reuse of benign gangue minerals as aggregate or filler

Low footprint
Minimize waste, effluents, GHG emissions, and water consumption

Scalability
Cost-effective and robust implementation with integrated energy and material streams

History and challenges encountered

Challenges in prior attempts to valorize pyrrhotite tailings [1,2] :

Thermal upgrading to ferronickel:

Cost of SO_2 management produced during dead roasting

Sulfide waste generated by lime addition

Smelting with limited pre-treatment:

Contaminants in pig iron (Cu, Zn, Pb, Cd)

Direct leaching in strong acids:

Large volume of salt effluents

Challenging Ni/Fe separation

Cost of neutralization and recovery of iron and acid

[1] Peek, E., et al, 2011. Nickeliferous pyrrhotite – "Waste or resource?" Minerals Engineering 24, pp 625-637.
[2] Sridhar, et, al., 1976. Recovery of nickel from nickeliferous pyrrhotite by a thermal upgrading process. Canadian Metallurgical Quarterly, 15(3), 255–262.

Geomega's process

Process chemistry and design:

Iron extraction:

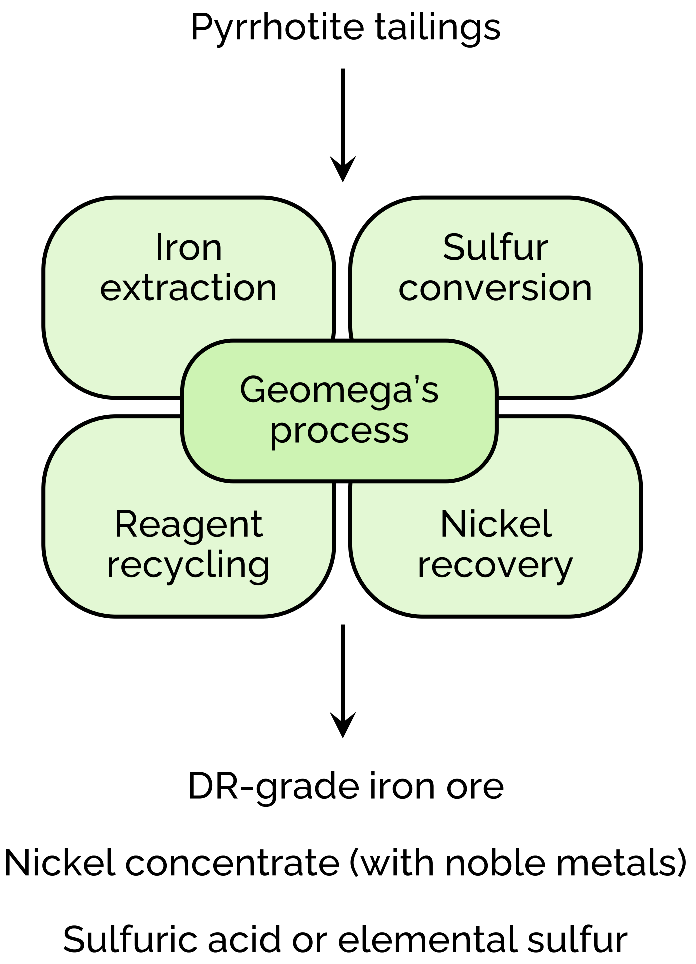
- ✓ No SO_2 off-gas
- ✓ High selectivity of Fe against Ni
- ✓ Ammonia-free, non-volatile leachant
- ✓ High product purity and recovery rates

Sulfur management:

- ✓ Flexible commercial strategies (H_2SO_4 vs. S elem.)
- ✓ Economical processing without need for sulfur sales

Recovery of critical metals:

- ✓ Ni, Co, noble metals concentrates



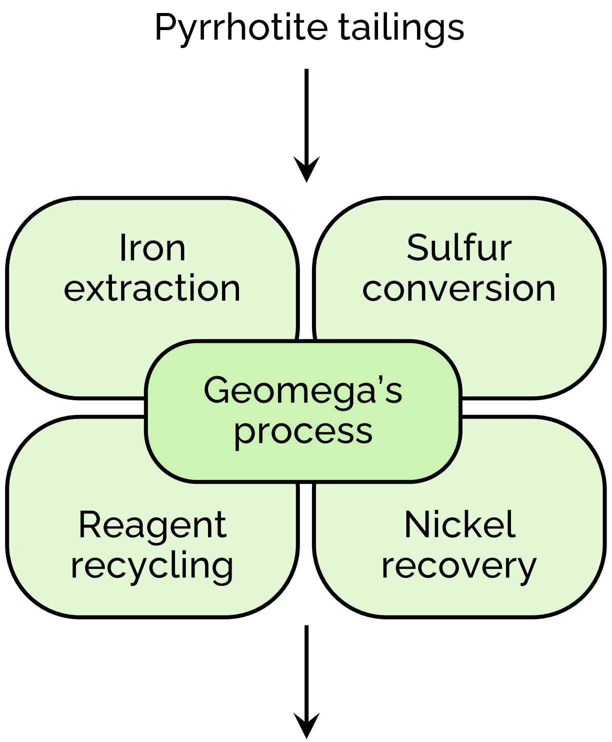
Geomega's process

Environmental footprint mitigation:

- ✓ Main reagents recycling
- ✓ No neutralization reagents
- ✓ No net CO_2 emissions using clean hydrogen and other clean energy sources
- ✓ Potential for net-zero water balance

Carbon footprint, including Scope 3:

1.5-1.9 kg CO_2/kg pyrrhotite



DR-grade iron ore

Nickel concentrate (with noble metals)

Sulfuric acid or elemental sulfur

Development status

- ✓ Technical maturity of different process steps between bench and piloting scales
- ✓ Process IP 100% owned by Geomega
- ✓ Applicable to sulphide tailings from other base metals mines (REE and other metals)

One of the winners on the
Pyrrhotite Resource Recovery Innovation Challenge
by Vale Base Metals

24.09.24 • Base Metals, ESG

Vale Base Metals announces laureates of circular mining innovation challenge

Vale Base Metals is pleased to announce the laureates of the Pyrrhotite Resource Recovery Innovation Challenge, a competition aimed at enhancing the recovery of valuable metals and minerals contained in pyrrhotite.

The challenge invited researchers, innovators, and entrepreneurs to propose novel technological solutions for processing low-grade pyrrhotite tailings, a residue remaining from the mineral processing of sulphide ore. After a thorough evaluation process, three outstanding solutions have been selected as laureates, who will each be awarded a prize of C$25,000.

"We are thrilled to recognize these innovative solutions that not only unlock value from waste but also contribute to sustainable mining practices," said Adam MacMillan, Director of Research and Innovation for Vale Base Metals. "The ingenuity and dedication demonstrated by the laureates are truly inspiring, and we look forward to seeing the impact of their work on the future of mining."

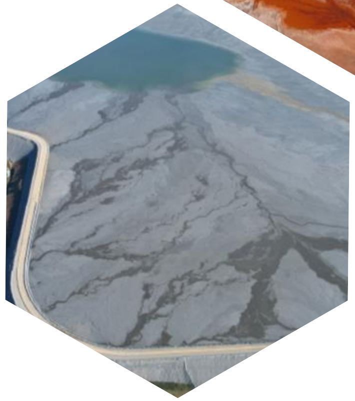
Processing secondary feeds

End-of-life

NdFeB magnet scraps

Industrial

Bauxite residues



Mining

Sulphide tailings

Transferring technical expertise to **low-grade ores**

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Case study: low-grade ores

About the Montviel carbonatite deposit:

Located in **Abitibi region, Quebec**	**82.4 Mt** of ore indicated	**> 184 Mt** ore inferred	**1.5 %** total REO	**0.17 %** Niobium

The **largest** bastnaesite resource in North America

Accessibility to power and logistics infrastructure and local workforce

Strong support from the **Quebec government, local communities, and the Cree First Nations**

Case study: low-grade ores

Our core technologies developed to process mining tailings, industrial wastes**,** post-consumer scrap

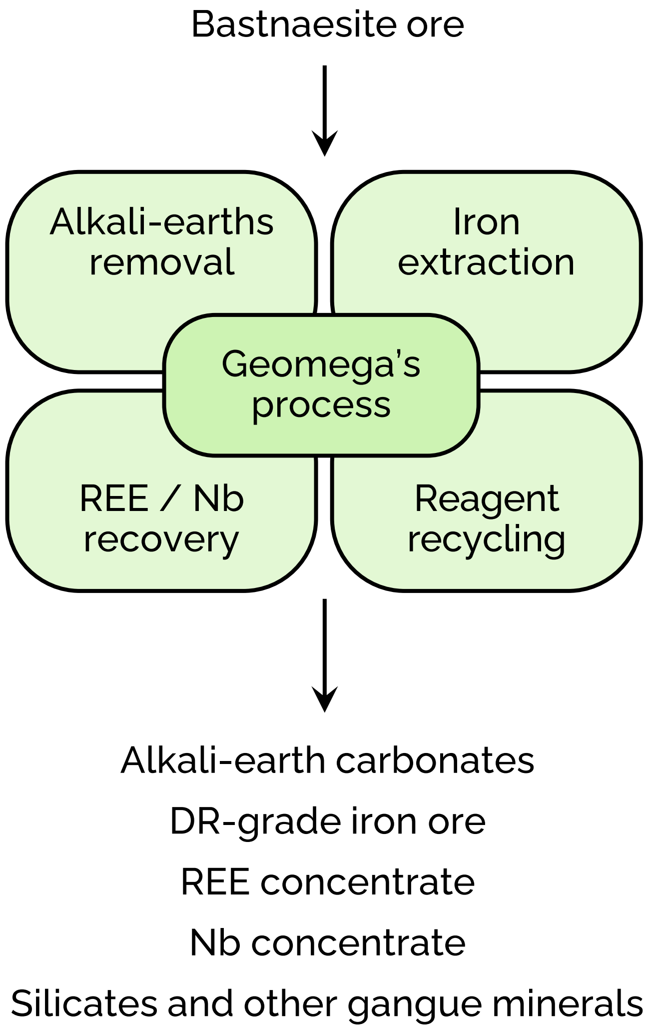
Emerging REE deposits in which conventional process technologies are challenging to implement

Expanding REE production capacity to close the future demand gap

REE and extraction from bastnaesite

Key advantages:

- ✓ No flotation needed
- ✓ Enhanced REE recovery
- ✓ Reagent recycling
- ✓ Lower water and reagent consumption
- ✓ Reduced carbon footprint
- ✓ High-grade iron by-product
- ✓ Limited or no tailings

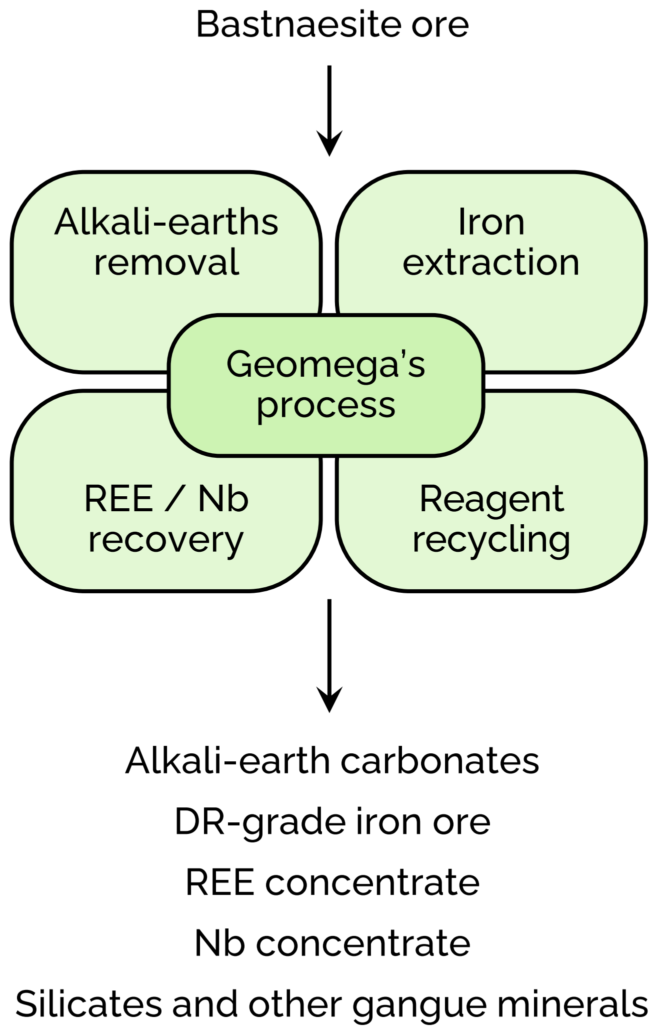


REE and extraction from bastnaesite

Development status:

- ✓ Initial process patented in 2015
- ✓ Work restarted on process improvements (at TRL 3)
- ✓ R&D financed by Quebec Government

Québec



Final remarks

Natural Resources Canada / Ressources naturelles Canada

Canada

NGen

CRITM
vecteur de transformation métallique

VALE

Strong support from industry and governments

Many drivers to recover bulk and critical metals from secondary sources

Many opportunities in various industries and mining sectors

Québec

RioTinto

SUSTAINABLE DEVELOPMENT TECHNOLOGY CANADA
TECHNOLOGIES DU DEVELOPPEMENT DURABLE CANADA

TECHNO CLIMAT

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