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Processing solutions for Rare Earth Elements

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Mineral production at NTNU

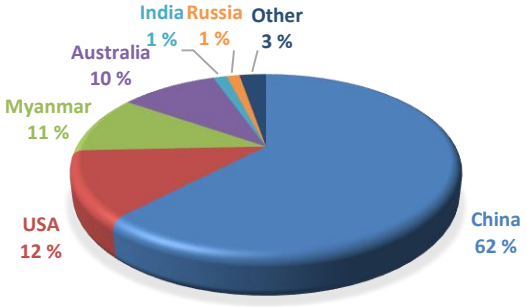
Laboratories - Processing
Pilot mineral processing hall
Flotation
Hydrometallurgy
Urban Mining
Micronization
Dry separation
Crushing
Sieving
Cleanroom

Laboratories - Analysis
Surface Analysis
Particle Analysis
Chemical-Mineralogical
Microscopy
Electron Microscopy
Sample preparation

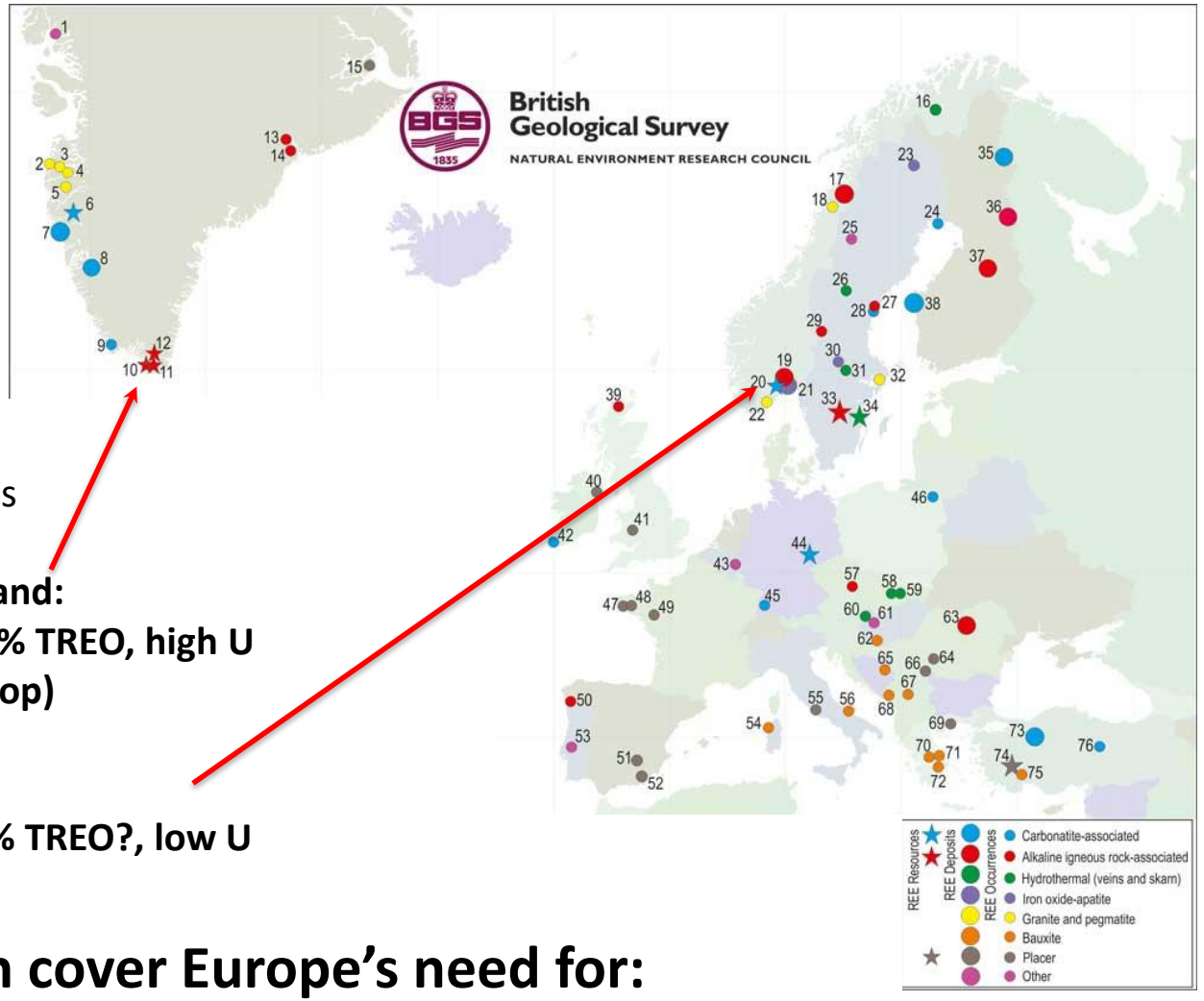
Background

- REE are strategic and critical for green-tech and high-tech applications (i.e. magnets, batteries, fuel cells, catalysts, alloys, medicine, biological tracers, water purification, soil remediation, light-/optics-/screen-tech, ceramics, glasses,..)

- The "Raw materials initiative" has identified 30 critical raw materials (incl. REE)
- REE-related industry accounts direct/indirect for 10 million jobs in Europe
- No primary REE mineral production in Europe
- EU is increasingly dependent on raw material imports
- 98% REE import from China comes at a cost of economic security and sustainable production (e.g. illegal REE mining)
- Assumed 700% and 2600% increase in the need for Nd and Dy (next 20 years)
- Europe's largest deposit is in Norway



EURARE



- Many small deposits
- **Kvanefjeld, Greenland:**
  ~1000 mill. Mt, 1.1% TREO, high U
  (Australia-China coop)
- **Fen, Norway:**
  ~4000 mill. Mt; >2% TREO?, low U

-> Fen alone can cover Europe's need for:

La, Ce, Pr, Nd (+Dy, Sm, Gd, Eu,..?)

Source: http://www.eurare.eu/

Primary production of REE minerals

- A REE mineral deposit may contain ca. 0.1-10% REE minerals and ca. 90-99.9% gangue minerals (e.g. carbonates, silicates, oxides, phosphates, sulphides, sulfates, fluorides, etc.)

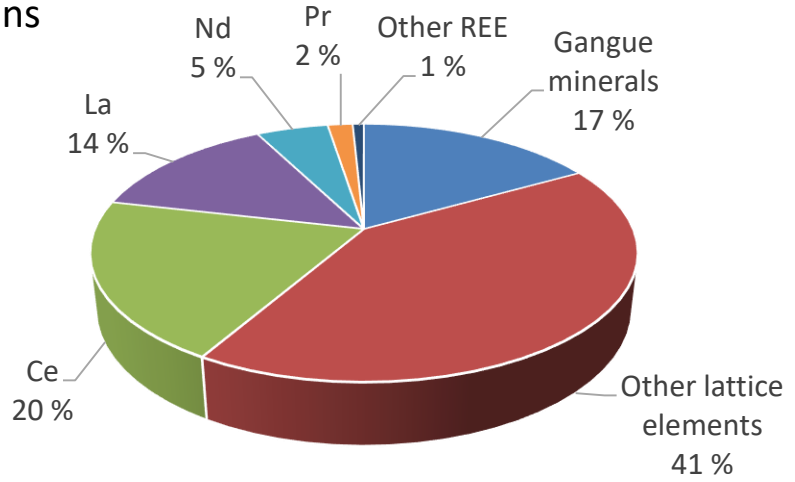
- Each REE mineral may contain several lattice-bound REE

Mineral group	Mineral	Formula	REE	% REE
Silicates	Allanite	(Ca,Sr,REE)2(Al,Fe,Mn,Mg)3Si3O12(OH)	Ce, La, Nd, Y, Pr,..	18-31
Phosphates	Monazite	(REE)PO4	Ce, La, Nd, Sm, Gd,..	45-56
Carbonates	Bastnäsite	(REE)CO3F	Ce, La, Nd,..	64-65
Carbonates	Parisite	Ca(REE)2(CO3)3F2	Ce, La, Nd,..	52-53

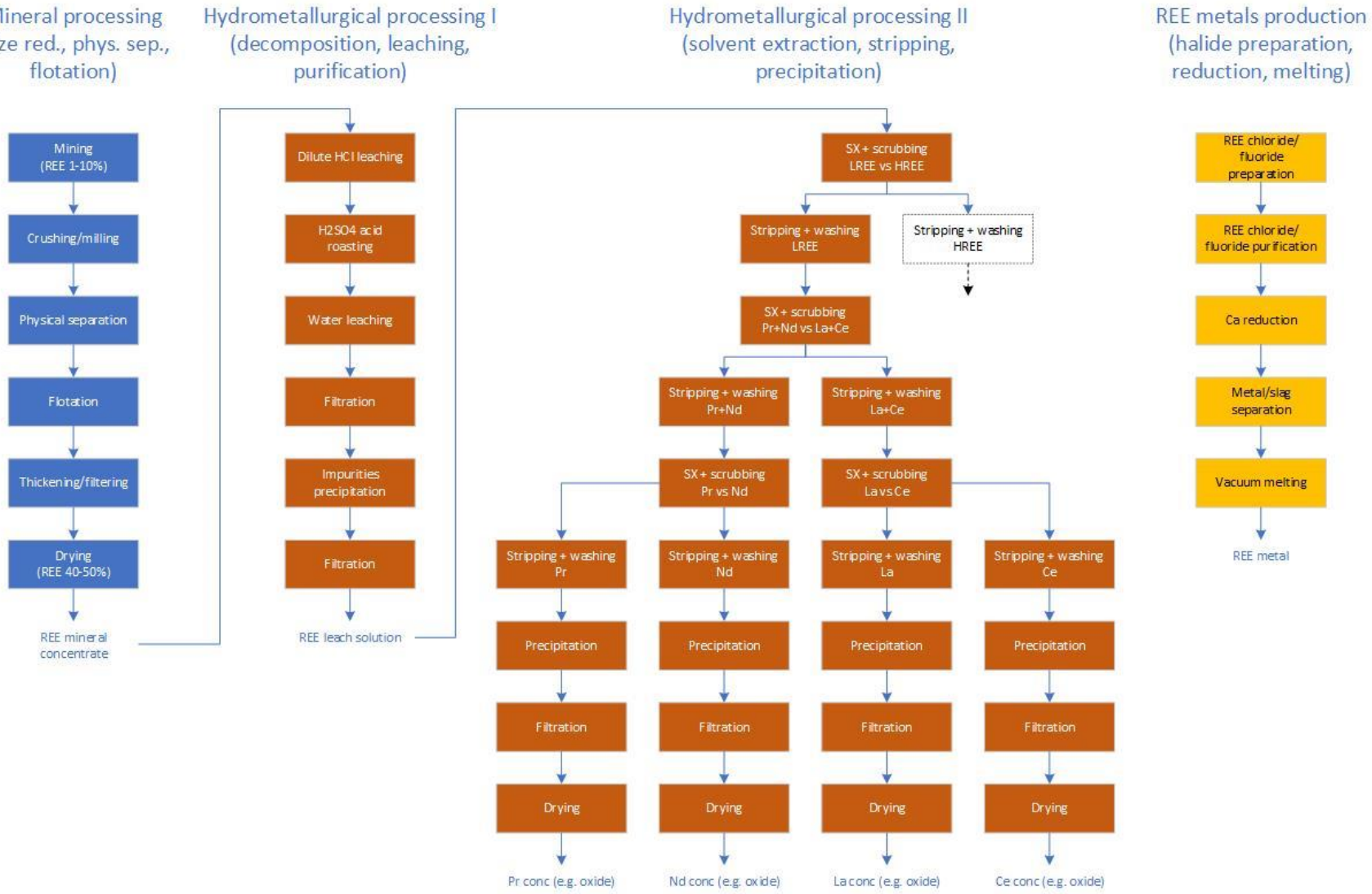
- A primary REE mineral concentrate is normally a mixture of REE minerals with a total REE content of 30-60% (concentrate purities may be in the range of 50-90%)

- The primary mineral concentrate contains a mixture of various REE

- Balance between grade, recovery, remaining gangue mineralogy, and subsequent processing

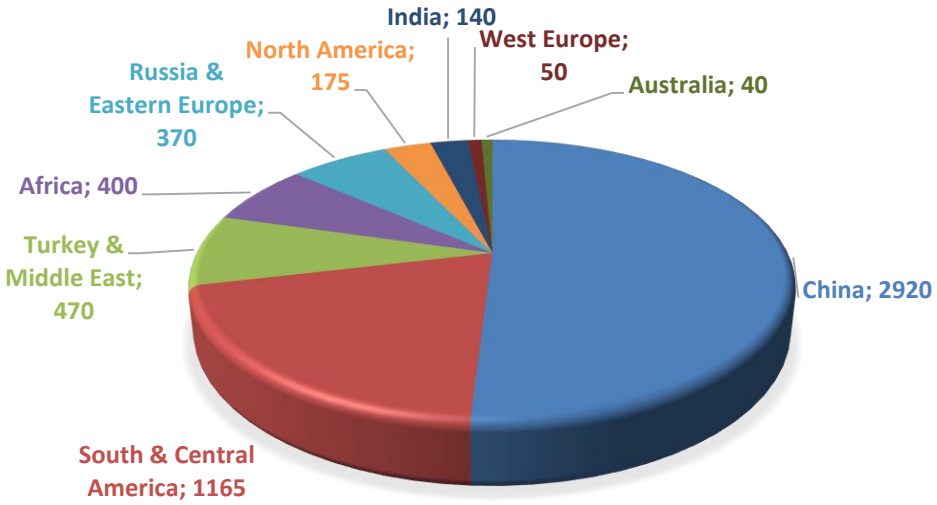


REE metal production (simplified..)



Challenges

- Lack of investment in mapping and mineral processing, lack of R&D, diverse and lengthy national permission procedures, low social acceptance
- Complex ore mineralogies and challenging fine particle processing
- Environmental concerns towards the most efficient conventional flotation chemicals
- Chemicals consumption and environmental and cost concerns regarding chemical treatment (hydrometallurgical operations) – enormous number of stages (may be >1000 for advanced SX operations only)
- Recycling cover a small portion of the demand (market growth and long retention times) and should be significantly more environmentally friendly
- Education (mineral processing graduates 2012)



Towards more sustainable REE processing

- Higher grade REE mineral concentrates with reduced amounts of gangue carbonate, silicate, fluoride and iron-containing minerals
- Improved mineral liberation and less production of fines in comminution operations
- Increased attention to the use of tailings as byproducts and the treatment of tailings
- Higher selectivity (e.g. solvents with higher separation factors and easier stripping) and capacity in hydrometallurgical REE separation (i.e. reducing number of stages from several hundreds)
- Converting to a regime of green surfactants in flotation and hydrometallurgical operations (i.e. biodegradable, non-toxic, recyclable) will reduce environmental impact

The race for REE ion separation

- **Solvent extraction (SX):** conventional method, low selectivity, generate large amounts of waste, high capex and opex – research on membrane technology, precipitative stripping, solvents (easier stripping, better separation factor, ionic liquids)
- **RapidSX:** reduced number of processing steps per SX stage, faster kinetics («weeks -> days/hours»),reduced reagent and power consumption, existing shelf-ware equipment - the next benchmark for competing technologies? (Innovation Metals Corp)
- **Ion exchange (IX):** abandoned for large scale operations?
- **Free flow electrophoresis (FFE):** no organic solvent, lower capex (Geomega & FFE Service)
- **High pressure liquid chromatography (HPLC):** "new and game changing process", environmentally friendly, high efficiency and competitive cost (REEtec)
- **Molecular recognition technology (MRT)**: column «filtration» through beds of solid phase large particles (SuperLig), high selectivity based on multiple parameters, rapid adsorption kinetics, high loading capacity, environmentally friendly, few stages (IBC Advanced Technologies)
- **Electrowinning (EW):** "environmentally benign and economically sustainable process", new acid digestion and novel separation and purification process (Rare Earth Salts & Battelle Memorial Institute)
- Other? (e.g. solid phase extraction, bacterial, vacuum metallurgy, **foam flotation**..)

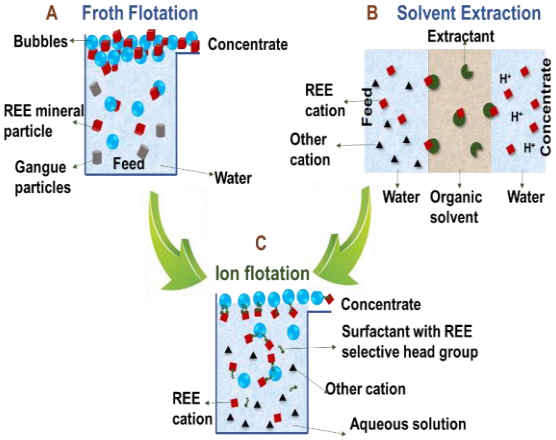
  - ***Several promising and potential game changing methods/applications***
  - ***Need to verify real capex, opex and environmental impact (compared to RapidSX, not SX?)***

Solvent extraction vs Foam flotation

Attributes	Solvent extraction	Foam flotation
Number of stages	50-1000	?
Kinetics of recovery of REE	Very slow (1-2 hrs/stage), molecular diffusion-limited	**Fast** (2 min- 1hr), macroscopic mass transport by foams
Separation of individual REEs	Yes	**Yes**
Toxic solvents/reagents	Acute/high (organic solvents with toxic chelating groups)	**Low** (air as extracting solvent and green surfactant (non-toxic, better recyclability))
Recyclability of solvents and reagents (organic as well as water)	Medium (expensive to re-process high volumes of used-solvent before recycling)	**High** (used surfactants and water are easily recoverable due to 2-phases only)
Use of corrosive chemicals	Very high (acidic medium needed for downstream extraction)	**Low**
Water consumption	Very high (large number of stages)	**Low** (less number of stages, easy to reuse and recycle)
Energy consumption	Medium	**Low**
Environmental overhead (post-treatment and waste disposal)	Very high	**Low**
Efficiency at low REE concentration	Low	**High**

NTNU/IGP – what happens in mineral processing

- **High voltage pulse fragmentation (HVPF):** better liberation along mineral boundaries and less fines
- **Electronics recycling:** environmentally friendly feeds for subsequent physical separation, flotation, pyro-/hydrometallurgical operations
- **Pyrometallurgy:** pre-treatment for subsequent physical separation, flotation, pyro-/hydrometallurgical operations
- **Froth flotation:** fine particle flotation with green chemicals
- **Foam flotation:** ion and nanoparticle flotation with green surfactants



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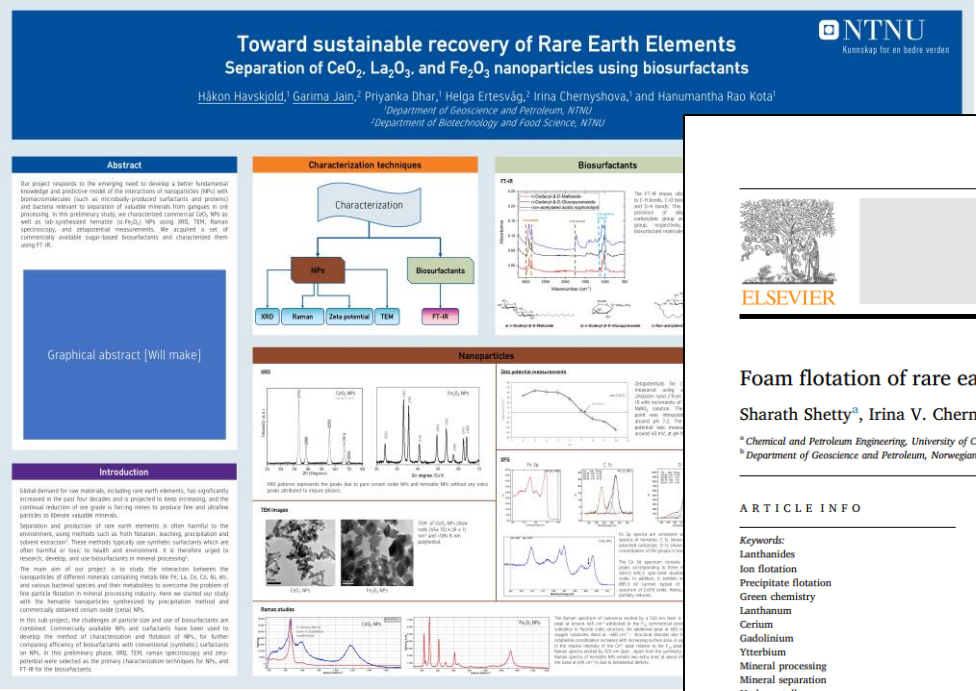
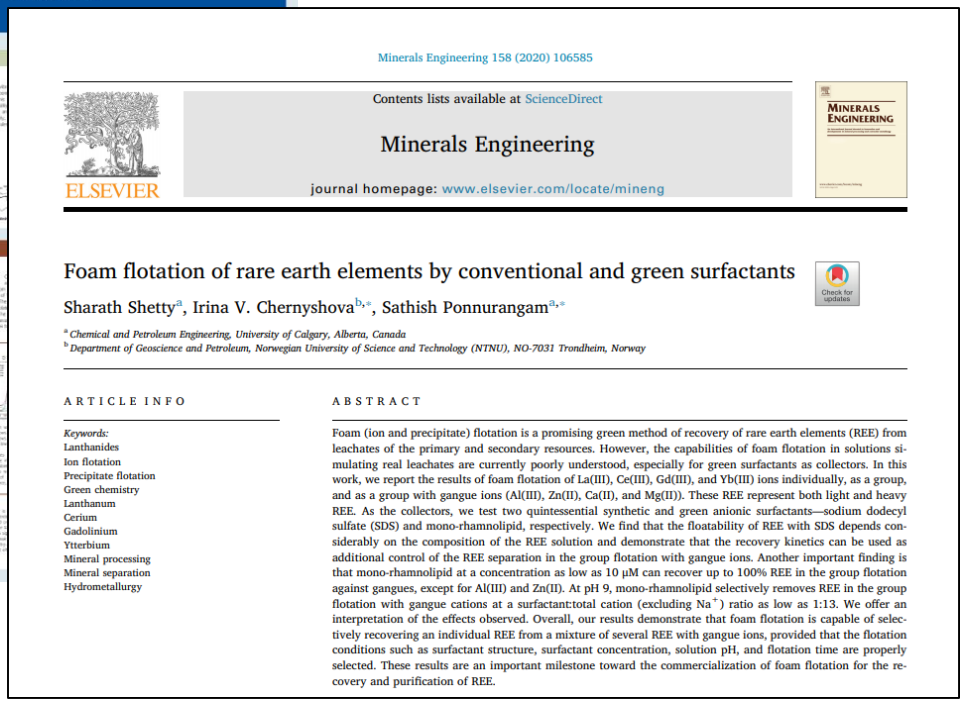
NTNU/IGP – recent and planned REE projects

- «Recovery of REE from a magmatic microcline-quartz pegmatite in southern Norway» (2012-2018)
- Process mineralogy of Norwegian REE deposits (2016-2019)
- «Green foam-based methods of mineral and ion separation» (2019-2020)
- «Foam flotation of rare earth elements by conventional and green surfactants» (2019-2020)
- Nanomorphology effects on the bioactivity and chemical activity of metal oxides, sulphides, and silicates (2018-2022)
- New Reflux Flotation Cell Technology Upscaling for Ore Flotation (2021-2024)
- HARARE – hydrogen as the reducing agent in the recovery of metals and minerals from metallurgical waste
- GEM – Green extraction of minerals, metals and rare earth elements (international partnerships for excellent education, research and innovation)
- GREEN – Green reagents for sustainable processing of primary and secondary raw materials
- FenREEs – A sustainable approach from REE ore to REE oxide based on material from the Fen Complex

Conventional flotation and foam flotation with green chemicals

- Surfactants from renewable sources or bioprocesses
- Biodegradable, non-toxic, better recyclability
- Bulky headgroups that complex REE (higher solubility, higher tolerance to high ionic strength)
- Green surfactants have been employed for remediation of heavy metal contaminated soils, and show promising results in froth flotation





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FenREEs

A holistic and sustainable approach from REE ore to REE oxide based on material from the Fen Complex, and the use of innovative and non-conventional methods in a non-linear value chain

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Thank you

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