Where to find rare earth primary resources in continental Europe & Greenland?

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Why?

- Obtain first estimates of primary REE resources potentials in continental Europe and Greenland
- Establish an European typology of REE deposits and occurrences
- Bring out guides for future exploration
- Provide input to the EURARE database structure
- Improve MFA model of specific REE for EU-28 taking into account lithospheric stocks
Overview of the presentation

- The geology of REE deposits
- REE occurrences in Europe and Greenland
- Where are economic potentials?
- Conclusions
The geology of REE deposits

A future new ore? Pink eudialyte crystals of the Motzfeldt Sø deposit, Greenland
Are the REE so rare?

Relative abundance of rare earth elements in the Earth's crust (Rudnick & Gao, 2003)
About REE mineralogy

REE are not so rare in abundance in the earth's crust unlike their mineralogical expression!

Higgins et al., 2010
## About REE mineralogy

<table>
<thead>
<tr>
<th>Mineral name</th>
<th>Chemical formula</th>
<th>Weight percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euxenite</td>
<td>([REE],U,Th)(Nb,Ta,Ti)₂O₆</td>
<td>16-30 &lt;4.3 3-9</td>
</tr>
<tr>
<td>Fergusonite</td>
<td>[REE]NbO₄</td>
<td>43-52 &lt;8 13.6</td>
</tr>
<tr>
<td>Loparite</td>
<td>(Na,[LREE],Ca,Sr,Th)(Ti,Nb,Ta)O₃</td>
<td>28-37 1.6 0.03</td>
</tr>
<tr>
<td>Pyrochlore</td>
<td>(Ca,Na,U,[REE])₂(Nb,Ta)₂O₆(OH,F)</td>
<td>&lt; 22 &lt;4 &lt;27</td>
</tr>
<tr>
<td>Uraninite</td>
<td>UO₂</td>
<td>&lt;1.5 &lt;12.2 50-98</td>
</tr>
<tr>
<td>Ancylite</td>
<td>Sr<a href="CO%E2%82%83">LREE</a>₂(OH).H₂O</td>
<td>46-53 &lt;0.4 &lt;0.1</td>
</tr>
<tr>
<td>Bastnäsite</td>
<td>[LREE]CO₃(F,OH)</td>
<td>58-75 &lt;2.8 &lt;0.1</td>
</tr>
<tr>
<td>Parisite</td>
<td>Ca[LREE]₂(CO₃)F₂</td>
<td>50-59 &lt;4 &lt;0.3</td>
</tr>
<tr>
<td>Synchysite</td>
<td>Ca[LREE]₂(CO₃)₂(F,OH)</td>
<td>48-53 &lt;5</td>
</tr>
<tr>
<td>Allathanite</td>
<td>([REE],Ca)₂(Al,Fe)₂Si₃O₁₂(OH)</td>
<td>2.5-17 &lt;3</td>
</tr>
<tr>
<td>Clay minerals</td>
<td>e.g. adsorbed REE on kaolinite / halloysite Al₂Si₂O₅(OH)₄</td>
<td>&lt;&lt;4 &lt;0.01 &lt;0.001</td>
</tr>
<tr>
<td>Eudialyte</td>
<td>(Na,[REE])₁₅(Ca,[REE])₆(Fe,Mn)₃(Si,Nb)₂(Zr,Ti)₃Si₁₂O₇₂(OH,F,Cl,H₂O)₆</td>
<td>1-10 &lt;0.1</td>
</tr>
<tr>
<td>Gadolinite</td>
<td>[REE]₂FeBe₂Si₁₀O₄₀</td>
<td>45-54 &lt;0.4</td>
</tr>
<tr>
<td>Steenstrupine</td>
<td>Na₄₄[LREE]₉Mn₂Fe₂(Zr,Th)(PO₄)₁₀Si₁₂O₃₆.₃(H₂O)</td>
<td>&lt; 31 &lt;6 &lt;1</td>
</tr>
<tr>
<td>Thorite</td>
<td>(Th,U,[REE])SiO₄</td>
<td>&lt;3 65-81 10-16</td>
</tr>
<tr>
<td>Zircon</td>
<td>(Zr,[HREE],Th,U)SiO₄</td>
<td>&lt; 19 0.01-0.8 0.01-4</td>
</tr>
<tr>
<td>Apatite</td>
<td>Ca₅(PO₄)₃(F,Cl,OH)</td>
<td>&lt;&lt;2* &lt;0.05</td>
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<tr>
<td>Monazite</td>
<td>([LREE],Th,Ca)(P,Si)O₄</td>
<td>35-71 &lt;20 &lt;16</td>
</tr>
<tr>
<td>Xenotime</td>
<td>([HREE],Zr,U)(P,Si)O₄</td>
<td>54-74 &lt;8.4 &lt;5.8</td>
</tr>
</tbody>
</table>

*Tuduri et al. (in prep)*

### Chemistry of most common REE-bearing minerals.

In bold currently used rare earth raw materials.
Different deposit models and different expressions of REE enrichment

**MAGMATIC**
- Carbonatite
  - Bayan Obo (CH)
  - Mt Pass (USA)
  - Maoniuping (CH)
  - MountWeld (AUS)
  - Araxa (BRE)
  - Catalao (BRE)
  - Sokli (FIN)
  - Fen (SWE)
- Alkali complexes
  - Khibiny (RUS)
  - Lovozero (RUS),
  - Posos de Caldas (BRE)
  - Strange Lake (CAN)
  - Thor Lake (CAN)
  - Kvanefjeld (GRO)
  - Norra Kärr (SWE)
  - Weshan (CH)

**SEDIMENTARY**
- Placer
  - Kerala (IND)
  - Elliot Lake (CAN)
  - Milne Land (GRE)
  - Queensland State (AUS),
  - Richards Bay (AFS)

**SECONDARY**
- Ion-adsorption clay
  - Longnan (CH)

**UNCONVENTIONAL**
- IOCQ / IOA
  - Hydrothermal
    - Olympic Dam (AUS)
    - Pea Ridge (USA)
    - Olserum (SWE)
    - Kiruna (SWE)
    - Browns range (AUS)

REE distribution:
- LREE >> HREE
- LREE = HREE
- LREE < HREE

REE grades:
- 10 kt to <1 Gt
  - 0.1 – 5 % REO
- 10 Mt to 1 Gt
  - 0.5 - 2 % REO
- <1 Mt to >100 Mt
  - < 0.5 % REO
- <10 kt
  - 0.3 – 0.3 % REO
- <1 Mt to >>100 Mt
  - 0.3% - 3 % REO

REE mineralogy:
- bastnaesite ore
- loparite ore and unconventional eudialyte ore
- monazite & xenotime ores
- clay ore
- monazite and apatite ores but mainly unconventional!
REE occurrences in continental Europe and Greenland

The Kvanefjeld REE, U, Zn project, Ilímaussaq complex, Greenland
Methods

Data mining

- Scientific publications in international journals
- European mining geodatabase (e.g. promine.gtk.fi)
- Press releases, websites, annual reports of exploration companies
- Statistical data (EUROSTAT, USGS, BGS, GTK, Roskill, WTA, etc.)

Owing to the unreliability of some data

- Systematic verification with published data in literature
- Harmonization of informations in a database
- Coherence verification, thanks to experts of concerned domains
Products

> 400 occurrences of REE in Continental Europe & Greenland
Results: great diversity of deposit models

**Endogene Deposits**

**Magmatic**
- Carbonatite
  - Fen-Seve (NO)
- Alkaline igneous rocks
  - Norra Kärr (SE)
- Pegmatite
  - Langensundsfjord-Loenvik (NO)
- Granite-related
  - Kavla (FI)

**Magmatic-Hydrothermal**
- Porphyry-High sulphidation
  - Barr (RS)
  - Skarn
    - Bastnäs (SE)
- Iron Oxide-Apatite
  - Kiruna (SE)

**Hydrothermal**
- Metasomatism
  - Luzenac (FR)
- Veins
  - Örebro (SE)
  - Northern Pennines (UK)
  - Alpine veins (F, AU)

**Exogene Deposits**

**Basinal**
- Placer
  - Nea Peramos (GR)
- Palaeoplacer
  - Milne Land (GL)
- Phosphorite
  - Tájö (SE)
  - Authigenic
    - Grand Fougeray (FR)

**Regolith**
- Ion-adsorption clays
  - Måkrå (FI)
- Bauxite - Laterite
  - Grebnik (KK)
  - Aghios Ioannis (GR)

**Images**
- Ilimaussaq complex in Kringlerne (Greenland)
- Luzenac talc deposit, Pyrenees (France)
- Bauxite deposit, Bédarieux (France)
Geological inheritance vs geological potentialities

Charles et al. (2014), Tuduri et al. (in prep)
REE occurrences are mostly located in the Palaeozoic domain.

But Palaeozoic are mainly characterized by monazite palaeoplacers which are (very) small and of little economic interest.

e.g. Bailleul (France)

3.5Mt @ 0.5% REO

$\approx$ 15kt REE
Where are economic potentials?

*Kringlerne project part of the Ilmaussaq complex in Greenland (© Tanbreez)*
REE production in Europe

~3 100t REO
(loparite-Russia-2012)

(Na, Ce, Ca)(Ti, Nb)O₃

TREO - 29-33%
TiO₂ - 37-40%
Nb₂O₅ - 7-9%
Ta₂O₅ - 0.5-0.8%
ThO₂ - 0.5%
REE exploration in Europe

(~ 2 Mt REO recognized)
REE exploration in Greenland (~ 40 Mt REO recognized)
Grade, tonnage and typology

Charles et al. (2014), Tuduri et al. (in prep)
Others opportunities

There are some unconventional deposits (apatite – FeOx, bauxite) where REE could be considered as by-products.
Conclusions

Detrital monazites from Brittany placers (Colin, BRGM)
# Updated, well-documented and “reliable” database for REE occurrences in continental Europe and Greenland

# Up to now 400 distinct occurrences (mine, project, showings), classified by typology in continental Europe and Greenland

# Heterogeneity of degree of knowledge by country

# Real potential for primary deposits (magmatic, hydrothermal) in North Europe and South Greenland

# Underexplored potential for secondary deposits (sedimentary, weathering) in South and West Europe
Perspectives

# Improve **synergy** with the **EURARE** Project

# Promote **scientific studies** for **REE** in **underexplored areas**

# Encourage the development of **new mineral processing**

# Better assess the **criticality** and **influence** of **future REE projects** on the economy (MFA, Sankey diagrams)
**Influence of exploration projects on REEs market**

**Norra Kärr**: 58.1 Mt @ 0.59% TREO (0.3% HREE)  
**Kvanefjeld**: 619 Mt @ 1.056% TREO (0.124% HREE)  
**Kringlerne**: 4,300 Mt @ 0.65% TREO (0.21% HREE)

Should one of the studied mining prospects enters production, criticality of heavy REEs should be significantly influenced.

Guyonnet et al. (2014)
Thank you for your attention

Sunset in the Kangerdluarssuk camp, Kringlerne REE deposit (Greenland)