Global correlation of oxygen and iron isotope on Kiruna-type Ap-Fe-Ox ores

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Despite the need for REE, iron is still the number 1 metal for modern industry...and will remain so for some time (e.g. USGS)

Kiruna-type Ap-Fe-oxide ores are the dominant source of industrially used iron in Europe

....and Sweden is the country with the dominant concentration of Kiruna – type ore deposits in Europe
What are apatite-iron-oxide ores?

- Also referred to as the "Kiruna-type". Often massive magnetite associated with apatite

- Grouped together with IOCG-deposits

- Usually associated with subduction zones and extensional settings

- Form lense-shaped or disc-like ore bodies

- Occur from Paleoproterozoic (e.g. Kiruna), through Proterozoic (Bafq) to Quaternary (e.g. El Laco)
What are apatite-iron-oxide ores?

- About 355 deposits and prospects worldwide
- Contain low-Ti magnetite as main ore mineral and F-rich apatite. Hematite may be present
- Known for large sizes and high grades (e.g. Kiruna, pre-mining reserve 2 billion tons, grade > 60%)
How do apatite-iron-oxide ores form?

- Their origin is not yet fully understood and a debate has been going on for over 100 years. **Two broad schools of thought exist:**

  - Orthomagmatic ore formation (high-T magmatic)
  - Hydrothermal ore formation (low-T fluids and associated replacement)

**Aim:** Investigate the origin of the massive apatite-iron-oxide ores from Sweden and elsewhere, using **stable isotopes of iron and oxygen – the main elements in magnetite**
**Hypothesis**

Magnetite that formed from magma should be in equilibrium with a magmatic source δ-value (magma or magmatic fluid) as fractionation temperatures should lie in the magmatic range.

Magnetite that formed from low-temperature hydrothermal processes should show no equilibrium with magma or magmatic fluid, but should do so with low-temperature hydrothermal sources.

**Ores formed from similar sources and under similar conditions should show a similar isotopic signature (reference samples).**
A global sample set...
Approach
(Analyse magnetite from...)

- **14** samples from Kiruna: dominantly massive ore
- **13** samples from Grängesberg: massive ore plus vein and disseminated ore
- **6** samples from El Laco (massive and extrusive) and **6** samples from Bafq (massive and banded)
- **6** additional hydrothermal ore samples for reference (Skarn, SedEx and BIF types)
- **6** samples from trad. layered igneous intrusions
- **13** recent volcanic reference materials including Taupo NZ, Tenerife and Krakatau, Indonesia
Reference samples
(low-temperature)

Hydrothermal ore samples:

• Skarn iron ore, Dannemora, Bergslagen, Sweden

• Banded iron formation, Striberg, Bergslagen, Sweden

• Stratiform sedimentary iron ore, Bandurrias, Chilean Iron Belt

• Limestone-hosted magnetite ore, Björnberget, Bergslagen, Sweden
Reference samples

(Layered igneous intrusions)

- Massive magnetite ore, Rustenburg Layered Gp., Bushveld Complex, RSA
- Massive magnetite ore, Panzhihua Intrusion, Sichuan Province, China
- Massive magnetite, Ruoutevare, Norbotten, Northern Sweden
- Massive magnetite, Taberg, Småland, Sweden
- Ti-rich massive magnetite ore, Ulvön Intrusion, Ångermanland, Sweden
- Magnetite from ankaramite dyke, Tenerife, Spain
- Magnetite from dacite lava of Mt. Ruapehu, New Zealand (Taupo zone)
- Magnetite from basaltic andesites from Java, Indonesia (Krakatau)
- Magnetite from a dolerite dyke, Troodos Massive, Cyprus
- Magnetite from mafic gabbro xenolith, Skjaldbreiður, Iceland
Fe-O-isotopes

- Oxygen and iron isotope analysis conducted on hand picked (clean) magnetite only.

- **53 new oxygen isotope analyses in total** *(analyzed at Cape Town University)*

- **58 new iron isotope analyses** *analysed at Victoria University Wellington and the Vega Center at Natural History Museum Stockholm*
Geological background: Kiruna

- **Kirunavaara deposit** is situated in Lappland (Northern Sweden)

- **Ore host rocks** for the Kiruna ore are:
  - Trachyandesites and rhyodacites
  - Rhyodacites are ignimbrites and tuffs
  - Aged between 1.9 and 1.8 Ga
  - Affected by regional metamorphism and local alteration

- **Host rocks** are strongly deformed and the ore body is related to an extensive fault zone – town is being resettled.
Geological background: Kiruna

- 2 billion tons of pre-mining reserves of Fe ore
- Magnetite is the main ore mineral; up to 30% of apatite can be present
- Grade of ore between 60 and 68%
- Ore is interpreted to be of magmatic origin due to vesicular ore textures and geochemical data, but various alternative opinions exist (e.g. Seafloor exhalative; hydrothermal)
Geological background: Grängesberg (GMD)

- **GMD situated in Western Bergslagen, Central Sweden**

- **Ore host rocks at GMD:**
  - Dacites, andesites, rhyolites
  - All between 1.87-1.91 Ga old
  - Host rocks affected by lower-amphibolite metamorphism

- **Bergslagen interpreted as former continental back-arc**
  (e.g. Taupo Volcanic Zone, NZ; Allen et al., 1996)
Geological background: El Laco

- El Laco comprises seven iron ore deposits at the flanks of the Pico Laco volcano in Northern Chile (e.g. Tornos et al., 2017)

- Ore hosted in Quaternary andesitic rocks (age 2.1 Ma)

- Host rocks affected by intense volcanic - hydrothermal alteration

- 500 million tons of high graded iron ore (ca. 60 % Fe)
Geological background: El Laco

- Magnetite is the main ore mineral but hematite is widely present as oxidation product.

- Ore is interpreted to resemble intrusive and extrusive volcanic activity, i.e., textures are lava-like with lobes and bubbles. Some are seemingly pyroclastic (e.g., Nyström and others).

- However, trace elements and some isotope studies imply low-T hydrothermal origin (Dare and others).
Geological background: GMD

- Iron ore consists of magnetite (80% of total ore) and hematite (ca. 20% of total ore)

- Grade of ore: 40-63%; 150 Mt already mined at GMD

- Lense-shaped ore body, striking NE-SW, dipping 70°-80° towards SE

- A further 150 Mt in reserve present
The **Bafq-Saghand** ore belt is located in the Kashmar-Kerman Tectonic Zone (KKTZ) in Central Iran.

IOA mineralization at Bafq are hosted by dolomitic and rhyolitic rocks of early Cambrian age.

modified after Majidi, 2015.
There are 34 recorded iron ore mineralization with nearly ~1500 Mt ore and an average grade of 55% of Fe

Several are actively mined Chadormalu, Choghart, Se-Chahun, Lakke Saih and Esfordi

The geological setting is Neoproterozoic to Early Cambrian orogenic activity in an active continental-margin environment
RESULTS: Oxygen isotopes

- Observation: Overlap of most apatite-iron oxide ores and Taylor’s range for igneous magnetites

- Clear distinction from non-magmatic ores, but notably ranges are seen for several deposits (El Laco, Kiruna)

- Notably, vein, disseminated and oxidised material overlaps with hydrothermal ores!
RESULTS:
Iron isotopes

- Overlap of apatite-iron oxide ores, layered igneous intrusions and volcanic reference material

- Clear distinction from non-magmatic ores

- Vein, disseminated and oxidised material overlaps with magmatic material
RESULTS: Iron isotopes

- Overlap of apatite-iron oxide ores, layered igneous intrusions and volcanic reference material
- Clear distinction from non-magmatic ores
- Vein, disseminated and oxidised material overlaps with magmatic material
• Most apatite-iron oxide ores overlap with magmatic magnetites in both iron and oxygen isotopes.

• Low-T samples show offset from volcanic field for O and Fe isotopes.

• Vein, disseminated samples show an overlap for hydrothermal magnetites in oxygen but less so in Fe isotopes.

• For these samples, re-crystallization and low-T hydrothermal processes (i.e. Secondary leaching and re-crystallisation via fluids) apply (green samples).
A conceptual model for Kiruna-type ore deposits

- Oxide-rich magmas form from dominantly intermediate parent magmas (liquid immiscibility, FC or else...)

- Upon ascent and differentiation within a volcanic system, magnetite massive ore is formed directly from arc-type mafic magma or associated high-T magmatic fluids ($T = 600-1000^\circ C$)

- Magmatic heat and fluids initiate hydrothermal activity, causing local re-mobilisation and (re-)precipitation of hydrothermal magnetite ($T < 400^\circ C$).
Conclusions

• Most of our samples are in equilibrium with magma or magmatic fluid at high-T, but lower-T samples are also seen, especially vein and disseminated samples.

• Similar results for El Laco, GMD, Kiruna and Bafq support a general ortho-magmatic primary origin for apatite-iron oxide ores.

• Overall a dominantly orthomagmatic origin for Kiruna-type magnetite ores, with subsequent volcanic slow down (hydrothermal death) is recorded in most suites.
Thank you!
https://www.nature.com/article/s41467-019-09244-4
Testing the oxygen and iron isotopes: Example

- Source re-calculation using: \(1000 \ln \alpha_{1-2} = \delta_1 - \delta_2\)
  (Hoefs 1997)

- GMD Sample KES090011, massive magnetite ore

- \(\delta^{18}O_{mgt} = 2.8 \permil\)

- \(1000 \ln \alpha_{mgt-dacite} = -4.3 \permil\) at normal magmatic T
  (Zhao & Zheng 2003)

- From Eqn: \(\delta^{18}O_{mgt} - \delta^{18}O_{dacite} = -4.3 \permil\)

  \[\Rightarrow 2.8 \permil - \delta^{18}O_{dacite} = -4.3 \permil\]

  \[\delta^{18}O_{dacite} = 7.1 \permil\]
Done for all samples, most magnetite samples are in equilibrium with andesite/dacite magma (red) or magmatic fluids (yellow) at high-T (600-1000°C)

• The Low–T hydrothermal reference samples are dominantly not in equilibrium however (blue)

• Frequently, vein, disseminated and oxidised magnetites are in equilibrium with fluid at lower-T (<400°C)

• Iron isotopes: Some ore sources (magmas or fluids) were enriched in heavy isotope $\rightarrow$ oxide-rich melts?
Geothermometry

- Temperature calculations using Grängesberg quartz-magnetite and apatite-magnetite pairs confirm magmatic temperatures (Jonsson et al 2013; Scientific Reports)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Magnetite $\delta^{18}$O</th>
<th>Quartz $\delta^{18}$O</th>
<th>Apatite $\delta^{18}$O</th>
<th>$\delta_{\text{qz/ap}} - \delta_{\text{mgt}}$</th>
<th>$T$ in °C</th>
<th>$2\sigma$ in K/°C</th>
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</tbody>
</table>
Compatible with e.g. Grängesberg regional values?
(Weis et al., in prep...)
Ore data are compatible with Grängesberg regional values!

- No distinct pattern can be seen on the map. Samples are plotted along two traverses across the ore body (grey), showing consistently magmatic values!