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

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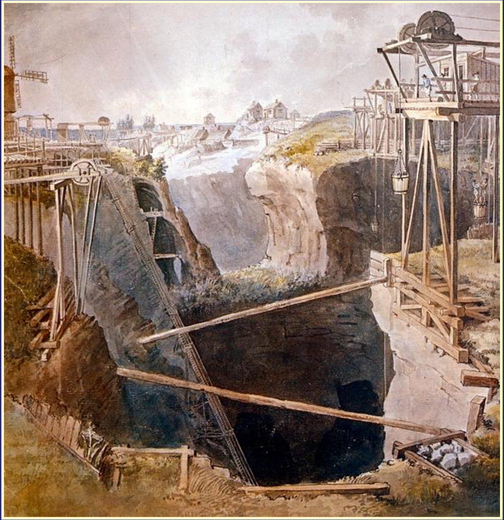
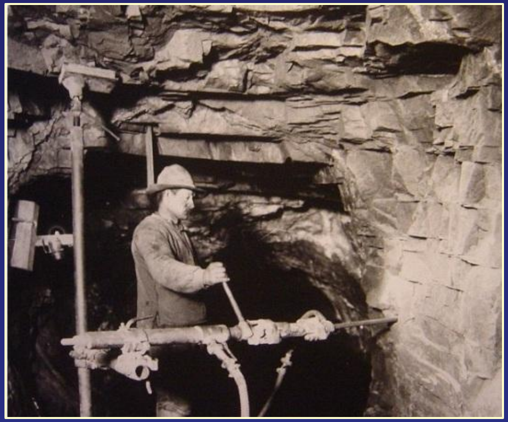
Iron is master of them all

- 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%)

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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***

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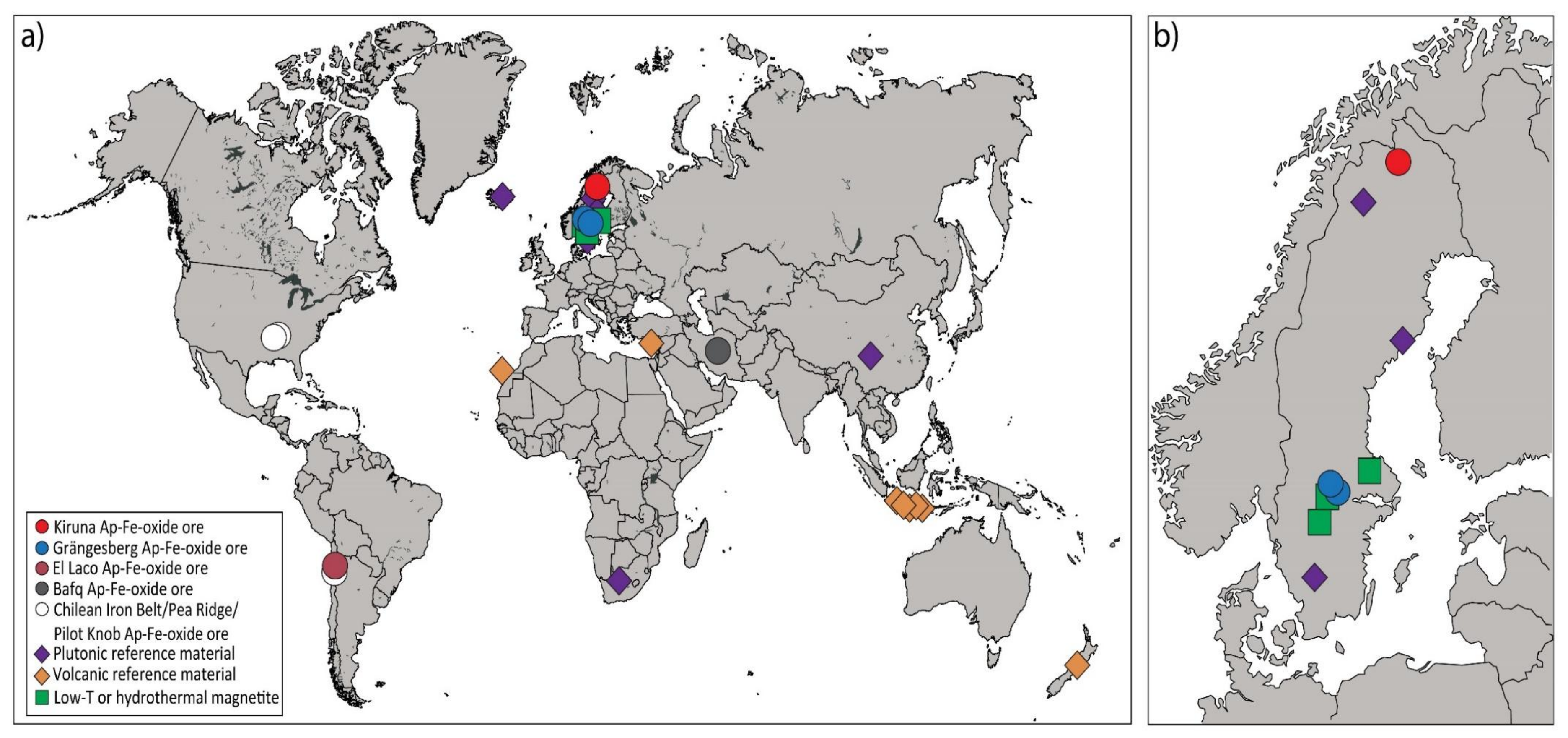
Hypothesis

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 hydroterhmal 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)

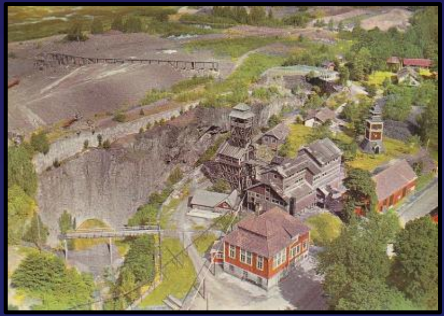
Hydrothermal ore samples:

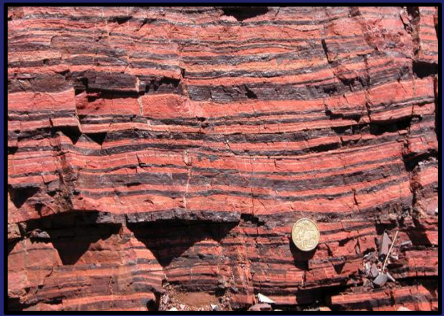
- Skarn iron ore, Dannemora, Bergslagen, Sweden

- Banded iron formation, Striberg, Bergslagen, Sweden

- Stratiform sedimentary iron ore, Bandurrias, Chilean Iron Belt

- Limestone-hosted magnetite ore, Björnberget, Bergslagen, Sweden

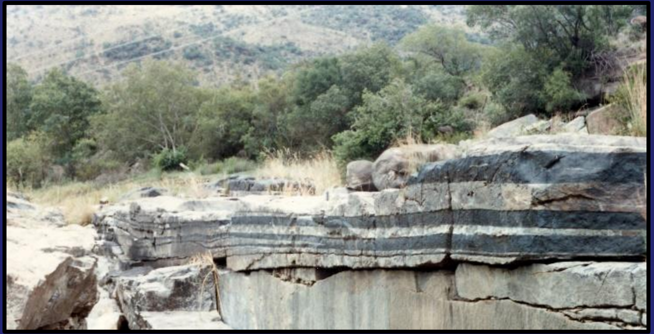




Reference samples

(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



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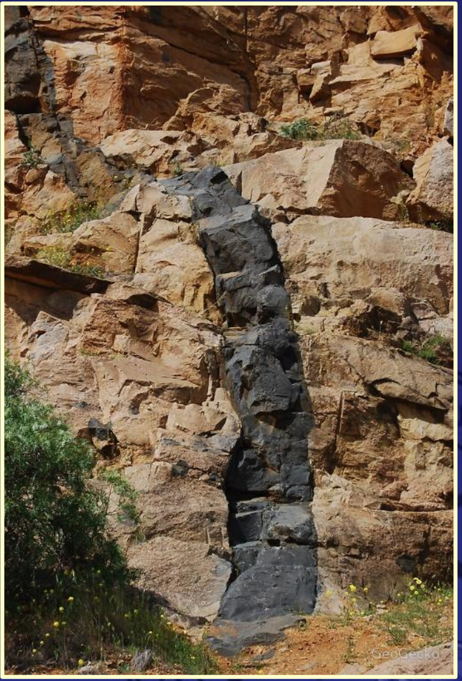
- Magnetite from ankaramite dyke, Tenerife, Spain
- Magnetite from dacite lava of Mt. Ruapehu, New Zealand (Taupo zone)
- Magnetite from basaltic andesites from Java, Indonesia (Krakatau)
- Magnetite from a dolerite dyke, Troodos Massive, Cyprus
- Magnetite from mafic gabbro xenolith, Skjaldbreiður, 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

Franz Weis

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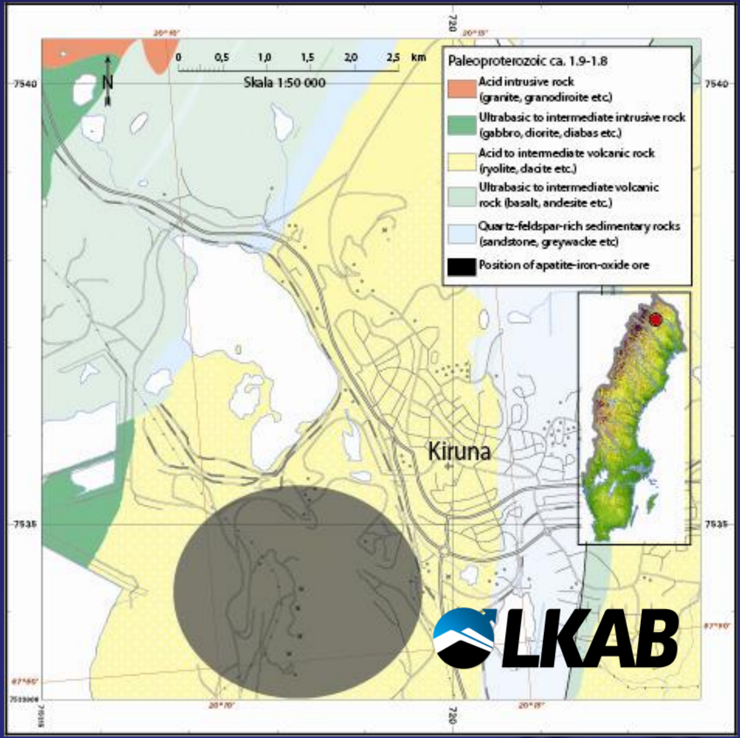
Geological background: Kiruna

- Kirunavaara deposit is situated in Lappland (Northern Sweden)

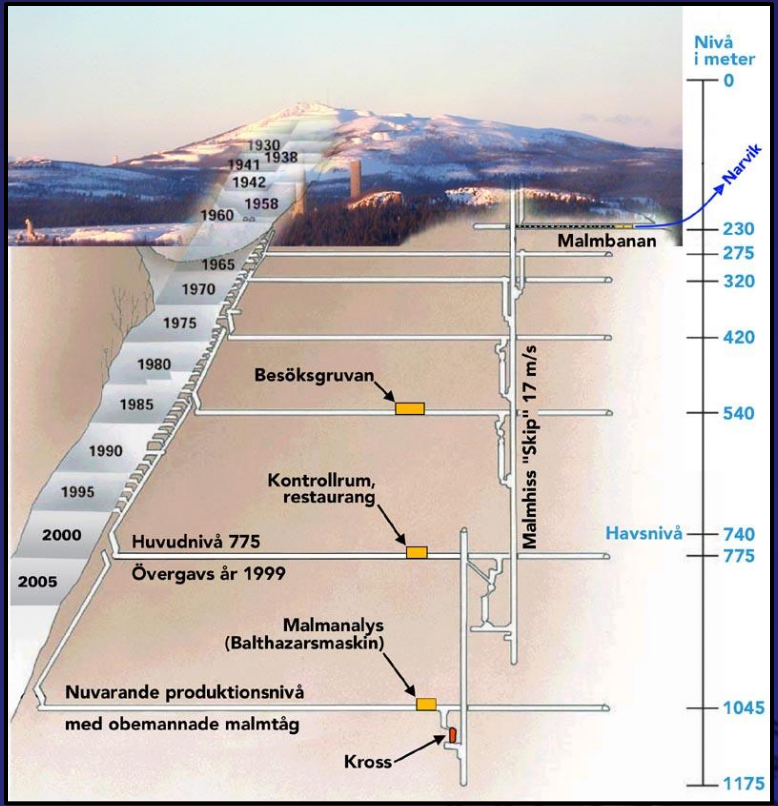
- Ore host rocks for the Kiruna ore are:
  - Trachyandesites and rhyodacites
  - Rhyodacites are ignimbrites and tuffs
  - Aged between 1.9 and 1.8 Ga
  - Affected by regional metamorphism and local alteration

- Host rocks are strongly deformed and the ore body is related to an extensive fault zone – town is being resettled



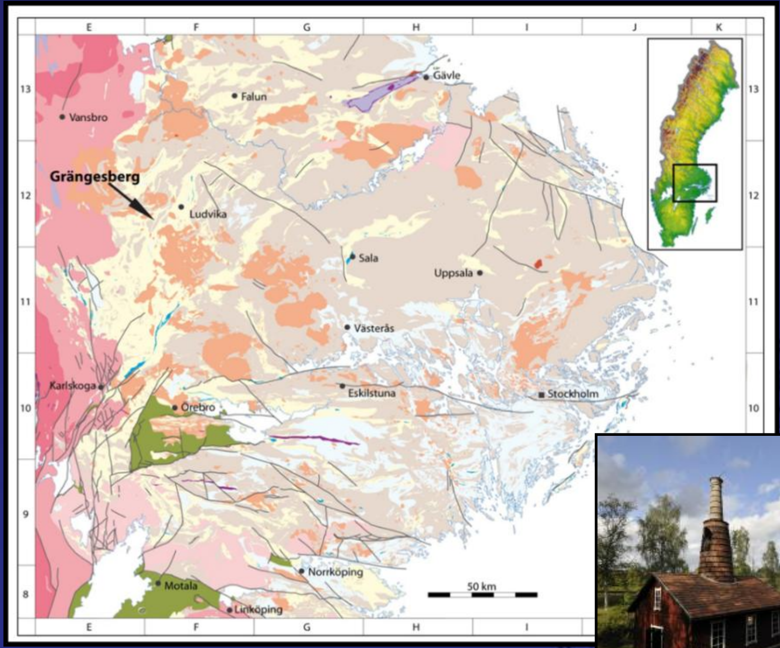
Geological background: Kiruna

- 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)



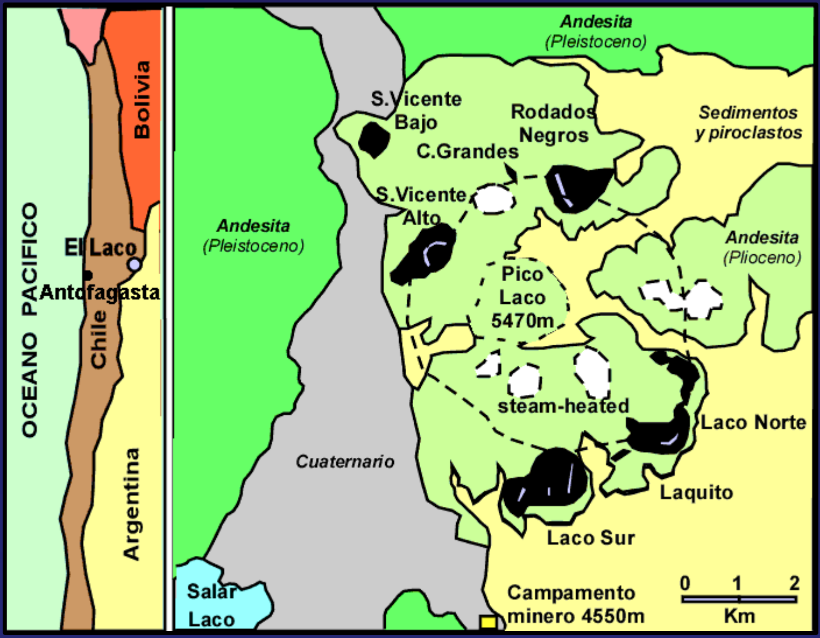
Geological background: Grängesberg (GMD)

- 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)

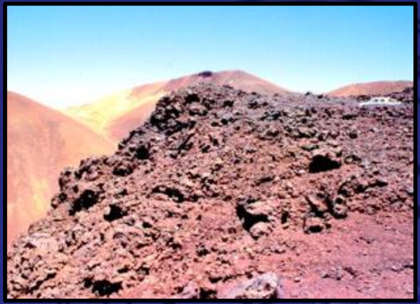


Geological background: El Laco

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

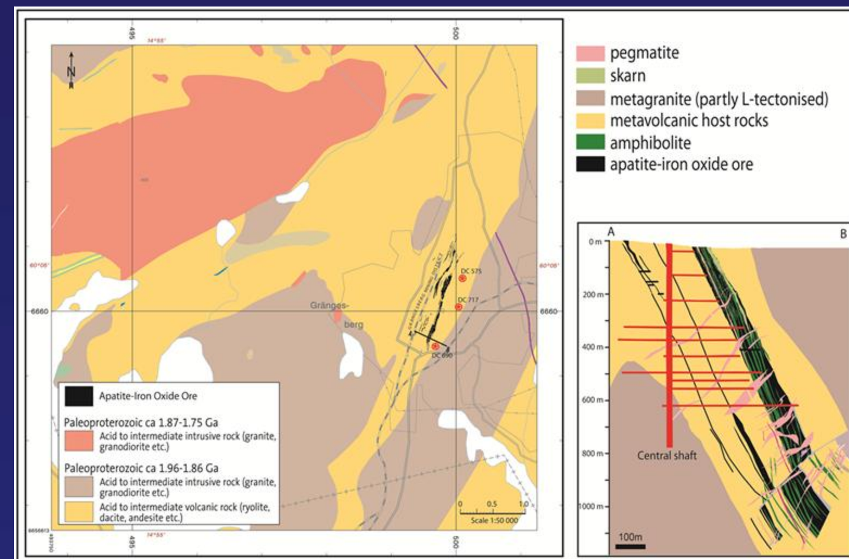
- Ore is interpreted to resemble intrusive and extrusive volcanic activity, ie textures are lava like with lobes and bubbles. Some are seemingly pyroclastic (e.g. *Nyström and others*).

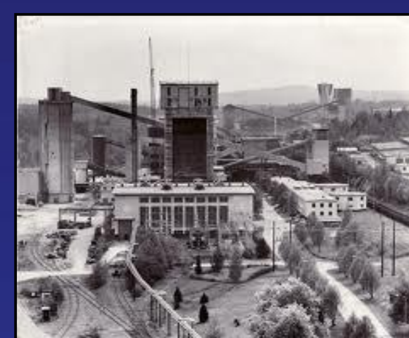
- However, trace elements and some isotope studies imply low-T hydrothermal origin (*Dare and others*)



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





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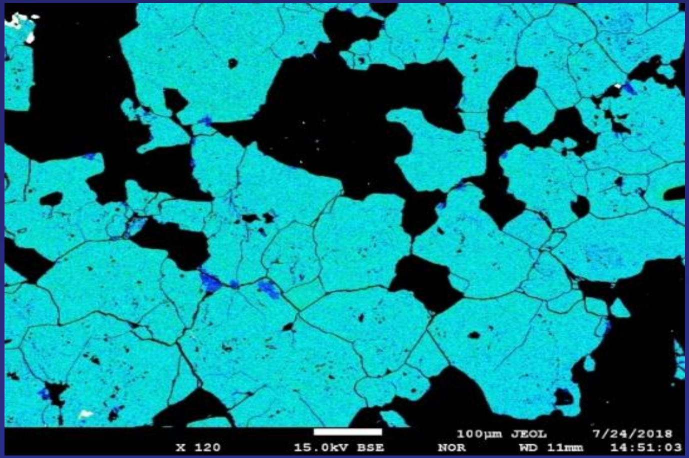
Geological background: Bafq

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



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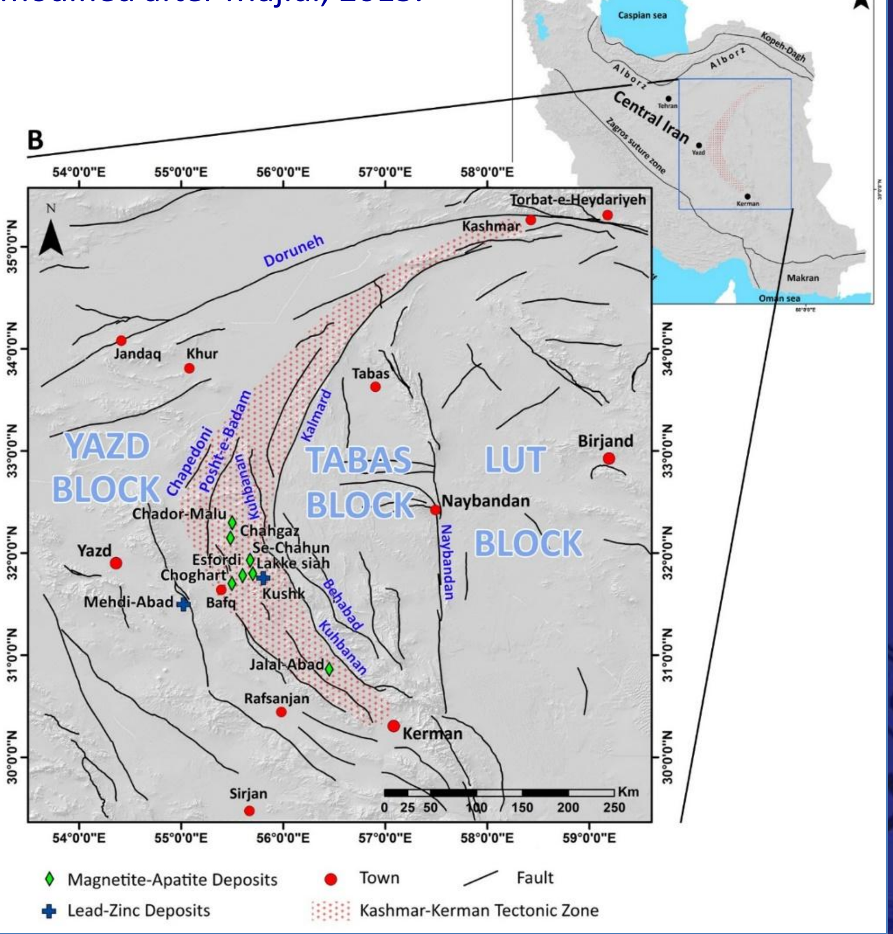
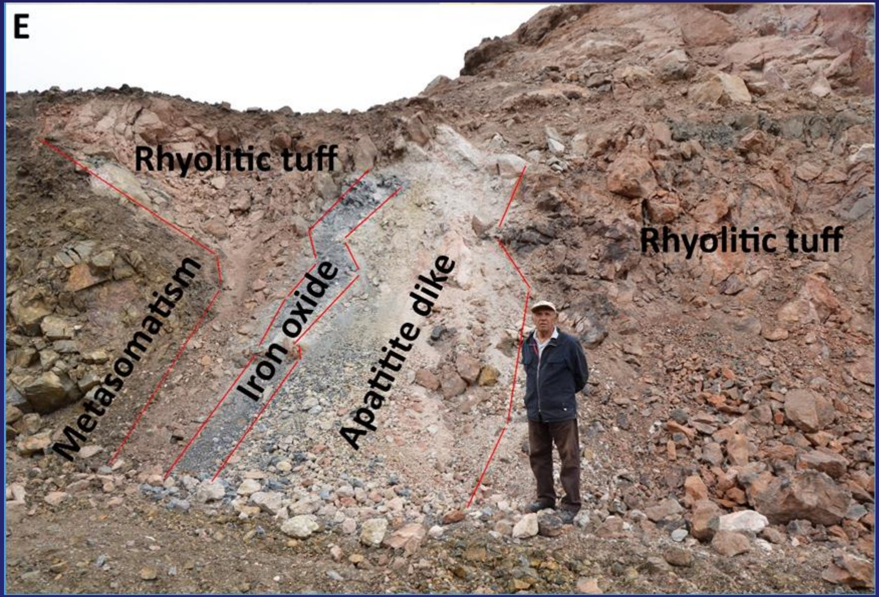


Geological background: Bafq

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

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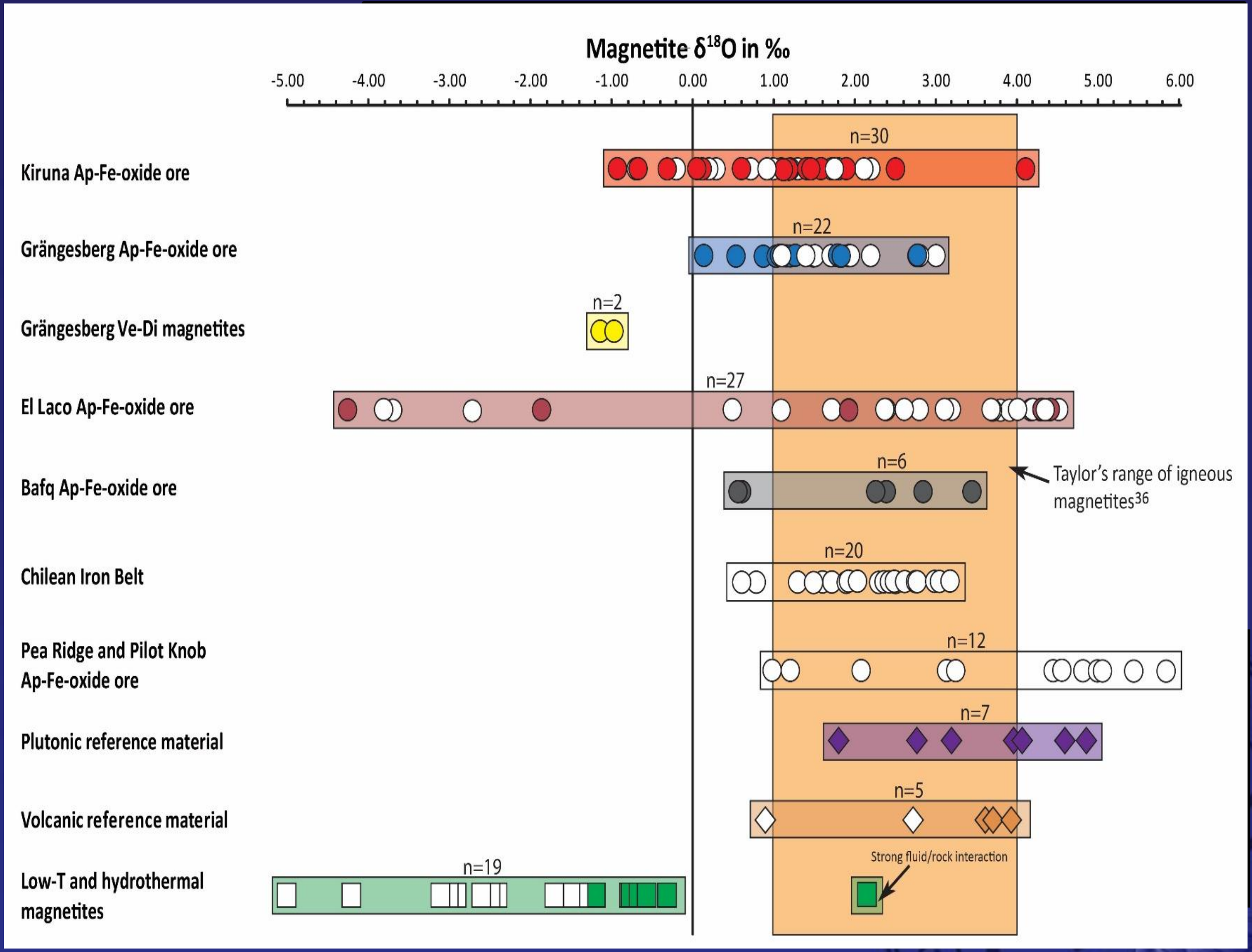
- Observation: Overlap of most apatite-iron oxide ores and Taylor's range for igenous magnetites
- Clear distinction from non-magmatic ores, but notably ranges are seen for several deposits (El Laco, Kiruna)
- Notably, vein, dis-seminated and oxidised material overlaps with hydrothermal ores!

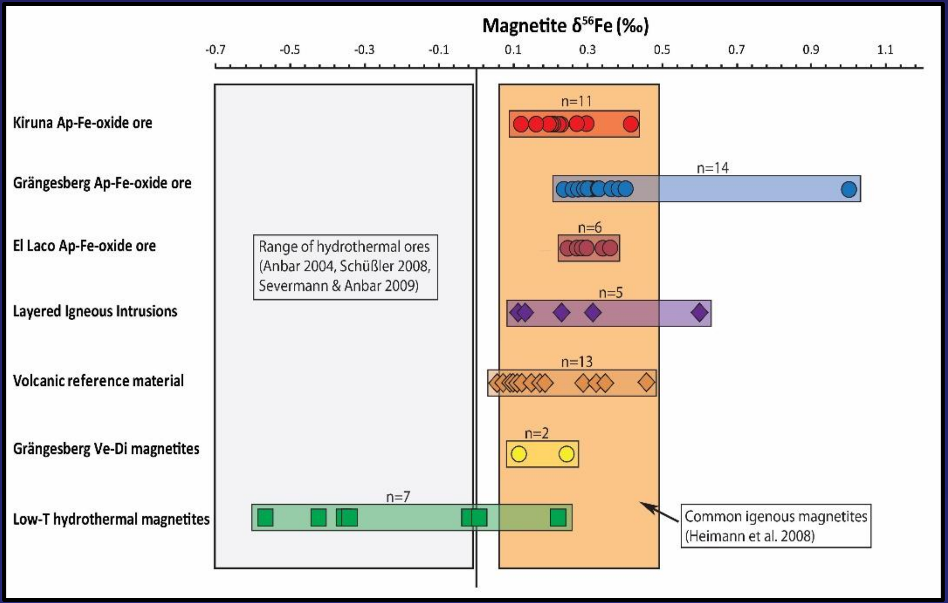


RESULTS:
Iron isotopes

- 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



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RESULTS: Iron isotopes

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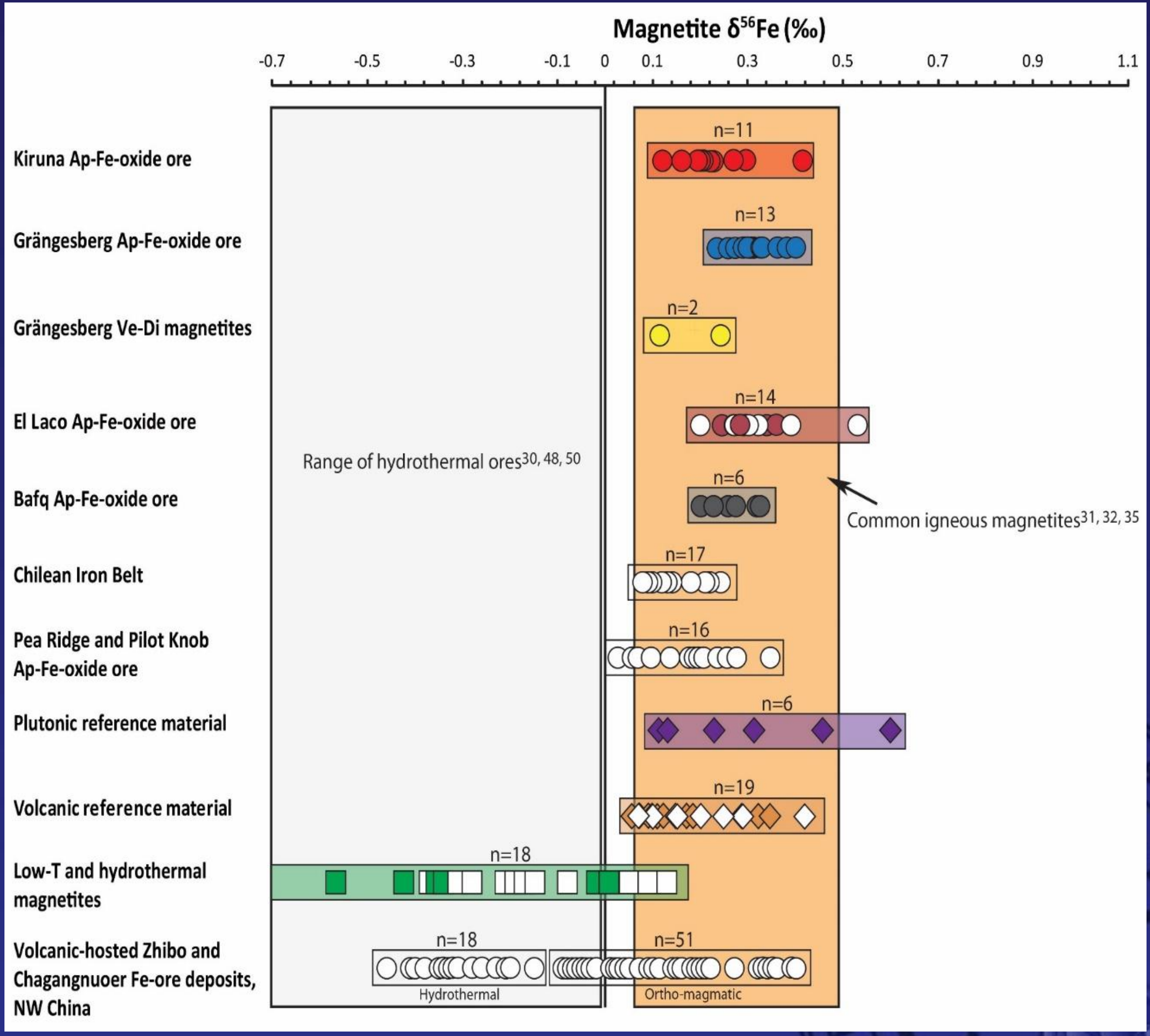

Isotope correlation

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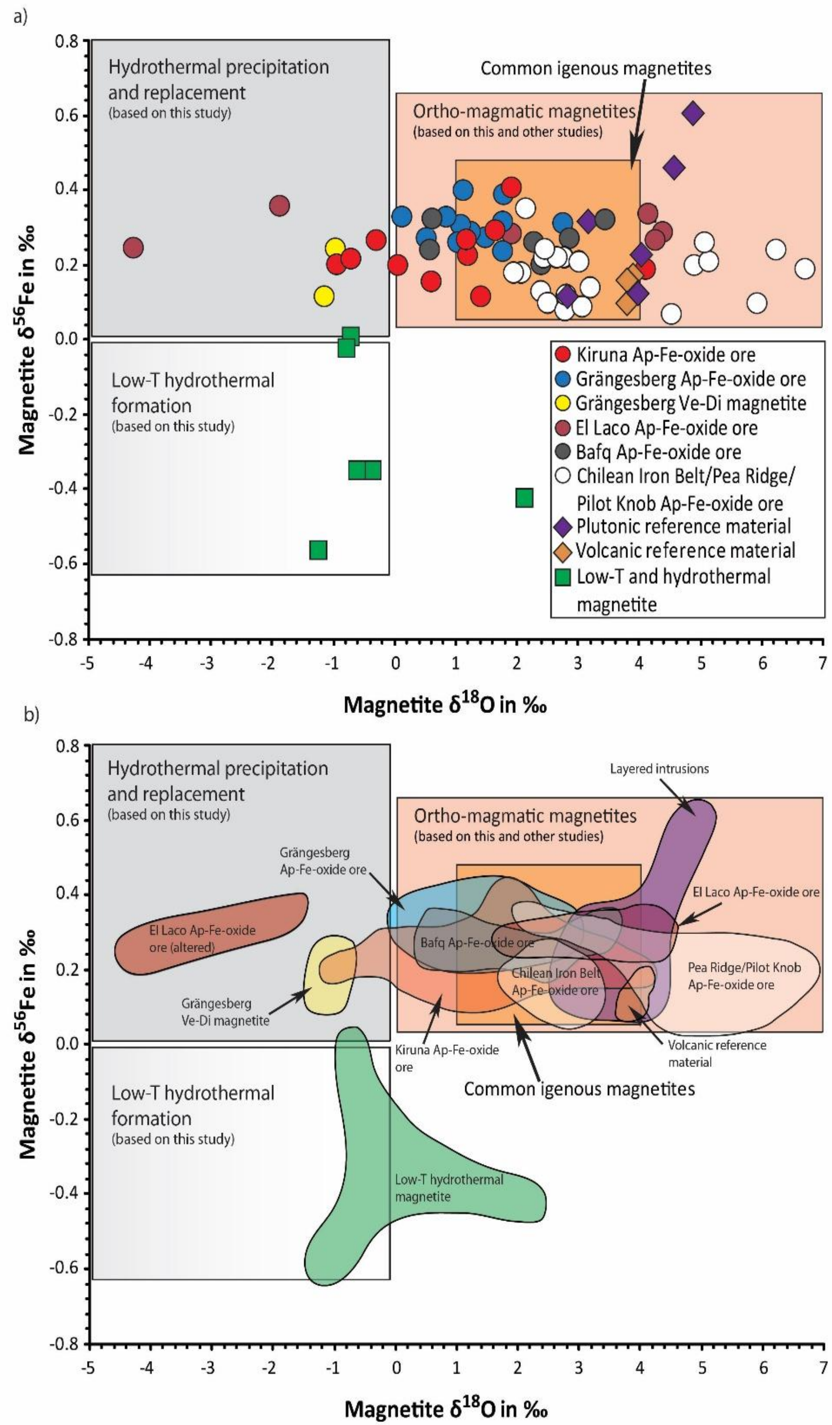
- Most apatite-iron oxide ores overlap with magmatic magnetites in both iron and oxygen isotopes
- Low- T samples show offset from volcanic field for O and Fe isotopes.
- Vein, disseminated samples show an overlap for hydrothermal magnetites in oxygen but less so in Fe isotopes
- For these samples, re-crystallization 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

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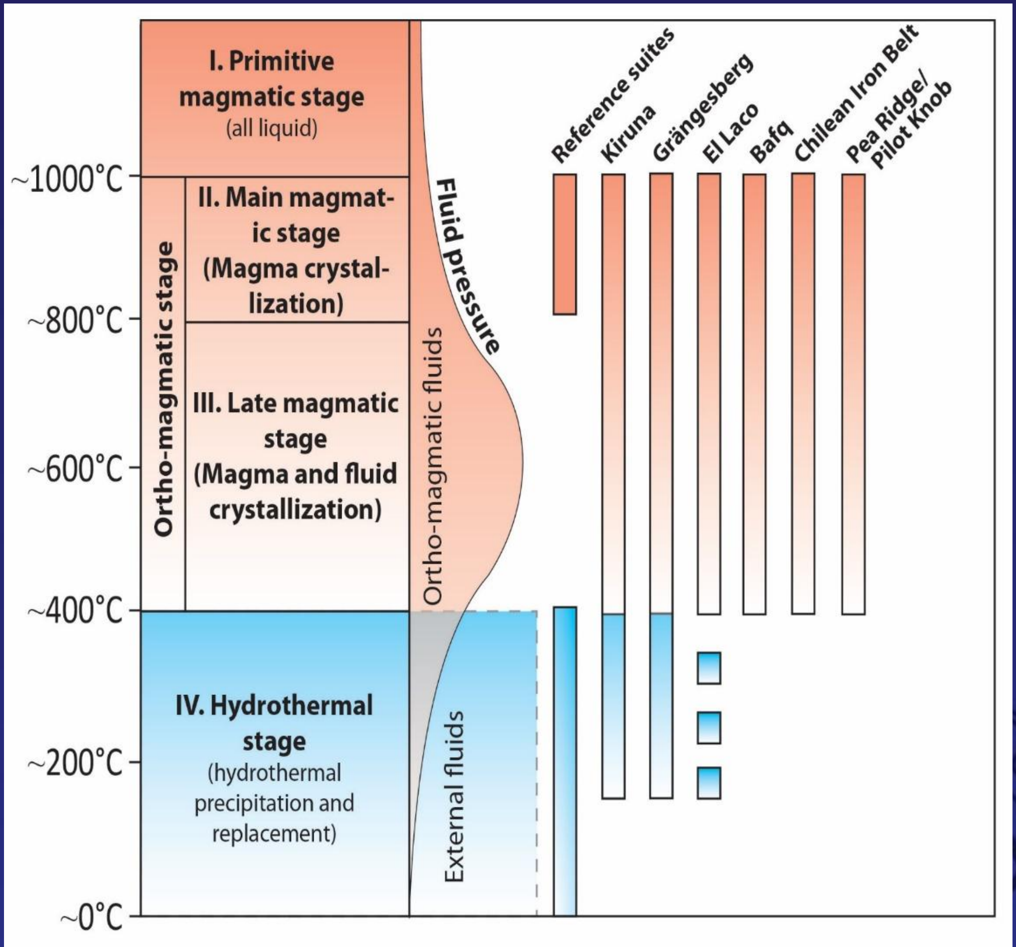
- Oxide-rich magmas form from dominantly intermediate parent magmas (liquid immiscibility, FC or else...)

- 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°C)

- Magmatic heat and fluids initiate hydrothermal activity, causing local re-mobilisation and (re-)precipitation of hydothermal magnetite (T< 400°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.

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Thank you !

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Global Fe–O isotope correlation reveals magmatic origin of Kiruna-type apatite-iron-oxide ores

Valentin R. Troll[1], Franz A. Weis[1,2], Erik Jonsson[1,3], Ulf B. Andersson[1,4], Seyed Afshin Majidi[5], Karin Högdahl[1,6], Chris Harris[7], Marc-Alban Millet[8], Sakthi Saravanan Chinnasamy[1,9,11], Ellen Kooijman[2] & Katarina P. Nilsson[3,10]

Testing the oxygen and iron isotopes: Example

- Source re-calculation using: **$1000 \ln \alpha_{1\text{-}2} = \delta_1 - \delta_2$**
- **(Hoefs 1997)**
- GMD Sample KES090011, massive magnetite ore
- $\delta^{18}O_{mgt}$ = 2.8 ‰
- $1000 \ln \alpha_{mgt\text{-}dacite}$ = -4.3 ‰ at normal magmatic T
- (Zhao & Zheng 2003)
- From Eqn: $\delta^{18}O_{mgt} - \delta^{18}O_{dacite}$ = -4.3 ‰

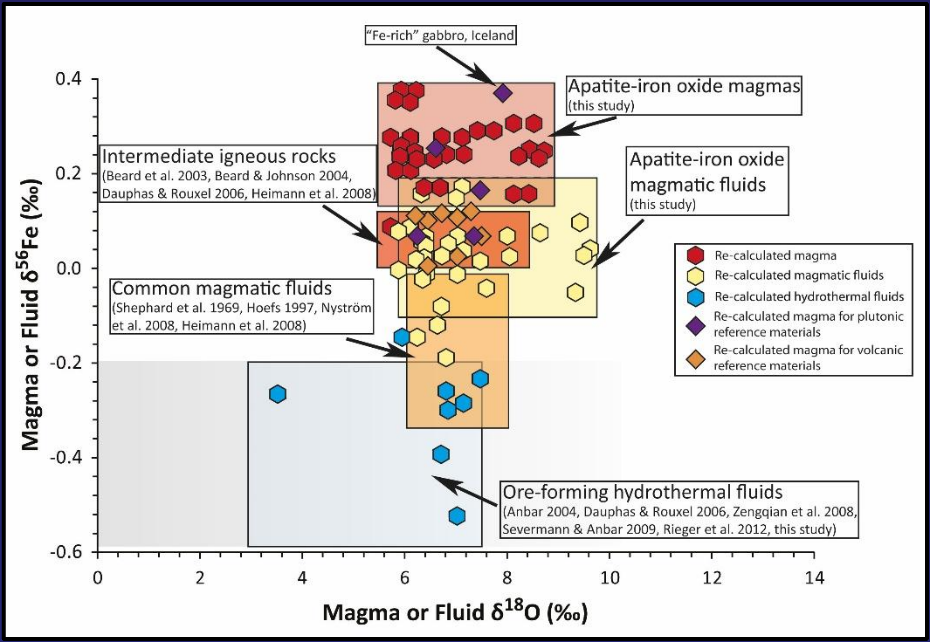
→ 2.8 ‰ - $\delta^{18}O_{dacite}$ = -4.3 ‰

$\delta^{18}O_{dacite}$ = **7.1 ‰**

Testing the oxygen and iron isotopes (all data)

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 <u>not</u> 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 → **oxide-rich melts?**



Geothermometry

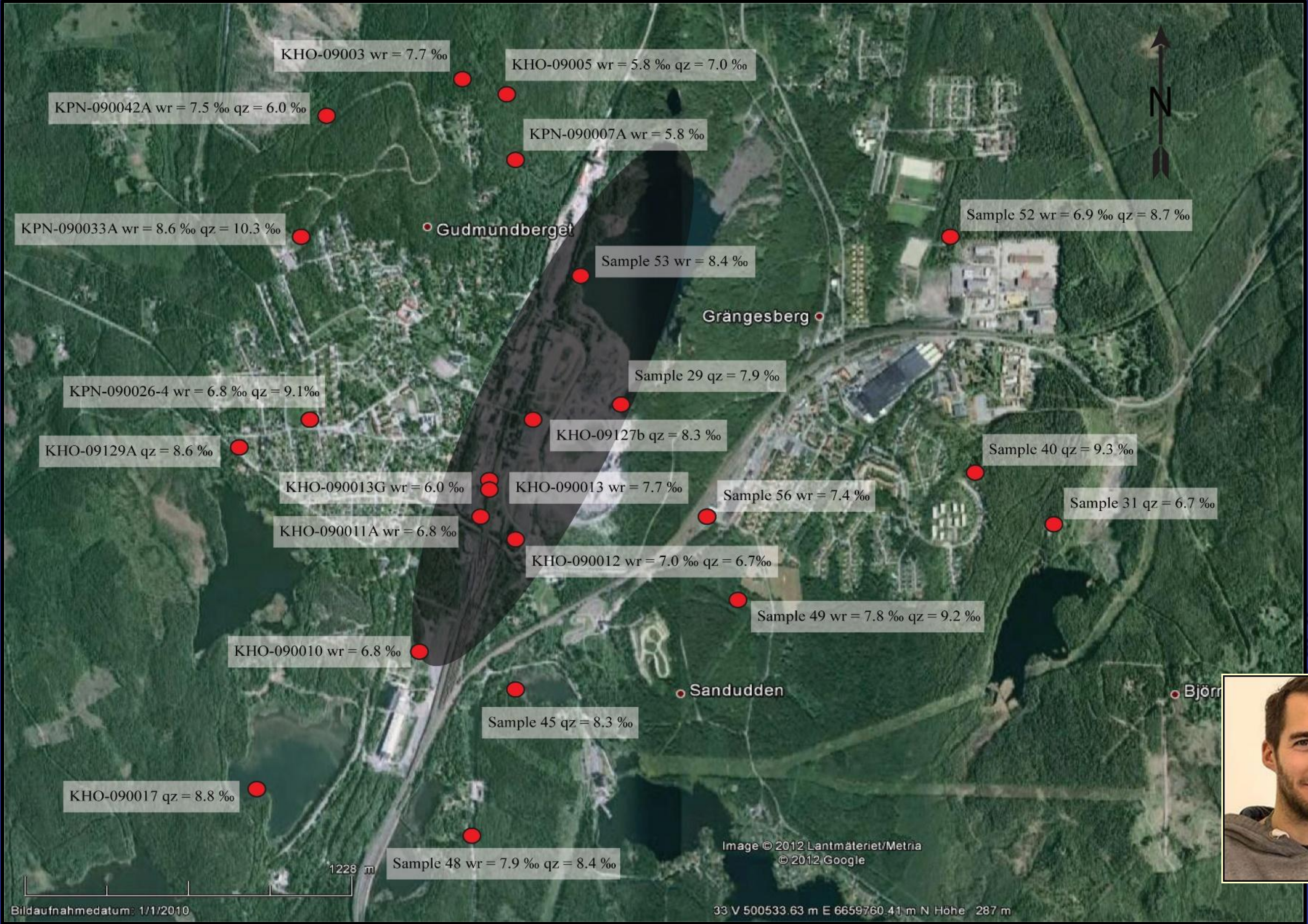
- Temperature calculations using Grängesberg quartz-magnetite and apatite-magnetite pairs confirm magmatic temperatures (Jonsson et al 2013; *Scientific Reports*)

Results for the geothermometric calculations

Sample	Magnetite $\delta^{18}O$	Quartz $\delta^{18}O$	Apatite $\delta^{18}O$	$\delta_{qz/ap} - \delta_{mgt}$	T in °C	2σ in K/°C
KES103003	0.2	7.6	-	7.4	**648**	±24
KES103016	1.5	7.9	-	6.4	**718**	±31
KES090073	1.3	-	5.5	4.2	**762**	±25

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 !**