

# New evidence for the timing of formation of Bastnäs-type REE mineralisation in Bergslagen, Sweden

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**Abstract.** The REE-Cu-Fe-(Au) deposits of Bastnäs-type in the Bergslagen ore province in central Sweden have a long history of mining as well as scientific study and discovery. Yet, relatively little information on their timing of formation has been available, and their overall genesis remains unclear. Here we present data and observations on an uncommon style of Bastnäs-type REE silicate mineralisation, from the Högfors deposit. It represents the only direct observation of this type of mineralisation that is apparently stratabound, inter-layered in a banded iron formation (BIF). The deposit is located in the northern part of the Riddarhyttan district. Here, cerite and västmanlandite-dominated, banded REE silicate mineralisation occurs within a hematite-dominated, quartz-banded iron formation together with modest amounts of associated, amphibole-dominated Fe-Mg-Ca skarn assemblages. The REE minerals, as well as the associated iron oxides, are extensively recrystallised to a granoblastic texture. Furthermore, these banded assemblages are extensively folded, and we conclude that REE mineralisation formed prior to the polyphase deformation and regional metamorphism associated with the c. 1.90-1.80 Ga Svecokarelian orogeny. These observations contradict post-orogenic processes as responsible for the Bastnäs-type REE deposits, and support a model involving syn-volcanic (Svecofennian), magmatic activity.

**Keywords.** Bastnäs-type deposit, BIF, Högfors, REE line, Bergslagen, Sweden

## 1 Introduction and background

The recent World-wide scramble for rare earth elements (REE), primarily a result of China's dominance in mine production during the past decades, combined with their new limitations on export quotas, has led to renewed interest in REE deposits old and new.

The first mining activity focused on REE in the Fennoscandian shield took place during the late 1800s in the Bastnäs mines in the central part of the Bergslagen ore province, significantly also the place of the original discovery of the element cerium (Hisinger and Berzelius 1804). Overall, the Bastnäs-type deposits (Geijer 1961) are arranged along a more than 100 km long, narrow belt that we collectively call "the REE line". It represents both a geological anomaly and a zone of significant concentration of mostly light REE, but to some extent also yttrium and heavy REE. Over time, the Bastnäs-type deposits have been debated both as to their process of formation and their temporal relations to surrounding host rocks and mineralisation types.

Their formation, together with that of associated skarn iron ores, was originally interpreted to be related to large-scale, so-called magnesia metasomatic processes, generated by granitoid intrusives, essentially synchronous with the waning stage of regional metamorphism (Geijer 1961; Magnusson 1970). Later studies have rendered this theory obsolete, and accumulating observations tend to favour a more or less syn-volcanic magmatic-hydrothermal scenario (cf. Holtstam and Andersson 2007, and references therein). Yet, no conclusive theory has been presented for these deposits.

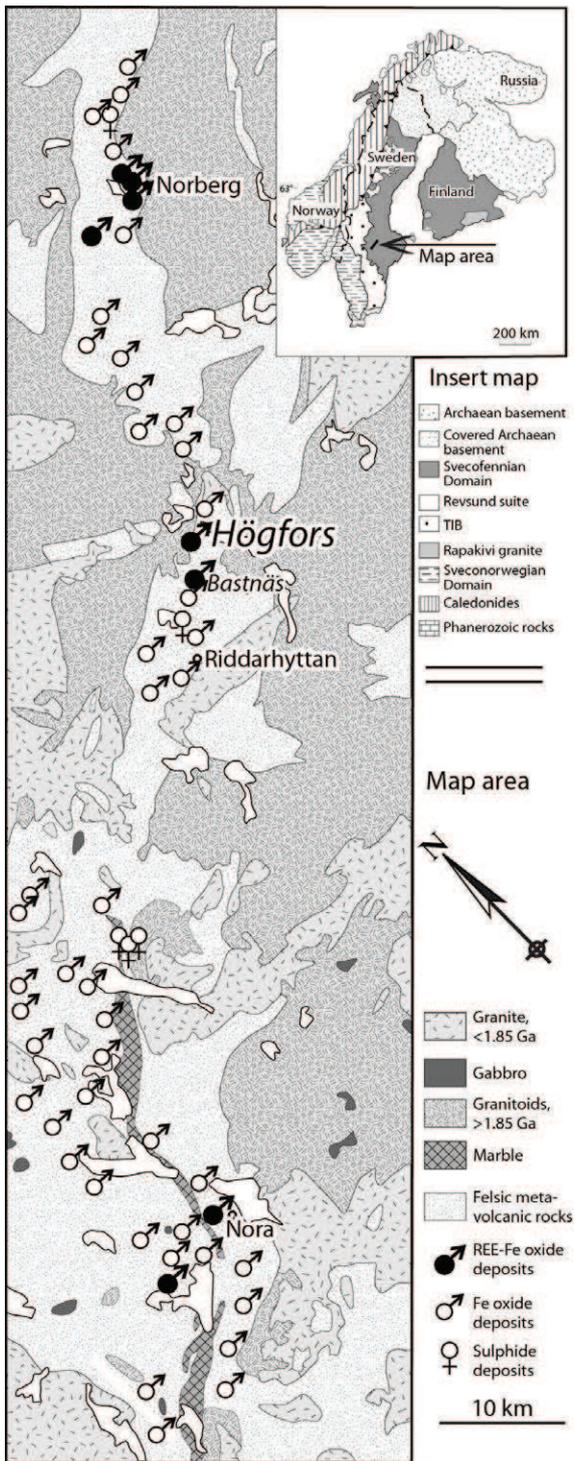
## 2 Geology and mineralisation

### 2.1 The Bergslagen ore province

The ancient Bergslagen ore province in south central Sweden is well-known for its abundance of mineral deposits, mainly in the form of base metals (Cu, Pb, Zn) and iron oxides (e.g. Tegengren 1924; Magnusson 1970). The primary ore-bearing rock sequence in Bergslagen is dominated by rhyolitic to rhyodacitic, alkali-rich metavolcanic rocks, together with smaller volumes of metabasic rocks, clastic metasedimentary rock units and marbles.

These rocks formed at c. 1.90-1.87 Ga during an early stage of the Svecokarelian (Svecofennian) orogeny. The predominantly felsic volcanic rocks and related penecontemporaneous intrusives were formed in a shallow marine, caldera environment, in a back-arc region inboard an active continental margin (Allen et al. 1996; Lundström et al. 1998; Stephens et al. 2009). During the orogenic evolution these rocks were subsequently metamorphosed under mainly greenschist and amphibolite facies conditions and subjected to polyphase deformation. Younger granites and associated pegmatites, post-dating the c. 1.85-1.80 Ga regional metamorphism, are ubiquitous in the province.

Mineralisation occurs both in the felsic metavolcanic rocks and the commonly occurring, interlayered carbonate rocks and associated skarns (variably Fe, Mg and/or Mn-bearing calc-silicate assemblages formed both as a variably isochemical consequence of regional metamorphism of impure carbonate rocks, as well as through metasomatic reactions between granite-derived fluids rich in silica and other components and carbonate rocks).



**Figure 1.** Geological overview map of the main part of the REE line in Bergslagen. Inset map of the geological outline of Fennoscandia with rectangle showing the position of the detailed map. Major REE-iron oxide ( $\pm$  Cu, Au, Co, Bi...) deposits are highlighted as filled iron ore symbols. Modified after Andersson (2004) and SGU datasets.



**Figure 2.** Chevron-style folding in hematite-quartz-dominated c. 1.90-1.88 Ga banded iron (BIF) ore at Högfors, central Bergslagen ore province. Estwing hammer for scale.

## 2.2 The “REE line” and the Högfors mines

The distribution of skarn iron ore-associated REE silicate mineralisation in Bergslagen is concentrated to a discontinuous belt or “corridor” of deposits within a sequence of mostly extensively altered felsic metavolcanic rocks (Fig. 1; cf. Geijer 1961). This belt is very narrow, yet the linear extent of REE mineralisation is, based on all available information, likely to be over 100 kilometers, and hence we suggest the term “REE line”. The deposits of the northern part of the line are centered around Norberg, whereas in the central and southern parts, they cluster around Riddarhyttan and Nora, respectively (Fig. 1). Based on mineralogy and REE geochemistry, Holtstam and Andersson (2007, and references therein) subdivided the Bastnäs-type deposits in two main classes; subtype one with predominant LREE enrichment (mainly the southern and central deposits, including Bastnäs itself), and subtype two, featuring both enrichment in LREE and Y+HREE (the latter typified by the Norberg area deposits).

The Högfors deposits are situated to the north of the well-known Bastnäs field, in the Riddarhyttan district (Fig. 1). The Högfors field is, in turn, subdivided into two smaller fields, the Lilla Högforsgruvan and Stora Högforsgruvan (Högbom and Lundqvist 1930). The presently studied material comes from the Stora Högfors mine. Although magnetite-dominated skarn ores comprise parts of these fields, the major ore type mined at Högfors was a hematite-dominated, modestly skarn-bearing banded iron formation (Fig. 2).

### 3 Mineralogy, textures and structures

An initial study of the REE silicate assemblages was performed utilising limited optical microscopy, powder X-ray diffraction and scanning electron microscopy with energy-dispersive microprobe analysis (EDS). Based on this, the predominating REE mineral in the studied samples is a fluorine-enriched cerite-(Ce), that occurs as a major component of folded REE silicate bands within the BIF (Figs. 3, 4), together with an iron-rich and fluorine-poor västmanlandite-like mineral (possibly identical to the close to end-member composition of the suggested Fe-analogue to västmanlandite-(Ce); cf. Holtstam et al. 2005; Fig. 4A, Tab. 1). A second assemblage type within the banded mineralisation comprises a similar västmanlandite-type mineral as the major component, with abundant anhedral inclusions of gadolinite-(Ce), minor fluorocarbonates and sparse euhedral to subhedral crystals of ferriallanite-(Ce) (Fig. 4B).

**Table 1.** General chemical formulae of REE minerals.

Mineral:	General formula:
Bastnäsite-(Ce)	(Ce, LREE)(CO <sub>3</sub> )F
Cerite-(Ce)	(Ce, LREE, Ca) <sub>9</sub> (Mg, Fe)(SiO <sub>4</sub> ) <sub>6</sub> (SiO <sub>3</sub> OH)(OH) <sub>3</sub>
Ferriallanite-(Ce)	Ca(Ce, LREE)Fe <sup>3+</sup> AlFe <sup>2+</sup> (SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )O(OH)
Gadolinite-(Ce)	(Ce, LREE, Y) <sub>2</sub> FeBe <sub>2</sub> Si <sub>2</sub> O <sub>10</sub>
Monazite-(Ce)	(Ce, LREE)(PO <sub>4</sub> )
Synchysite-(Ce)	Ca(Ce, LREE)(CO <sub>3</sub> ) <sub>2</sub> F
Västmanlandite-(Ce)	(Ce, LREE) <sub>3</sub> Ca(Mg, Fe) <sub>2</sub> Al <sub>2</sub> Si <sub>5</sub> O <sub>19</sub> (OH) <sub>2</sub> (F, OH)

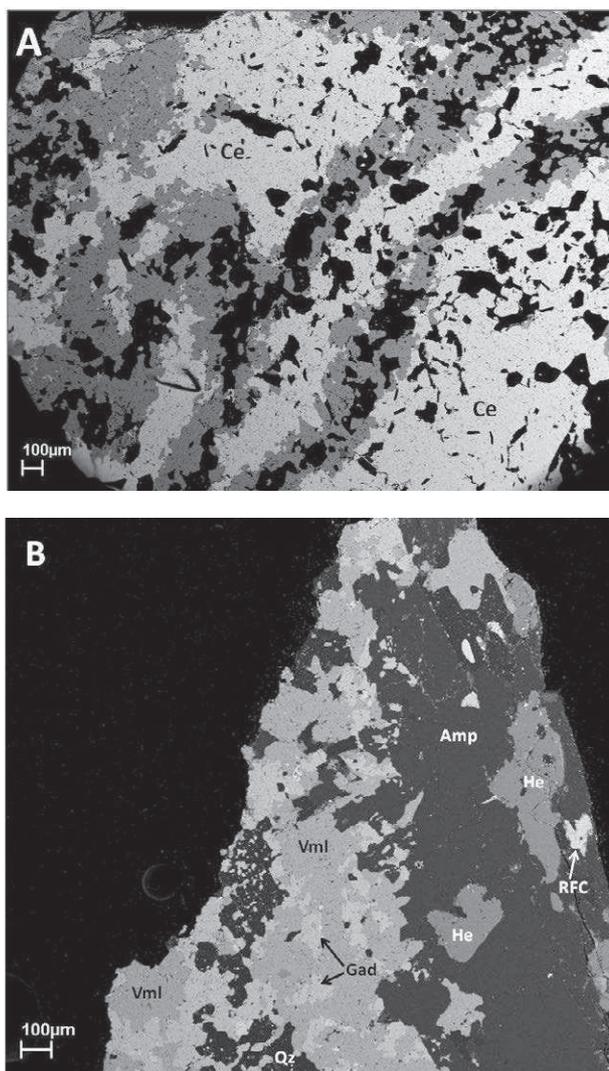
REE fluorocarbonates (and possibly fluoride(s)) occur throughout the studied assemblages in relatively sparse amounts, often exhibiting heterogeneous compositions and textures, indicating incipient alteration and breakdown to secondary phases. Based on SEM-EDS data, the predominating minerals comprise bastnäsite-(Ce) together with phases with compositions between synchysite-(Ce) and röntgenite-(Ce). Of these, bastnäsite seems to be the earliest-formed phase.



**Figure 3.** Hand-specimen scale folding of REE silicate bands in metamorphosed banded iron (BIF) ore at Högfors. Lighter cerite-(Ce)-dominated band is faulted and offset by a quartz vein (lower left). These veins carry additional allanite-type minerals. Scale bar equals 1 cm.

Additionally, sparse anhedral, rounded crystals of a partly sulphur and silicon-substituted monazite-(Ce) (Ce>La>Nd) occur within the REE silicate bands.

The folded, banded REE silicate assemblages exhibit a re-crystallised texture, with internal grain fabric being mostly granoblastic. All phases except sparse inclusions of ferriallanite are anhedral. The overall interpretation is of an extensively metamorphosed (and deformed) assemblage. A second generation of REE silicate(s), predominantly an allanite mineral, occur as more coarse-grained and distinctly euhedral crystals in thin quartz veins. These cross-cut and displace banded assemblages (including the BIF) at high angles (Fig. 3). We presently interpret these quartz vein-hosted assemblages as more likely to represent remobilisation of pre-existing REE, rather than a second mineralising event.



**Figure 4.** Field emission SEM back-scattered electron (BSE) images of representative textures of REE silicate assemblages in a metamorphosed banded iron formation at Högfors.

A. Complexly folded bands of cerite-(Ce) (Ce in figure) and a västmanlandite-type mineral (grey) and other silicates and quartz (black). Scale bar equals 100 micrometers. B. Irregular bands of a västmanlandite-type mineral (Vml) with inclusions of gadolinite-(Ce) (Gad), minor REE-fluoro-carbonates (RFC), hematite (He) and associated silicates including amphibole (Amp) and quartz (Qz). Scale bar equals 100 micrometers.

## 4 Discussion

The overall mineralogy and chemistry of the REE silicate assemblages at Högfors shows similarities with both subtypes of deposits in the classification by Holtstam and Andersson (2007). The two most abundant REE minerals here are cerite-(Ce), similar to Bastnäs (subtype 1), and a Ce-dominated västmanlandite-like mineral, typical of deposits in the Norberg area (subtype 2). Several of the minerals show enrichment in iron, which is not unexpected considering the BIF environment. The local, but relatively high abundance of the beryllium mineral gadolinite-(Ce) is an additional similarity with the deposits of subtype 2. Cerite-(Ce) is relatively enriched in fluorine, but other than the sparsely distributed fluorocarbonates, minerals with essential fluorine seem to be lacking. This is in accordance with the relatively low amounts of Y+HREE encountered at Högfors, considering the higher degree of complexing and transport possible for HREE in fluoride-rich fluids (cf. discussion in Holtstam and Andersson 2007).

The textural and structural interpretations of the Högfors assemblages are relatively unambiguous, and clearly suggest that REE mineralisation formed during an early stage of the Svecofennian orogeny.

Based on the present observations, we cannot say whether the REE rich bands formed as a primary, interlayered component, syngenetic in relation to the banded iron formation, or if REE mineralisation was introduced later, as an epigenetic replacement of selected bands (e.g. carbonate-dominated). What is clear is that the formation of the REE silicate assemblages predates peak regional metamorphism and associated folding of the ores and its host rocks. This can be compared with the Bastnäs molybdenite Re-Os data of Holtstam (2004), yielding ages between c. 1.86-1.85 Ga, albeit with rather large errors. These ages seem too low for Svecofennian volcanic-associated processes. In order to clarify this contradicting evidence, tests will be made to attempt chemical dating of the monazites in the Högfors sample material.

It has been suggested that in the Norberg region, the banded iron formations belong to a higher “etage”, or stratigraphic level, than the neighbouring skarn iron ores including Bastnäs-type deposits (e.g. Magnusson 1970). Thus, speculatively, in the comparable setting of the nearby Riddarhyttan area, the Högfors field with its REE-mineralised BIF's could represent an originally seafloor or shallow sub-seafloor expression of the process responsible for deeper situated, coarse, skarn-hosted REE silicate mineralisation represented by the Bastnäs deposits proper. An alternative, and perhaps more realistic, interpretation is that both the Bastnäs and Högfors mineralisations could have formed similarly through carbonate-replacement, the only major difference being the primary availability of carbonate: abundant at Bastnäs, while sparse within the Högfors banded iron formation.

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