THE PALAEOPROTEROZOIC SKARN-HOSTED REE MINERALISATIONS OF BASTNÄS-TYPE: OVERVIEW AND MINERALOGICAL – GEOLOGICAL CHARACTER

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Abstract

The Bastnäs-type rare earth element (REE) deposits are located in the Palaeoproterozoic Bergslagen ore province in the Swedish part of the Fennoscandian Shield. These deposits comprise magnetite-skarn-hosted REE silicate mineralisations that occur along a discontinuous belt, c. 100 km in length, hosted by metamorphosed c. 1.90-1.87 Ga Svecofennian volcanosedimentary rocks. The major REE-minerals are LREE-enriched silicates, e.g. cerite-(Ce), and carbonates, e.g. bastnäsite-(Ce). Available evidence suggest that the Bastnäs-type deposits formed through replacement reactions between c. 1.9 Ga carbonate units and hydrothermal, magmatic-dominated fluids, most likely related to volcanic-subvolcanic activity coeval with the younger parts of the host rock sequence. Despite their known relatively small sizes, several are studied by exploration companies.

Introduction

The increasing global interest in rare earth elements (REE) and their deposits has prompted both new exploration as well as renewed interest in known occurrences. Overall, the Nordic part of the Fennoscandian Shield is considered one of the areas with highest potential for exploration in Europe today, not least for iron, base and noble metals. In addition, several projects for rare and critical metals including the REE are presently in different stages of development. Advanced REE projects include the syenite-hosted Norra Kärr deposit in southern Sweden[1]. Yet, the most classic of REE-rich mineralisations in the Shield are the skarn-hosted deposits of Bastnäs-type, in the Palaeoproterozoic Bergslagen ore province of south central Sweden (Fig. 1). The element cerium was discovered in cerite-(Ce) from the Bastnäs mines[2], and a succession of early studies led to the discovery of additional new elements and minerals. Subsequently, a number of similar deposits were identified in the west central part of the province, and brought together under the classification "Bastnäs-type deposits" [3]. Active during the 1800s, the mines of the Bastnäs field were most likely the first hard-rock deposits ever mined explicitly for REE extraction. Still today, the abundant mine dumps exhibit mineralised material, typically with significant REE contents (Table 1.).

Over time, the Bastnäs-type deposits have been debated both as to their formation and relations to host rocks and other types of mineralisation. Their genesis, together with that of the associated skarn iron ores and the extensive host-rock alteration, was originally interpreted to be related to large-scale, so-called magnesia metasomatic processes, generated by granitoids emplaced at the waning stage of regional metamorphism[3,4,5]. Presently hydrothermal scenarios are favoured, involving reactions between magmatic-hydrothermal fluids and pre-existing limestone layers[6,7,8,9].

REE mineral names are mostly given with recommended Levinson modifiers[10] (Table 2). Where detailed mineral chemical information is lacking, this is not applied. Occurrences of what is referred to as "orthite" in older literature, and where sufficient data is not available, are represented here by "allanite", as "orthites" reported from this area have been shown to represent an array of different species.

Table 1: Whole rock REE concentrations in mine dump samples, Bastnäs-type deposits.

Locality	Y ppm	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm	REE_{tot} %
Bastnäs	151	29400	44400	4001	13600	1500	173	836	71	262	34	53	4	19	2	9
Johanna	3633	16305	29275	2851	10000	2102	158	1687	197	750	131	297	37	179	24	7
Malmkärra	7780	54300	136500	17500	67900	11600	855	6900	686	2450	305	493	42	172	18	31
Rödbergsgruvorna	1200	17100	27300	2800	10500	1300	78	845	63	210	27	42	4	15	2	6
Södra Hackspik	5080	47100	71900	7600	28300	3600	340	2100	196	812	114	220	19	86	9	17
Östanmossa	3970	28300	53700	6100	24600	3700	171	2300	201	709	97	171	14	61	7	12
Östra Gyttorp	1994	25874	63800	6652	10000	4659	180	2716	282	815	91	178	24	131	18	12

Concentrations of Ce, La, Nd, Pr>10000 ppm, Gd, Pr, Sm >1000 ppm were analysed by ICP-AES. All other elements were analysed by ICP-MS at ALS, Vancouver, Canada.

Table 2: REE-minerals in the Bastnäs-type deposits

Mineral	*General formula*
Allanite-(Ce)	$Ca(Ce,LREE)Fe^{2+}Al_2[SiO_4][Si_2O_7]O(OH)$
Bastnäsite-(Ce)	$(Ce,LREE)(CO_3)F$
Bastnäsite-(La)	$(La,LREE)(CO_3)F$
Cerianite-(Ce)	$(Ce,LREE)O_2$
Cerite-(Ce)	$(Ce,LREE,Ca)_9(Mg,Fe)(SiO_4)_6(SiO_3OH)(OH)_3$
Dissakisite-(Ce)	$Ca(Ce,LREE)MgAl_2[SiO_4][Si_2O_7]O(OH)$
Dollaseite-(Ce)	$Ca(Ce,LREE)Mg_2Al[SiO_4][Si_2O_7]F(OH)$
Ferriallanite-(Ce)	$Ca(Ce,LREE)Fe^{2+}AlFe^{3+}[SiO_4][Si_2O_7]O(OH)$
Fluocerite-(Ce)	$(Ce,LREE)F_3$
Fluocerite-(La)	$(La,LREE)F_3$
Fluorbritholite-(Ce)	$Ca_2(Ce,LREE)_3[SiO_4]_3F$
Gadolinite-(Ce)	$(Ce,LREE,Y)_2FeBe_2Si_2O_{10}$
Gadolinite-(Y)	$(Y,REE,)_2FeBe_2Si_2O_{10}$
Håleniusite-(La)	$(La,LREE)OF$
Lanthanite-(Ce)	$(Ce,LREE)(CO_3)_3F \cdot 8H_2O$
Monazite-(Ce)	$(Ce,LREE)(PO_4)$
Parisite-(Ce)	$Ca(Ce,LREE)_2(CO_3)_3F_2$
Percleveite-(Ce)	$(Ce,LREE)_2Si_2O_7$
Synchysite-(Ce)	$Ca(Ce,LREE)(CO_3)_2F$
Törnebohmite-(Ce)	$(Ce,LREE)_2Al[SiO_4]_2(OH)$
Västmanlandite-(Ce)	$(Ce,LREE)_3Ca(Mg,Fe)_2Al_2Si_5O_{18}(OH)_2(F,OH)$

Geological setting

The REE-line[7] is located in the western part of the Palaeoproterozoic Bergslagen ore province in the c. 1.9-1.8 Ga Svecokarelian orogen (Fig. 1). Archaean and older Palaeoproterozoic rocks outline the northeastern boundary of the orogen, and to the south and southwest it is succeded by the 1.85-1.65 Ga Transscandinavian Igneous Belt.

During the Svecokarelian orogeny the Palaeoproterozoic rocks in the Bergslagen province formed in a back-arc setting inboard of an active continental margin[11]. The oldest, 1.90-1.87 Ga rocks, belong to a volcanosedimentary succession with coeval intrusive rocks. Polyphase deformation and LP-HT greenschist to amphibolite facies metamorphic occurred between c. 1.85 and 1.80 Ga. A suite of younger intrusive rocks was emplaced after the main deformation stage and are dominated by granites and associated pegmatites. The succession of metavolcanic rocks is estimated to be c. 8 km thick, and are mainly of rhyolitic to dacitic compositions, with subordinate occurrences of mafic rocks. The felsic metavolcanic rocks, typically with intercalated marbles and associated skarns, host most of the base metal and iron oxide mineralisations in the province[4,12], including the Bastnäs-type deposits.

The REE-line (Fig. 1) stretches about 100 kms in a NE-SW direction with a moderately to steeply dipping foliation, and is interpreted to be located in the core of an antiform[13]. It hosts a number of groupings of REE-rich iron oxide skarn deposits with associated BIF occurrences, as well as similar mineralisations without elevated REE contents. The mineralisations follow marble horisons interlayered with the metavolcanic rocks. Near the skarn deposits these rocks were strongly hydrothermally altered, and subsequently transformed during regional metamorphism into cordierite and/or andalusite-bearing mica schists or quartzites[14,15]. Meso-scale, ductile folds have been recorded along the REE-line[7] and the mineral assemblages in the deposits are recrystallised, indicating that they were formed at an early stage of the orogenic evolution. Mining of the iron oxide deposits in this area was active from the Middle Ages and into the 1980s.

Table 3: Observed REE minerals in the bastnäs-type deposits

Locality	Allanite	Bastnäsite	Cerite	Cerianite	Dissakisite	Dollaseite	Fluorbritholite	Fluocerite	Ferriallanite	Gadolinite group	Håleniusite	Lanthanite	Monazite	Parisite	Percleveite	Synchysite	Törnebohmite	Västmanlandite	REE-epidote	Fe-analogue to västmanlandite	Mg-analogue to gewlandite?	Unknown Ce-REE-silicate	Unknown W-REE-silicate
Bastnäs	x	x	x	x	x			x	x	x	x	x	x		x		x			x		x	x
Danielsgruvan (Knutsbo area)	x					x											x						
Haggruvan	x																						
Högfors	x	x	x							x			x			x				x	x		
Johanna		x	x			x				x								x					
Lerklockan	x																x						
Malmkärra		x	x		x	x	x			x				x			x	x			x	x	
Myrbacksfältet	x																		x				
Rödbergsgruvorna	x	x	x						x											x			
Södra Hackspik		x	x		x	x	x										x	x					
Storgruvan	x		x														x						
Stripåsen	x	x																					
Stålklockan	x					?																	
Åsgruvan			x			x																	
Östanmossa	x	x	x		x	x	x			x			x	x					x				
Östra Gyttorp	x	x								x				x									

Based on recent analytical work and [illegible]

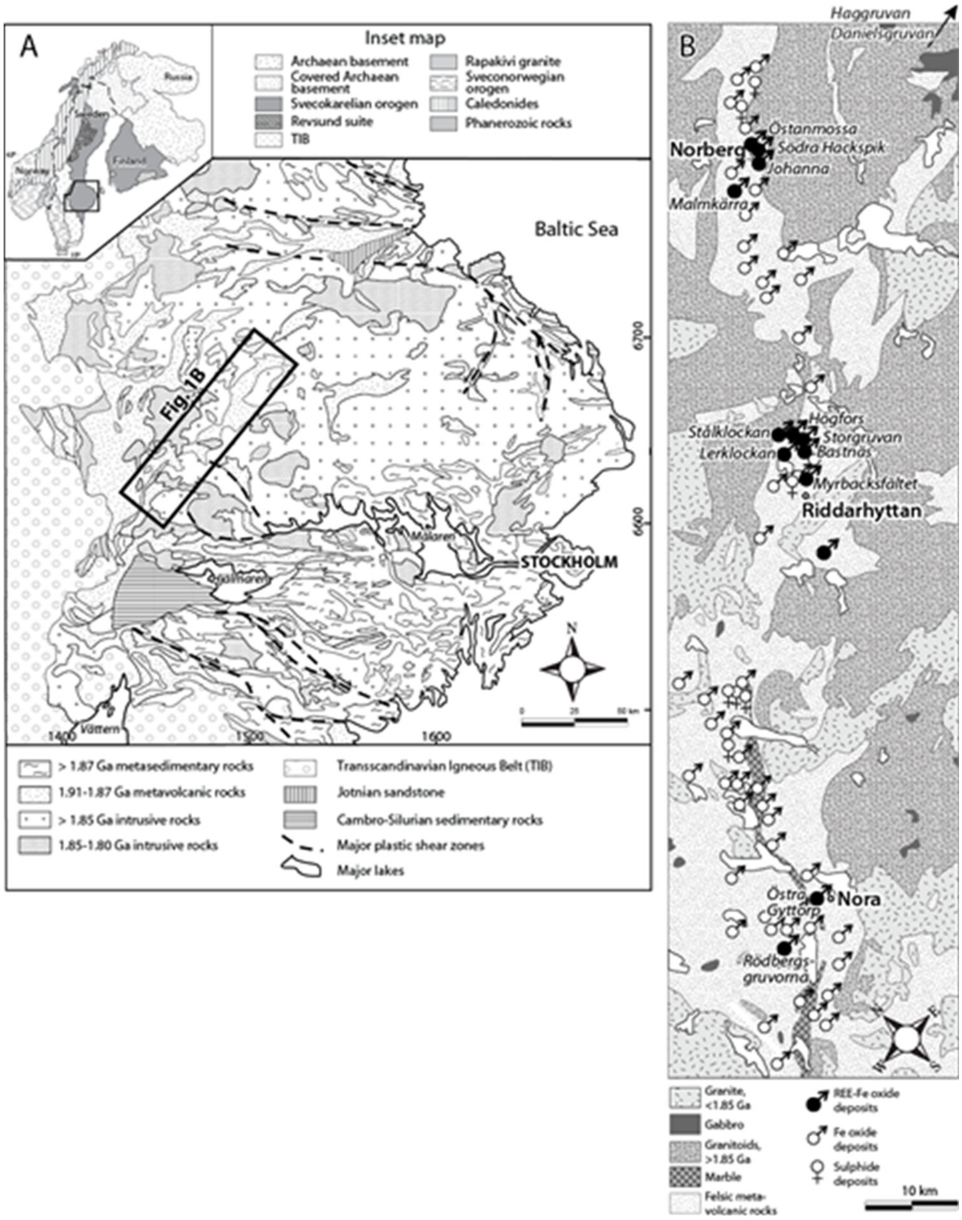

Figure 1: Geological overview map of the Bergslagen ore province, south central Sweden. Inset map shows the Bergslagen province and its position in the Fennoscandian shield (left). Geological map showing the major depsosits of the REE-line, the linear occurences of Bastnäs-type deposits in west central Bergslagen (right)7,20.

The Bastnäs-type deposits

The iron oxide skarn-associated REE silicate mineralisations occur within a specific sequence of the altered metavolcanic rocks, and they have been separated into subgroup 1 and 2 based on their location and their mineralogy and geochemistry9. Subtype 1 includes more iron-rich silicates and mainly LREE enrichment and subtype 2, exhibiting more magnesium and fluorine-rich silicates and enrichment in both LREE and Y+HREE. Their complex and diverse REE mineralogy and the variability between deposits is shown in Tables 2 and 3.

The Nora area

Two occurrences are known from the Nora area (Fig. 1). The predominant REE-assemblage at Rödbergsgruvorna consists of cerite-(Ce), allanite-Ce) – ferriallanite-(Ce), bastnäsite-(Ce), and a västmanlandite-like mineral, in clinoamphibole skarn associated with magnetite and minor sulphides[9,16]. REE mineralisation at the Östra Gyttorp mine occurs in the form of allanite-(Ce)-dominated lenses associated with magnetite ore, hosted by felsic metavolcanic rocks[6,16,17]. During mining, approximately 100 tons of "allanite"-dominated rare earth ore was produced and sold during the late 1800s, beside the iron ore[12]. Minor occurrences of "allanite" as well as other REE minerals have been noted in the greater Nora area, in addition to the deposits of Bastnäs-type.

The Riddarhyttan area

The Riddarhyttan area (Fig. 1) includes the most well-known deposit of this type, in the form of the eponymous Bastnäs mines. However, REE mineralisation in this area occurs also at several other locations within the same, partly altered, metavolcanic unit[14,15]. The Nya Bastnäsfältet is composed of two parallel ore horisons, featuring skarn-hosted (polymetallic) ores with locally abundant REE minerals, and banded iron formations, respectively (Fig. 2). The former are magnetite-dominated, and occur as pods in mainly clinoamphobole-dominated skarn, wholly or partly replacing marble. In the western part of the Bastnäs field unreacted portions of the marble bed are present.

Rich REE mineralisation was encountered at Ceritgruvan (the cerite mine; Fig. 2). The REE deposits here are of characteristic magnetite-skarn type, but with locally significant Cu-Co-Ni-Bi-Mo sulphides as well as minor Te, Hg-bearing minerals[18] and gold-silver alloys. At Bastnäs the most characteristic REE mineralisation type comprises either only "allanite" (ferriallanite-(Ce)), or an assemblage of cerite-(Ce) and ferriallanite-(Ce), with variable amounts of bastnäsite-(Ce) and törnebohmite-(Ce). It is stated that the overall REE ore production from the Cerite mine was c. 4500 tons, of which cerite alone accounted for several hundreds of tons[14,19]. Later reworking of the old dumps at Nya Bastnäs yielded significant additional amounts (B. Högrelius, pers. comm.).

Storgruvan is another REE mineralisation comprising cerite associated with "allanite" and törnebohmite where c. 5 tons of REE-mineralised material were separated and sold[14]. The Högfors field to the NE features REE mineralisation within a banded iron formation[3,7], with sparse bands dominated by cerite-(Ce), a västmanlandite-type mineral, ferriallanite-(Ce) and gadolinite-(Ce) as well as additional minor minerals that occur as fine-grained, recrystallised assemblages in folded bands or layers[7].

Outside of this major, ore-bearing unit, REE mineralisation was also encountered at Lerklockan, Stålklockan, Myrbacksfältet and others. Additional REE-mineralised zones at depth in the greater Bastnäs area were noted during exploratory drilling for gold and base metals in the 1980s[15].

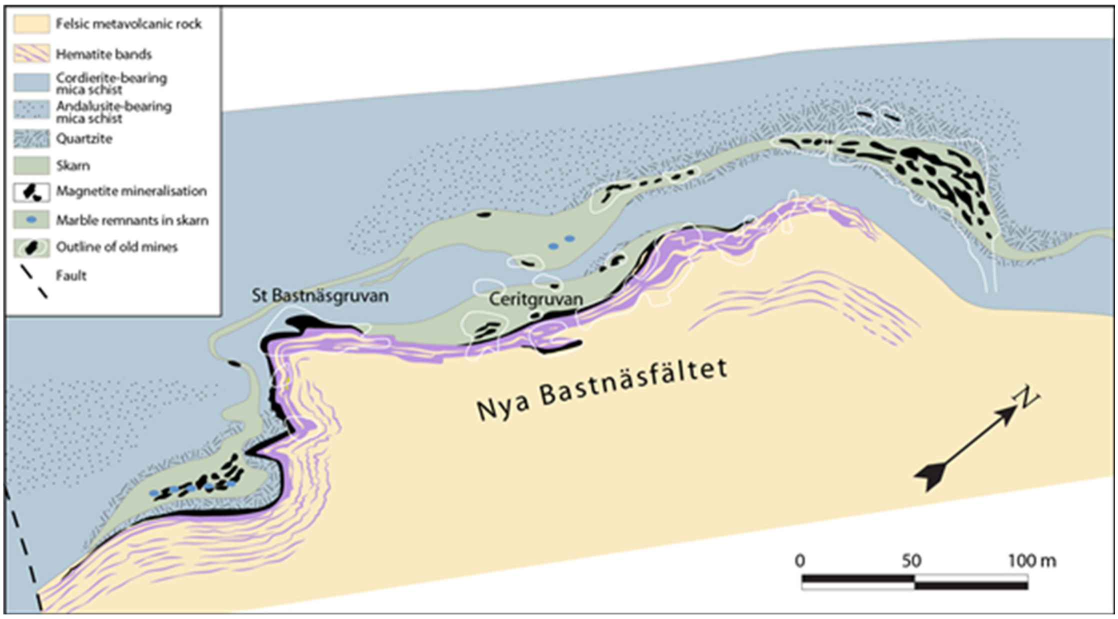

Figure 2: Detailed geological map showing the relations in the Bastnäs ore field, Riddarhyttan. Modified after Geijer14.

The Norberg area

The major occurrences of Bastnäs-type REE mineralisation in the Norberg area (Fig. 1) are the Östanmossa, Malmkärra, Johanna, Åsgruvan and Södra Hackspik mines, all of them magnetite-dominated, magnesium-rich skarn iron ore deposits. The relative abundance of fluorine in the Norberg area deposits (subtype 2) is manifested by the abundance of humite-group minerals, including norbergite. These occur intimately with REE mineralisation, such as at Johanna, where norbergite is present as subhedral crystals included in REE silicates. The presence of humite-group minerals is also indicated by the common occurrence of "ophicalcite"; a carbonate rock containing pseudomorphs of humite-minerals.

The Malmkärra mines are magnetite skarn deposits occurring within a narrow layer of marble. Here, REE mineralisation in the form of fluorbritholite-(Ce), västmanlandite-(Ce) as well as REE-carbonates[9,20] occurs in a skarn zone in that marble at the contact towards cordierite schists. In the Johanna mine magnetite mineralisation is associated with tremolitic skarn with "ophicalcite" pods[21], and associated REE mineralisation in the form of dollaseite-(Ce) associated with sparse cerite-(Ce), REE-carbonates and gadolinite-group minerals. At Åsgruvan, another magnetite skarn deposit in marble, carries sparse REE mineralisation, mainly as "allanite" [21]. The mines at Östanmossa were operated on a magnetite mineralisation similar to that at Åsgruvan[21], but feature more abundant REE mineralisation as dollaseite-(Ce) and fluorbritholite-(Ce), characteristically associated with norbergite[9,16,21]. The Södra Hackspik mine is another deposit in fluorine-rich skarn, featuring locally REE-rich assemblages, with cerite, törnebohmite, dissakisite-(Ce), dollaseite-(Ce), bastnäsite-(Ce and La), and fluorbritholite-(Ce)[3,9,16]. In addition, REE enrichment, mainly hosted by "allanite" and REE-enriched epidote has been noted in a number of other iron and base metal mineralisations, such as Stripåsen.

The deposits forming the northeasternmost continuation of the REE-line are not represented in Fig. 1, as they are located significantly farther to the east, yet decidedly forms an offset part of this structure. At Knutsbo, Danielsgruvan and Haggruvan have been noted for their REE contents, with e.g. "allanite" and törnebohmite described from a talc-bearing amphibole skarn[3].

Discussion and conclusions

The Bastnäs-type deposits represent a style of mineralisation without directly similar deposits occurring outside of the Bergslagen province. All available evidence suggest that the Bastnäs-type deposits formed as a consequence of submarine volcanic to subvolcanic, magmatic-dominated hydrothermal activity at around c. 1.9 Ga. The iron ores and the associated skarn as well as REE mineralisation were generated through reactions between pre-existing marble beds within the volcanosedimentary sequence, and hydrothermal fluids, most likely in a sub-seafloor position. The differences in mineralogy between the deposits may originate both from local fluid (and mineral) evolution, the degree of fluid-rock interaction[9], as well as in variations in the local ore-forming systems, including volcanic-hydrothermal facies.

Despite the modest known size of individual Bastnäs-type deposits, their high grades and extended distribution along the REE-line suggest relevant exploration potential, not least when considering the presence of other metals. A potential problem for the beneficiation of these deposits is their mineralogical complexity. Yet, in most cases, a few REE silicates (e.g., cerite-(Ce), dollaseite-(Ce), ferriallanite-(Ce), fluorbritholite-(Ce)) tend to dominate, which may improve their chances of utilisation.

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