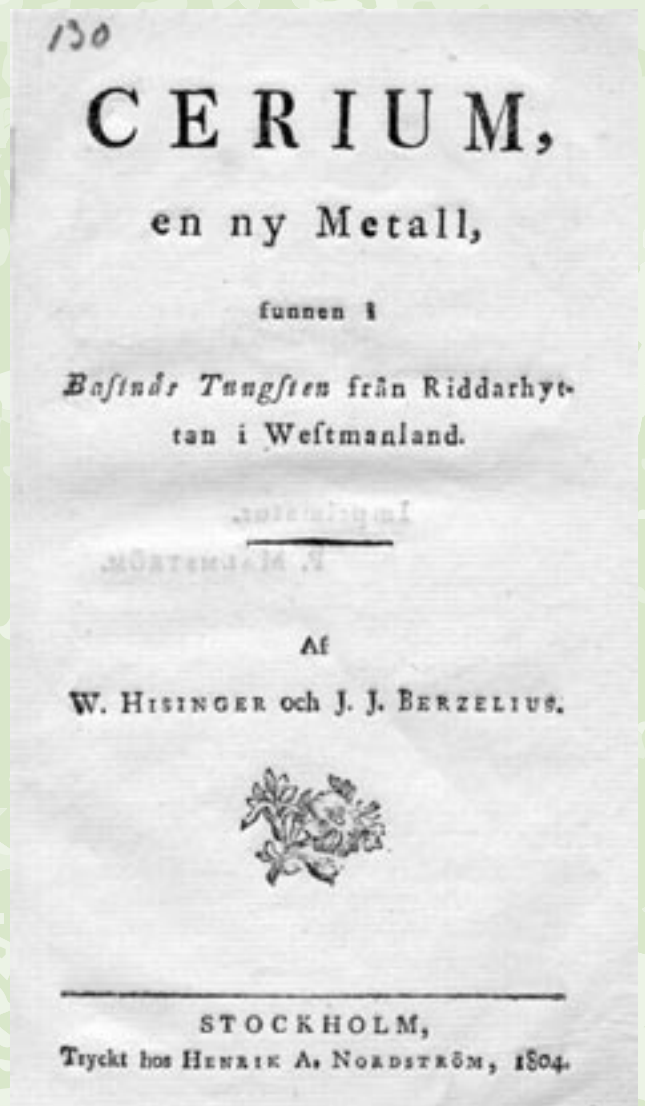# The Bastnäs-type REE-mineralisations in north-western Bergslagen, Sweden

– a summary with geological background and excursion guide

Ulf B. Andersson (ed.)

CERIUM,

en ny Metall,

funnen i

Baſtnds Tungſten från Riddarhyttan i Weſtmanland.

Af

W. Hisinger och J. J. Berzelius.

STOCKHOLM,
Tryckt hos Henrik A. Nordström, 1804.

SGU

Sveriges geologiska undersökning
Geological Survey of Sweden

The Bastnäs-type REE-mineralisations in north-western Bergslagen, Sweden
– a summary with geological background and excursion guide

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Cover photograph: Title page of the pamphlet where the discovery of cerium was first announced (Hisinger & Berzelius 1804a). It was printed in no more than 50 copies. This one was kept by Hisinger himself, and is in now in the possession of Naturhistoriska riksmuseet, Stockholm.

FOREWORD

At a time when exploration for base- and precious metals in Sweden prosper and new copper, zinc and gold mines are put into production, it can be appropriate to remind about other, more exotic metals and minerals that are found and have been mined in Sweden. Among those are the rare earth element (REE) deposits with cerium as the most common element.

The Swedish REE mines have been closed for a long time but the increasing demand for REE by modern optic and electronic technology can make these deposits economically significant again in the future.

The REE deposits also have an interesting history in that many of the REEs were first discovered in minerals from Swedish deposits, and later named after Scandinavian chemists or deposits. For example, the elements yttrium, ytterbium, erbium, and terbium are all named after the Ytterby mine, whereas the Bastnäs mine has given name to one of the most important REE-minerals, bastnäsite.

In the present volume, the history of the discovery of the most common rare earth element, cerium, is described and several geological and mineralogical aspects of the REEs are discussed. The excursion guide to the Bastnäs-type REE mineralisations in north-western Bergslagen provides the geological background and detailed descriptions and guides to some of the most famous REE deposits in Sweden.

The Geological Survey of Sweden regards this volume as an important contribution to the knowledge of Swedish mineral deposits.

Anders Hallberg, SGU
Project leader, ore documentation

PREFACE

In 1804 Hisinger & Berzelius published their discovery of the element cerium, isolated from cerite specimens recovered from the Bastnäs deposit, Västmanland county, Sweden. To celebrate the 200-year anniversary of this important contribution to science, the Mineralogical Society of Sweden (Svenska Mineralogiska Sällskapet, SMS) arranged a minisymposium with the theme: "CER200 – Rare earth elements in minerals" on September 24, 2004. The symposium was held at Swedish Museum of Natural History and was attended by scientists from eight countries. Following the symposium, on September 25–26, an excursion to the Norberg and Riddarhyttan ore fields in Västmanland county was arranged by the Society, in order to show the Bastnäs-type REE deposits and their geological settings. Sixteen participants joined the excursion that was led by the contributors to this volume. This compilation is an outgrowth of the informal guidebook that was prepared for the excursion and is intended to present an up-to-date review on these remarkable mineralisations, and their geological context. We wish to thank the Geological Survey of Sweden for the opportunity to publish this material in *Rapporter och meddelanden*.

Ulf B. Andersson   Jaana Hode Vuorinen
SMS, head organizer   SMS, chairman

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THE BASTNÄS-TYPE REE-MINERALISATIONS IN NORTH-WESTERN BERGSLAGEN, SWEDEN – A SUMMARY WITH GEOLOGICAL BACKGROUND AND EXCURSION GUIDE

Edited by U.B. Andersson
with contributions by D. Holtstam, I. Lundström, U.B. Andersson, J. Langhof, and P. Nysten

REGIONAL OVERVIEW
U.B. Andersson

The Fennoscandian Shield

The Fennoscandian Shield (Fig. 1) comprises an Archaean nucleus in its north-eastern part to which Proterozoic terranes have been successively accreted along the southern and western flanks (e.g. Gaál & Gorbatschev 1987). The post-Archaean development started by periods of rifting of the craton interior and margin between 2.45 and 2.0 Ga (e.g. Park et al. 1984, Gaál & Gorbatschev 1987, Nironen 1997). This was followed by the formation of juvenile crust at 2.1–1.93 Ga in several arc systems around the craton in the south-west resulting in 'microcontinents' in certain areas, including the Bergslagen area (e.g. Nironen 1997, Nironen et al. 2002, Lahtinen et al. 2004). This earliest 'proto-Svecofennian' development (Andersson et al. 2004a) is documented by only a few preserved outcropping rocks, none of which have been found in Bergslagen (e.g. Wasström 1993, 1996, Skiöld et al. 1993, Lahtinen & Huhma 1997, and references therein), but by abundant old, >1.91 Ga, detrital zircons found in associated metasedimentary rocks (Claesson et al. 1993, Lahtinen et al. 2002, Andersson et al. 2004b, Sultan et al. 2004). The main early Svecofennian rock-forming phase (1.91–1.86 Ga) resulted in a thorough reworking, partly including rift-related volcanism, of the early arc systems in addition to major formation of juvenile crust in areas between the microcontinents, and the final accretion of this complicated collage to the craton margin at about 1.86 Ga (e.g. Vivallo & Claesson 1987, Baker et al. 1988, Lagerblad 1988, Vivallo & Willdén 1988, Gaál 1990, Allen et al. 1996, Nironen 1997). After completed accretion, subsequent east- and northward subduction resulted in pervasive reworking of the newly formed crust during the late Svecofennian (c. 1.85–1.75 Ga). This reworking resulted in the voluminous Transscandinavian Igneous Belt (TIB) along the south-west margin, as well as pene-contemporaneous, mainly granitoid magmatism and regional metamorphism further towards the continent, e.g. in Bergslagen (Patchett et al. 1987, Andersson 1991, Andersson et al. 2004c).

Bergslagen

The Bergslagen area (Fig. 2) constitutes the south-western part of the southern Svecofennian province (SSP) (Gaál & Gorbatschev 1987) and comprises a volcano-metallogenetic district rich in mineralisations of several types. These include banded iron formation (BIF), apatite-iron oxide, skarn-iron, and specialised Mn-Fe (e.g. the famous Långban deposit), as well as massive sulphide, and W-Mo deposits (summarized in Frietsch 1986). Mining activities have been documented back almost a millenium in certain places. The SSP ore belt extends eastwards into southern Finland and the Orijärvi district (e.g. Gaál 1990). Its northern and western areas are dominated by volcanic formations, whereas sedimentary successions of the Sörmland basin dominate in the south-east (e.g. Stålhös 1991, Allen et al. 1996, Romer & Öhlander 1995). The rocks of the Sörmland basin have recently been interpreted to be an accretionary prism (Korja & Heikkinen 2000). In the north-east, early Svecofennian intrusions dominate, e.g. the Uppland batholith (Fig. 2). Crystallization ages of rocks belonging to the early Svecofennian magmatic phase in Bergslagen are generally between 1.91 and 1.86 Ga (e.g. Welin 1987, Kumpulainen et al. 1996, Lundström et al. 1998, Persson & Persson 1999, and references therein). The Bergslagen volcano-plutonic complexes have been interpreted as formed
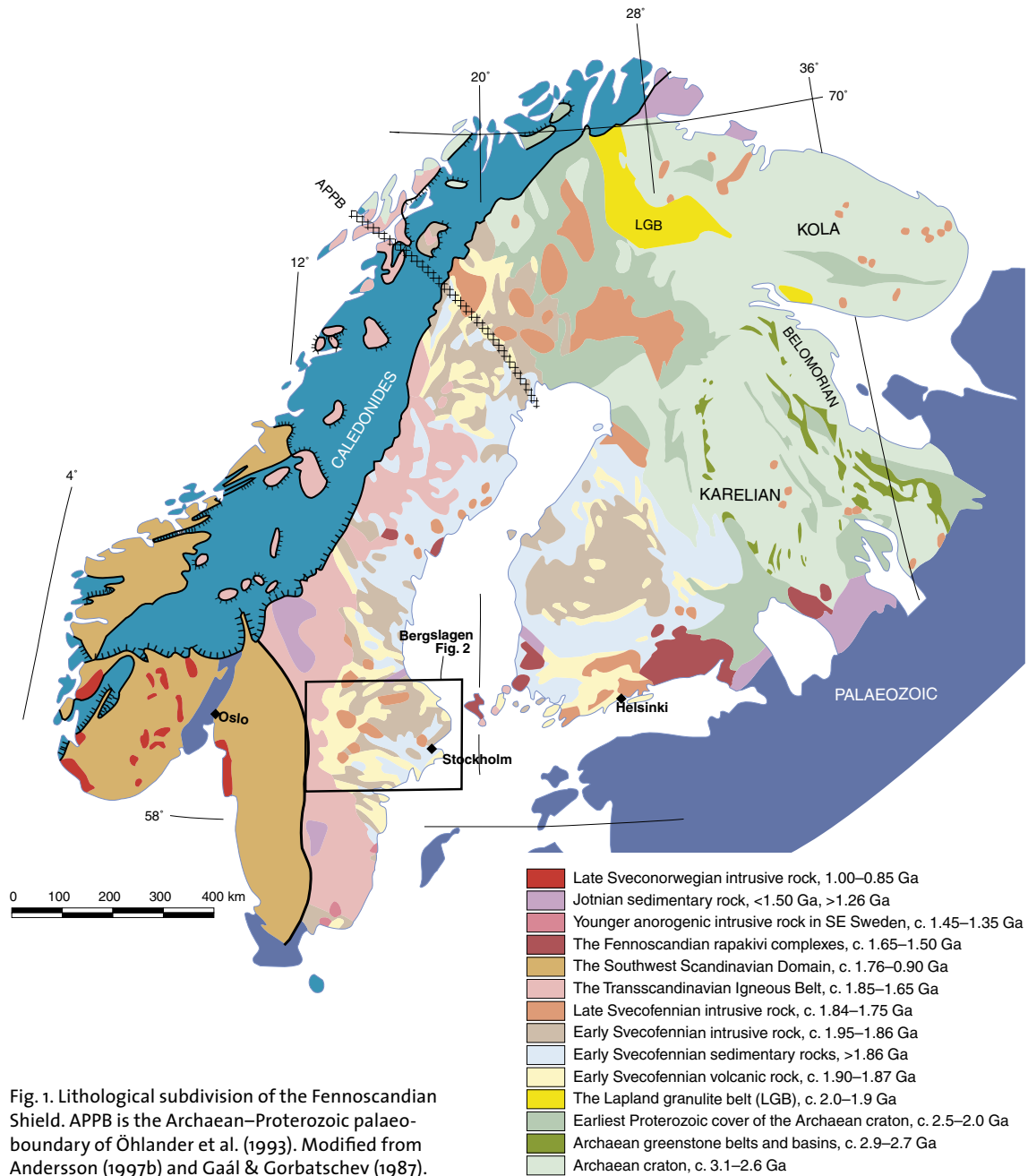
Fig. 1. Lithological subdivision of the Fennoscandian Shield. APPB is the Archaean–Proterozoic palaeo-boundary of Öhlander et al. (1993). Modified from Andersson (1997b) and Gaál & Gorbatschev (1987).

■ (red)	Late Sveconorwegian intrusive rock, 1.00–0.85 Ga
■ (light purple)	Jotnian sedimentary rock, <1.50 Ga, >1.26 Ga
■ (pink)	Younger anorogenic intrusive rock in SE Sweden, c. 1.45–1.35 Ga
■ (dark red)	The Fennoscandian rapakivi complexes, c. 1.65–1.50 Ga
■ (tan)	The Southwest Scandinavian Domain, c. 1.76–0.90 Ga
■ (light pink)	The Transscandinavian Igneous Belt, c. 1.85–1.65 Ga
■ (orange)	Late Svecofennian intrusive rock, c. 1.84–1.75 Ga
■ (grey-tan)	Early Svecofennian intrusive rock, c. 1.95–1.86 Ga
■ (light blue)	Early Svecofennian sedimentary rocks, >1.86 Ga
■ (pale yellow)	Early Svecofennian volcanic rock, c. 1.90–1.87 Ga
■ (yellow)	The Lapland granulite belt (LGB), c. 2.0–1.9 Ga
■ (pale green)	Earliest Proterozoic cover of the Archaean craton, c. 2.5–2.0 Ga
■ (dark green)	Archaean greenstone belts and basins, c. 2.9–2.7 Ga
■ (light green)	Archaean craton, c. 3.1–2.6 Ga

in a rifted, mature (continental) arc setting (Oen et al. 1982, Vivallo & Claesson 1987, Baker et al. 1988, Lagerblad 1988, Vivallo & Willdén 1988, Gaál 1990, Allen et al. 1996). The metamorphic grade (Rickard 1988, Stålhös 1991) is high (upper amphibolite facies) in southern Bergslagen, including the Sörmland basin, where paragneisses characteristically are sillimanite-bearing. Locally, in the vicinity of TIB-intrusions, granulite facies (600–900 °C and 3–6 kbar) is attained (Andersson et al. 1992, Wiktröm & Larsson 1993, Andersson 1997a, Sjöström & Bergman 1998). A gradual shift into lower–middle amphibolite facies conditions is observed towards northern Bergslagen, where paragneisses are characteristically andalusite-bearing (c. <600 °C and 2–4 kbar; Stålhös 1991, Ripa 1994, Sjöström & Bergman 1998), with a minor area of greenschist facies rocks in the north-west (Fig. 2; e.g. Lundström 1995). A relatively abrupt change in metamorphic conditions to higher (upper amphibolite facies) grade occurs in northernmost Bergslagen and southern Norrland (Stålhös 1991,
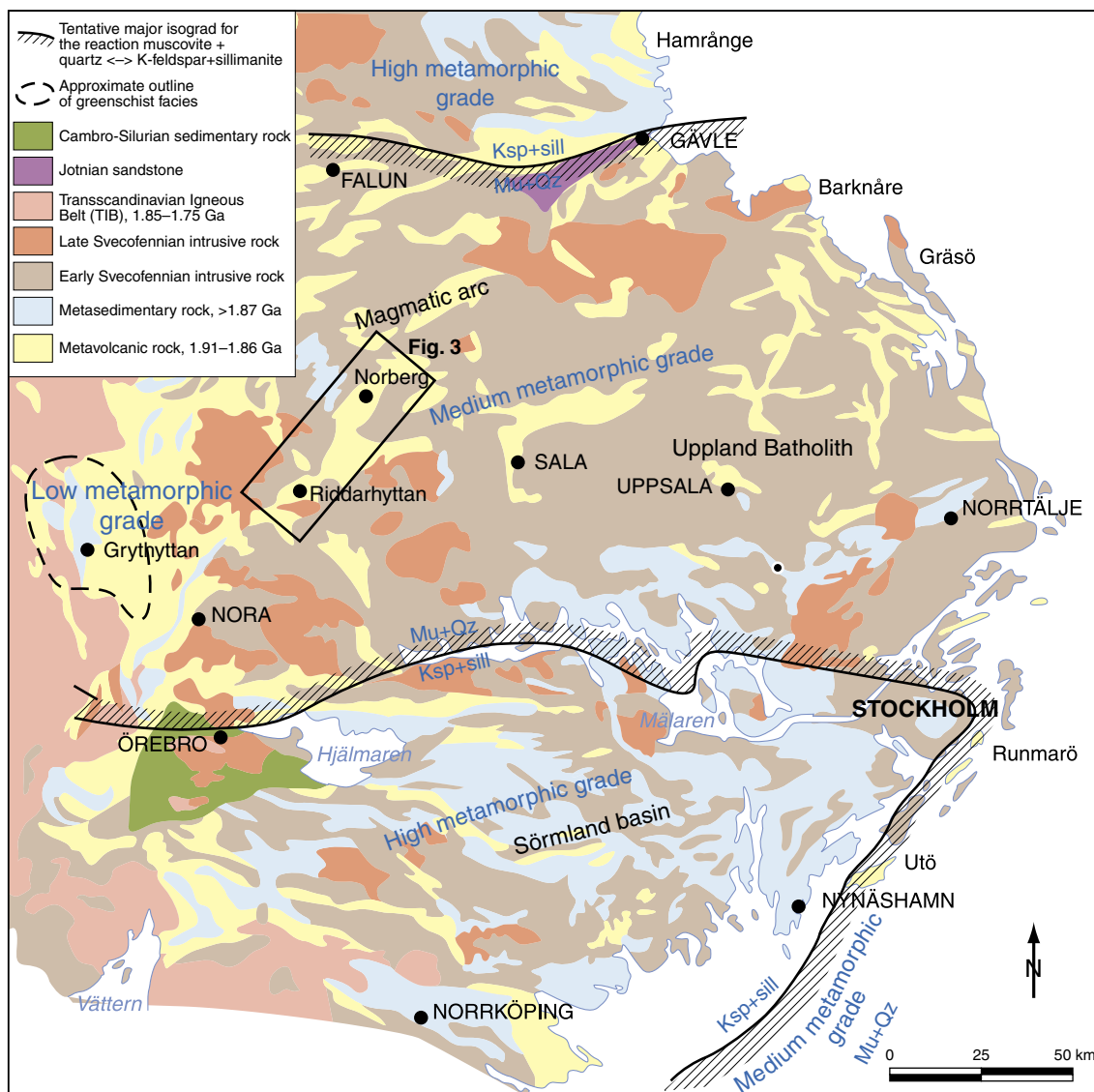
Fig. 2. Geological overview of Bergslagen (modified from Stålhös 1991).

Sjöström & Bergman 1998). The age of metamorphism in Bergslagen has traditionally been considered to be late Svecofennian, 1845–1780 Ma, but relatively few direct age determinations exist (Romer & Öhlander 1994, 1995, Andersson 1997a, Andersson et al. 2004a). This metamorphism was also considered to be related to the same tectono-magmatic heat flow event that caused the coeval late Svecofennian and TIB magmatism (Öhlander & Romer 1996, Andersson 1997a), possibly imparted by mafic underplating (Andersson 1991, Sjöström & Bergman 1998, Wikström & Andersson 2004). Recent findings, however, have emphasized a more widespread preservation of an early metamorphic phase (c. 1.89–1.86 Ga) in northern Bergslagen (Andersson et al. 2000, 2004b, Bergman et al. 2004, Hermansson et al. 2004).

DEPOSITIONAL HISTORY, STRATIGRAPHY, ORE TYPES, AND ALTERATIONS IN BERGSLAGEN
I. Lundström

The Bergslagen mining region is the westernmost and most intensely mineralised part of a Palaeoproterozoic supracrustal belt, which extends from south-central Sweden to southern Finland (Lundström

& Papunen 1986, Gaál 1990). It contains thousands of iron and base-metal sulphide deposits but, at present, only two Zn(-Pb) ore-fields (Zinkgruvan and Garpenberg) are still in operation.

Most sulphide and iron ores occur in distal, subaqeous, rhyolitic metavolcanic ash-siltstones that are mostly situated in the upper part of the metavolcanic pile. The ores have been interpreted to be either syngenetic, stratiform, ash–siltstone-hosted Zn-Pb ores or stratabound, volcanic-associated, limestone-skarn-hosted Zn-Pb impregnation ores (Allen et al. 1996, 2003). The latter are commonly associated with extensive footwall alteration and probably related to nearby subvolcanic intrusions.

Proximal, felsic pyroclastic rocks, their rapidly redeposited equivalents and subvolcanic intrusions characterize the lower part of the volcanic pile (Allen et al. 1996). The pyroclastic rocks are mainly pumice and glass-rich ash-flow deposits erupted from large calderas. In some places, these deposits are interbedded with mature, deltaic continent-derived metasandstones, containing Palaeoproterozoic to Archean detrital zircons (e.g. Kumpulainen et al. 1996, and references therein). Evidence for an older, felsic, continental basement thus exists in the lower part of the metavolcanic stratigraphy. Although this basement does not outcrop, its existence is corroborated by geochemical and isotope data. Instead, the metavolcanic rocks are locally found to rest upon turbiditic metasedimentary rocks, at least in the eastern part of Bergslagen (e.g. Allen et al. 1996, and references therein).

The explosive character, abundant accretionary lapilli and other depositional features suggest that the volcanic rocks initially were erupted and deposited in shallow water to subaerial conditions. With time, the depositional basin subsided, probably due to an extensional tectonic regime. Thus, deep-water environments became successively more frequent, and distal, frequently planar-bedded, metavolcanic ash-siltstones terminate the metavolcanic part of the stratigraphy (Allen et al. 1996). The supracrustal sequence is completed by planar-bedded, turbiditic mudstones. Hence, the metavolcanic rocks appear to be interlayered between turbiditic metasedimentary rocks, thus indicating a volcanic episode that more or less overprinted the ambient sedimentation. The metavolcanic rocks yield U-Pb (zircon) ages around 1880–1900 Ma (e.g. Lundström et al. 1998, and references therein). The tectonic setting of the area has been interpreted as a subsiding continental platform or margin, possibly in a continental back arc setting (Allen et al. 1996).

Differentiated, I-type granitoids (stops 5 and 6) intruded the supracrustal sequence and this assemblage was later folded and altered by low pressure metamorphism under low- to high-grade conditions. This deformation and metamorphism was associated with the Svecokarelian orogeny, and peaked after about 1850–1840 Ma (Andersson 1997a). The orogenic activity was accompanied and followed by the emplacement of numerous 1840 to 1750 Ma old S- to A-type granites (stop 7), some of which are associated particularly with tungsten and molybdenum mineralisations (Sundblad & Bergman 1996, Öhlander & Romer 1996, and references therein), as well as 1820 to 1785 Ma old (Romer & Smeds 1994, 1997) pegmatites (stops 4 and 8).

Metasomatic, mostly syndepositional, hydrothermal alterations occurred in large areas in Bergslagen, where they are thought to be related to much of the metallogeny (e.g. Lagerblad & Gorbatschev 1985, Allen et al. 2003.) The regional distribution of the various alteration types is mostly diffuse and therefore left unexplained, although stratigraphic controls have conventionally been invoked for the distribution of Na- and K-alterations (e.g. Frietsch 1982a). Where the overprint of regional deformation and metamorphism is weak enough, a zoned, concentric alteration pattern, centred on metabasite dikes, may locally be discerned.

Several alteration types are recognized (see e.g. Hallberg 2003):

1. Na-K-metasomatism has occurred in most of the metavolcanic rocks (Fig. 3, stop 1). Likewise, many synvolcanic and shallow, early orogenic intrusions (stop 6) have been affected by Na-metasomatism (cf. Baker 1985). This type of metasomatism is manifested by albite- or microcline-rich, alkali-extreme rock compositions. Compared to K-metasomatism, Na-metasomatism appears to have been favoured by stratigraphic depth or proximity to heat sources, such as intrusions. Na-metasomatism generally seems to have postdated K-metasomatism, possibly as a consequence of rising geotherms due to nearby intrusions (e.g. Lundström 1995, Hallberg 2003).

Fig. 3. Felsic metavolcanic rock: metatuff with skarn layers, possibly alkali-metasomatized. Roadcut at Viken, Klackberg (see stop 1). Photo: Dan Holtstam.

Fig. 4. Porphyroblasts of cordierite in Mg-enriched mica-schist (altered felsic metavolcanic rock). Roadcut along road 68 at Högfallsåsen (see stop 4). Width of photograph approximately 25 cm. Photo: Per Nysten.

2. Mg-metasomatism (cf. Baker & de Groot, 1983) locally affected the same rocks that were previously alkali-metasomatized (stops 2, 4 and 10), and is now recognized in quartz-, muscovite-, and phlogopite-rich rocks (Hallberg 2003) that are feldspar-free. In the low-grade, Mg-altered areas, chlorite is common, but in the high-grade areas, chlorite was replaced by biotite, phlogopite, and cordierite (Fig. 4; Trägårdh 1991). In thoroughly Mg-altered areas, anthophyllite-gedrite blastesis is not uncommon (Fig. 5; stop 4). In many places, Mg-metasomatic alteration is seen to have started along fractures in the precursor rock and seems to have been favoured by high water/rock ratios (e.g. Lundström 1995).

3. Actinolite-tremolite blastesis is regionally common in carbonate rocks, but occurs also enveloping metabasite dykes in both metavolcanic and early orogenic, intrusive rocks (e.g. Lundström 1995). In close vicinity to the metabasite dykes, this blastesis grades into spectacular actinolite veins and blebs, which locally are associated with magnetite or pyrrhotite growth. For more details see Allen et al. (1996) and references therein.

LOCAL GEOLOGY OF THE NORA–RIDDARHYTTAN–NORBERG AREA
I. Lundström

The Nora–Riddarhyttan–Norberg area forms an approximately 80 km long, north-east to south-west trending lens of supracrustal rocks (Fig. 6). It is surrounded by intrusive rocks on its eastern side, and intrusive and supracrustal rocks on its western side. The south-western part of the area consists of the Guldsmedshyttan syncline, which is situated more or less along strike from the Riddarhyttan area. The rocks of the Guldsmedshyttan syncline have a higher metamorphic grade, but are stratigraphic equivalents to the rocks that outcrop in the well preserved key area at Grythyttan, further west. As in Grythyttan, a Na-rich, alkali-rhyolitic, partly quartz-keratophyric sequence of massive, metavolcanic

Fig. 5. Radiating, metamorphic Mg-amphiboles (gedrite-anthophyllite) in mafic layer within mica-schist (Mg-altered, felsic metavolcanic rock). Roadcut along road 68 at Högfallsåsen (see, stop 4). Width of photograph approximately 30 cm. Photo: Per Nysten.

rocks forms the lowermost unit. In the Guldsmedshyttan syncline, corresponding rocks are called the Vassland formation (Lundström 1983). A K-rich, alkali-rhyolitic unit, dominated by metavolcanic ash–siltstones (the Usken formation), makes up the upper parts of the volcanogenic pile. The Usken formation becomes increasingly sedimentary stratigraphically upwards. Overlying the metavolcanic units, metasedimentary, andalusite-bearing mica-schists, stratigraphically corresponding to the well-known Grythyttan slate, occur. Locally, as on the eastern limb of the Guldsmedshyttan syncline, this sequence was replaced by the partly intrusive Storsjön formation, consisting of plagioclase-phyric dacites to quartz-andesites. For details, see Lundström (1983).

Due to structural complications, this stratigraphy is difficult to recognize in the Riddarhyttan–Norberg area, at least in detail. Extensive, synvolcanic, metasomatic alterations have furthermore obscured much of the volcanic and sedimentary details in the Riddarhyttan–Norberg area. Hence, the stratigraphic position and many depositional features remain largely unknown here. However, in the Norberg area, quartzitic metasandstones clearly stratigraphically underlie the metavolcanic rocks (Ambros 1983a, 1988), thus indicating a low stratigraphic position for this part of the metavolcanic pile. According to Stephens et al. (1999), there is also evidence that the nearby greywackes of the Larsbo formation underlie the metavolcanic part of the stratigraphic pile.

The Guldsmedshyttan syncline is folded along flat-lying, approximately north–south-trending fold axes, formed during an early folding phase (Lundström 1983). Good "way-up" determinations, as well as gravimetric studies and observations from the geology of the numerous mines of the area, demonstrate that the stratigraphic sequence is comparable to the better preserved sequence in the Grythyttan syncline. The synclinal structure and stratigraphy of the Guldsmedshyttan area is, however, difficult to trace further into the Riddarhyttan area, possibly due to a significant structural break in the latter area, as reported by Stephens et al. (1999).

Evidence of all the synvolcanic, hydrothermal alteration types listed above, is common in the Nora–Riddarhyttan–Norberg area. However, particularly in the Riddarhyttan-Norberg subarea, Mg-metasomatic phenomena are extremely pervasive (stops 2, 4 and 10). As pointed out by Geijer (1961), the famous REE occurrences (stops 3, 9 and 10) are all located within these extensively Mg-altered rocks. Because Geijer (1961) related Mg-alteration to the early, differentiated, I-type granitoids, he also thought that the REE mineralizations were due to them. However, with the current understanding of the Mg-metasomatism as synvolcanic, the regional coincidence of the REE mineralisations within areas of Mg-altered rocks (see maps in Geijer 1923, 1936, or Frietsch 1982b) is not yet fully understood.
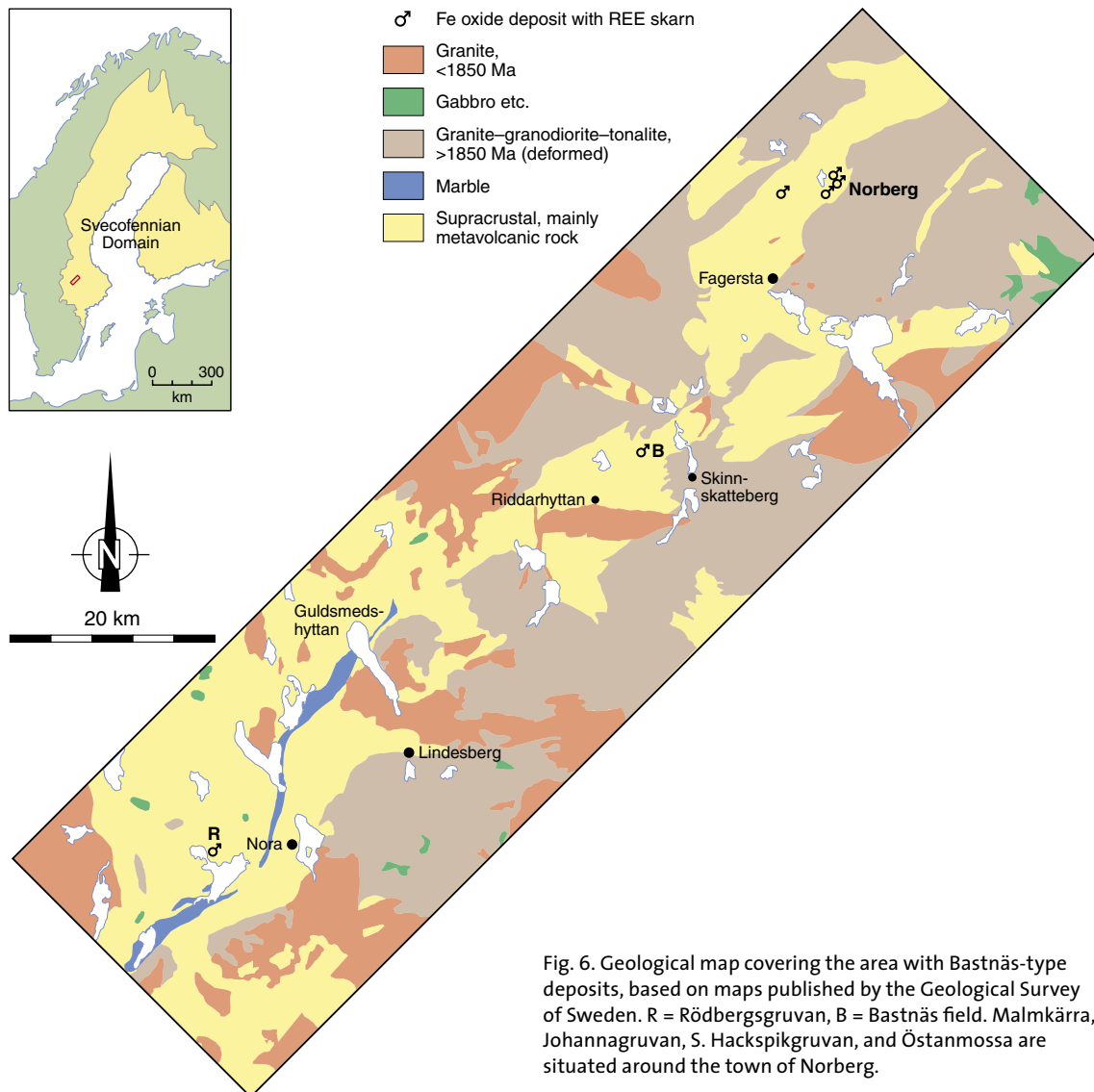
Fig. 6. Geological map covering the area with Bastnäs-type deposits, based on maps published by the Geological Survey of Sweden. R = Rödbergsgruvan, B = Bastnäs field. Malmkärra, Johannagruvan, S. Hackspikgruvan, and Östanmossa are situated around the town of Norberg.

Although much of the primary lithological detail of the area has been destroyed, Trägårdh (1988) managed to identify on geochemical grounds Mg-metasomatites with different alteration histories and precursors.

As in the rest of Bergslagen, regional metamorphism of low-pressure type affected also the Nora–Riddarhyttan–Norberg area some 50–100 Ma after the deposition of the supracrustal rocks, see above.

THE BASTNÄS-TYPE REE DEPOSITS
D. Holtstam

Riddarhyttan area (subtype 1)

In the Riddarhyttan ore field (Riddarhytte malmfält in Swedish), Skinnskatteberg district (Fig. 7), the oldest bedrock is dominated by Palaeoproterozoic felsic metavolcanic rocks, but metacarbonate layers of varying thicknesses are rather common (Geijer 1923, Ambros 1983b). Numerous iron oxide and base metal sulphide deposits are hosted by the supracrustal units. The metavolcanic rocks were
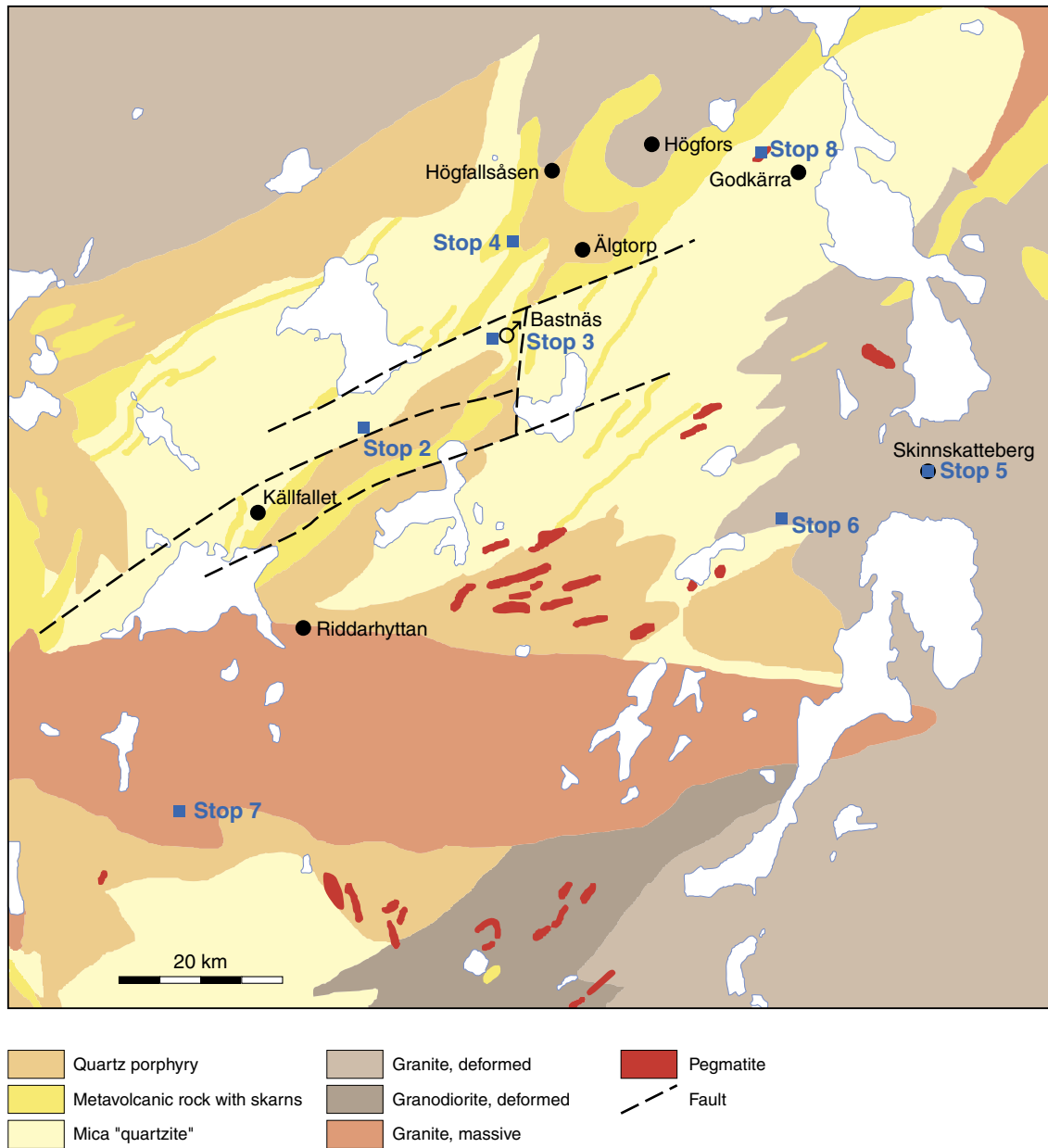
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Fig. 7. Geological map of the Riddarhyttan area (after Ambros 1983b).

locally hydrothermally and metasomatically modified during the early, volcanic stage (cf. stops 2 and 4) and later became metamorphosed under amphibolite-facies conditions. The major iron ore horizons are stratiform and some of them are thought to be of volcano-sedimentary origin (cf. stop 4), deposited during quiet periods in the volcanic activity (Ambros 1983b). The above units were intruded by two generations of granitoids. The older suite ranges from tonalite to granite in composition and is normally foliated (cf. stops 5 and 6), whereas the younger one comprises essentially undeformed granites sensu stricto (cf. stop 7).

A few REE mineralisations (e.g. Högfors, Bastnäs) are known from the Riddarhyttan ore field, where they coexist with Fe ore, as replacements of dolomitic marble lenses. Allanite (sensu lato) and cerite-(Ce), found in association with amphibole skarns, are the chief REE hosts here (Fig. 8, Table 1).

Nya Bastnäs

At the Nya Bastnäs deposit (stop 3), situated 4 km north-east of the village Riddarhyttan, quartz-banded hematite ore occurs in proximity with a magnetite-skarn ore, the latter replacing a carbonate (mainly dolomitic) horizon. The dominant country rock is a metasomatized volcanic rock: a quartz-rich, commonly cordierite-bearing mica-schist (stops 2 and 4). The cerite ore was worked in two shallow mines, Ceritgruvan and Sankt Göransgruvan, where it formed restricted zones (up to 0.6 m thick) composed mainly of cerite-(Ce), tremolitic amphibole, ferriallanite-(Ce), bastnäsite-(Ce), törnebohmite-(Ce) and talc (Geijer 1921; Holtstam et al. 2003a). The ore-bearing zone in total, including the hematite and magnetite ores, has an average width of approximately 8 m and can be traced some 400 m along the surface. In the deepest mine, Stora Bastnäsgruvan, Fe ores were still encountered at 114 m depth (Geijer & Magnusson 1944).

Sulphide minerals, dominantly chalcopyrite, bismuthinite and molybdenite, are closely associated with the REE minerals, and usually interstitial to them. Minor opaque phases detected are carrollite, bornite, covellite, wittichenite, emplectite, hodrushite, tetradymite, kupcikite, native copper and bismuth. Uraninite is locally found within blebs of asphalt (solidified hydrocarbons). Gold-silver alloys (40–60% Au) occur as rare microscopic grains in association with the sulphides (Holtstam & Ensterö 2002, Ensterö 2003). Lanthanite-(Ce) and various hydrated copper sulphates (of which some might be post-mining formations) are the latest formed minerals at Nya Bastnäs.

Although originally worked as a copper and iron deposit, about 160 metric tons of REE ore (mainly cerite) produced from Nya Bastnäs was sold over the period 1860–1919 (Carlborg 1923). The cerite ores ended at 20–30 m depth. The mine dumps have been used as source of Ce, La etc. after the abandonment. The common types of ore and skarn rocks are still available on the dumps. Cerite ore can be seen in situ where a horizontal adit (Nya Bastnässtollen, made in 1922) intersects with the ore.

REE mineral assemblages

Cerite-(Ce) is translucent with a reddish to gray colour and the luster is resinous. Individual crystals are usually small and anhedral, but they may form aggregates up to 20 cm across. The mineral is commonly associated with bastnäsite-(Ce) and ferriallanite-(Ce). Cerite was first described from Bastnäs by Hisinger & Berzelius (1804a,b).
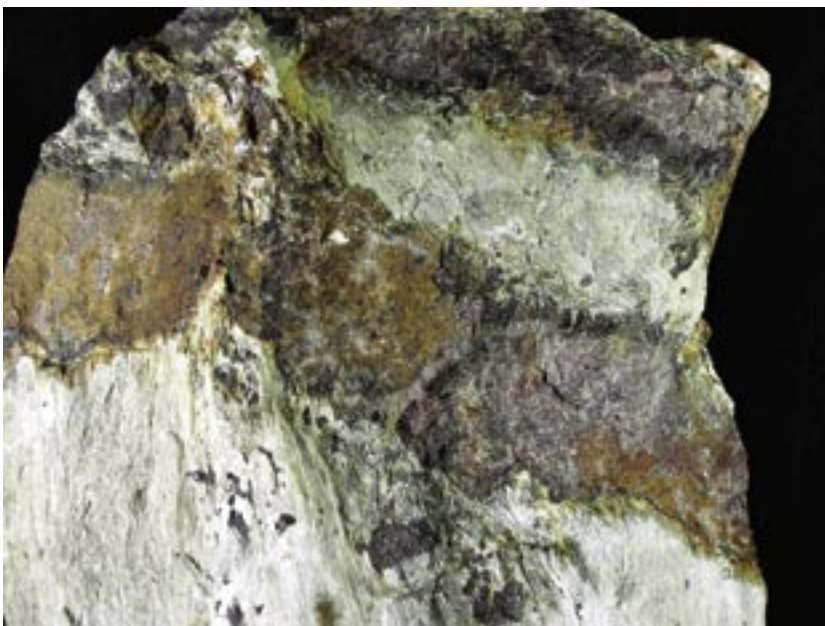

Fig. 8. A specimen with cerite-(Ce) as massive, reddish gray layers up to 3 cm wide, in contact with black ferriallanite-(Ce) and greenish white, fibrous actinolite. From the mine Sankt Göransgruvan, Bastnäs. Now in the mineral collection of Naturhistoriska riksmuseet, catalogue no. LK4838. Photo: Dan Holtstam.

Ferriallanite-(Ce) from Bastnäs was observed long before its true nature was established. Early designations like "schwarzen Wolfram" and "cerine" were superseded by "allanite" in the late 19th century. Recent electron-microprobe analyses have shown that representative samples of "allanite" correspond to ferriallanite-(Ce) in their composition (Holtstam et al. 2003a).

Coarse-grained ferriallanite-(Ce) in some cases forms up to 2 cm long euhedral crystals with bastnäsite-(Ce)–bastnäsite-(La), quartz, and sulphide minerals. The crystals are commonly twinned on {100}. Rounded aggregates of fine-grained cerite-(Ce) with lesser amounts of bastnäsite-(Ce) are commonly surrounded by margins of anhedral, irregular ferriallanite-(Ce) grains. The general impression is that ferriallanite-(Ce) has replaced cerite-(Ce) in these assemblages (cf. Fig. 8, Holtstam & Andersson 2002).

Törnebohmite-(Ce) and an unnamed, gatelite-related mineral species (the Fe^{3+}-O analogue of västmanlandite, cf. below), c. $(Ce,La)_3CaAl_2(Fe,Mg)_2[Si_2O_7][SiO_4]_3(O,F)(OH)_2$, are commonly closely associated with the ferriallanite-(Ce).

Bastnäsite-(Ce) is quite common as a fine-grained material associated with cerite-(Ce), of which it may be an alteration product. Larger, homogeneous aggregates of this yellowish mineral (or the La-dominant analogue) are locally found with ferriallanite-(Ce), quartz and sulphide minerals. Individual crystals are platy and may reach a length of several centimetres. Bastnäsite was first described from the locality, under the name "basiskt fluor-cerium", by Hisinger (1838).

Törnebohmite-(Ce) is less common than ferriallanite-(Ce) but has a similar paragenetic position. It forms irregular green grains. Törnebohmite was first described from Bastnäs by Geijer (1921).

Gadolinite-(Ce) has been observed only in one thin section and is probably rare.

Fluocerite-(Ce), commonly partly altered to **cerianite** and bastnäsite-(La), occurs sporadically as small, pale yellow grains in cerite-bearing assemblages.

Percleveite-(Ce) is a newly described mineral species (Holtstam et al. 2003b), so far known only from a single sample of cerite ore. It occurs together with cerite-(Ce), bastnäsite-(Ce), quartz, and amphibole. It has a yellowish gray to white colour, with a greasy to resinous luster and a white streak. The

Table 1. REE minerals in the Bastnäs-type deposits.

Mineral	Formula	Subtype 1	Subtype 2
Allanite-(Ce)	$(Ce,La)CaFe^{2+}Al_2[Si_2O_7][SiO_4]O(OH)$	x	x
Bastnäsite-(Ce)	$(Ce,La)CO_3F$	x	x
Bastnäsite-(La)	$(La,Ca)CO_3F$	x	
Cerianite	CeO_2	x	
Cerite-(Ce)	$(Ce,La,Nd,Ca)_9(Mg,Fe)Si_7O_{24}(O,OH,F)_7$	x	x
Dissakisite-(Ce)	$Ca(Ce,La)MgAl_2[Si_2O_7][SiO_4]O(OH)$	x	x
Dollaseite-(Ce)	$Ca(Ce,La)Mg_2Al[Si_2O_7][SiO_4]F(OH)$		x
Ferriallanite-(Ce)	$(Ce,La)CaFe^{2+}AlFe^{3+}[Si_2O_7][SiO_4]O(OH)$	x	
Fluocerite-(Ce)	$(Ce,La)F_3$	x	
Fluocerite-(La)	$(La,Ce)F_3$	x	
Fluorbritholite-(Ce)	$Ca_2(Ce,Nd)_3[SiO_4]_3F$		x
"Fluorbritholite-(Y)"	$Ca_2(Y,REE)_3[SiO_4]_3F$		x
Gadolinite-(Ce)	$(Ce,Nd)_2Fe^{2+}Be_2Si_2O_{10}$	x	x
Gadolinite-(Y)	$(Y,REE)_2Fe^{2+}Be_2Si_2O_{10}$		x
Håleniusite-(La)	$(La,Ce)OF$	x	
Lanthanite-(Ce)	$(Ce,La)(CO_3)_3 \cdot 8H_2O$	x	
Parisite-(Ce)	$Ca(Ce,La)_2(CO_3)_3F_2$		x
Percleveite-(Ce)	$(Ce,La)_2Si_2O_7$	x	
Törnebohmite-(Ce)	$(Ce,La)_2Al[SiO_4]_2(OH)$	x	x?
Västmanlandite-(Ce)	$(Ce,La)_3CaAl_2(Mg,Fe)_2[Si_2O_7][SiO_4]_3(F,O)(OH)_2$		x

hardness is c. 6 on Mohs's scale. Imperfect cleavage occurs parallel to {001}. The mineral is transparent and colourless in thin section, with low interference colours. Optically, percleveite is uniaxial positive with ω = 1.840(2) and ε = 1.846(2).

Håleniusite-(La) is quite widespread in the deposit, but was not characterized as a mineral until recently (Holtstam et al. 2004). It is an alteration product of bastnäsite-(La) and occurs as yellow, powdery coatings in most cases, commonly in association with emerald green brochantite.

Lanthanite-(Ce) is a secondary mineral which appears as thin coatings on cerite-ferriallanite ore. Fresh crystals, lath-like to platy in habit, are pinkish to colourless and normally less than 1 mm across. The present official type locality for lanthanite-(Ce) is Britannia Mine in North Wales (Bevins et al. 1985). This is unfortunate, since lanthanite-(Ce) from Bastnäs was described and analysed by Berzelius (1825).

Norberg area (subtype 2)

The Norberg district (Norbergs bergslag) was an important mining area for centuries. Operations started in the Middle Ages and ceased completely in 1980. The iron deposits were worked for quartz-banded ore, skarn ore and carbonate-hosted Mn-Fe ores. Generally, all ore types appear in a continuous belt with a south-west to north-east strike of mainly altered volcanogenic (stop 1) and subordinate metasedimentary rocks (Ambros 1983a, 1988). The supracrustal units are surrounded by deformed (early Svecofennian, c. 1.89 Ga) intrusive rocks (granite–granodiorite–tonalite). Granites of the younger, undeformed generation are practically absent here (Fig. 9). The numerous mines and prospects belong to different mining fields ("fält" in Swedish) according to their geological and geographical position. Locally, Cu sulphide ores were also important, e.g. at Kallmora (Kapellgruvan) and Stripåsen. REE mineralisation has clearly been subeconomic in the area.

The skarn ore deposits are characterized by large amounts of silicate skarns and Fe oxides in association with marble (dolomitic or calcitic). Allanite-(Ce) has been noted from practically every deposit of this kind, but only a few of them have been shown to exhibit a richer, more diversified type of REE mineralisation and are considered to be "Bastnäs-type deposits" (Geijer 1961). Three of the deposits are situated close to the lake Noren (Fig. 9), in the vicinity of the town of Norberg: the Östanmossa mine (Röbergsfältet), the presently inaccessible mine Södra Hackspikgruvan (Smörbergsfältet), and the mine Johannagruvan (Bojmossefältet). The mine Malmkärragruvan lies in a more isolated position, 5 km south-west of Norberg, close to the tarn Stora Malmtjärnen.

Malmkärra

The Malmkärragruvan deposit (stop 10) is hosted by a dolomitic marble, that forms a conformable layer with the surrounding metavolcanic succession, and which can be traced some 10 km to the south-west (Fig. 9). The carbonate layer appears to have its maximum thickness at this location, as a consequence of folding. Local faulting, mainly by vertical movements, has divided the deposit into segments (designated as separate ore bodies; Geijer 1936; Fig. 10). The underlying bed (the footwall) consists of Mg-rich mica-schist, that grades into less altered metavolcanic rock at varying distances. The skarn ore replaced certain parts of the carbonate along its contact with the metavolcanic rock.

Light green amphibole (essentially tremolite), humite minerals, and phlogopite are the dominant skarn silicates. Magnetite is the major ore mineral, and typically occurs as subhedral grains, normally in aggregates of up to 0.5 mm size, enclosed by amphibole. Well-developed, isolated crystals have a distinct octahedral habit.

Ophicalcite, i.e. recrystallized (calcitic) carbonate, with patches of serpentine and chondrodite, is common within dolomite marble in proximity to the ore. Sulphide minerals (chalcopyrite, pyrite,
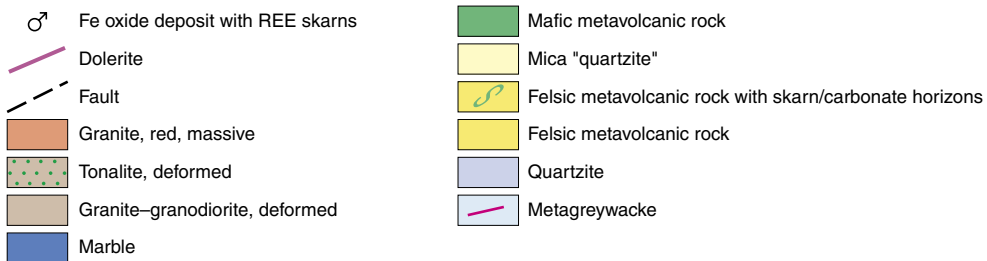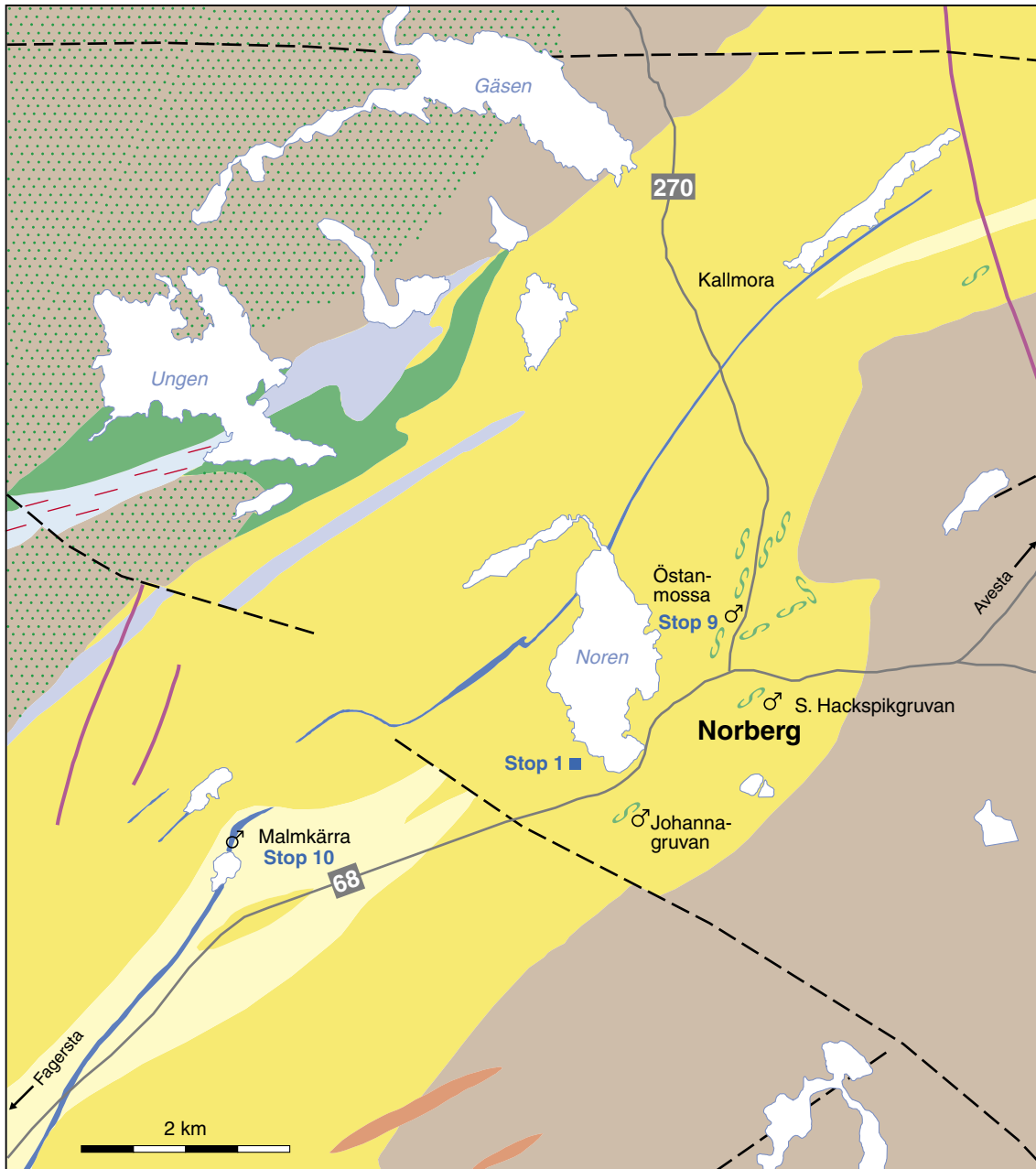
Fig. 9. Geological map of the central Norberg District (modified after Ambros 1988).
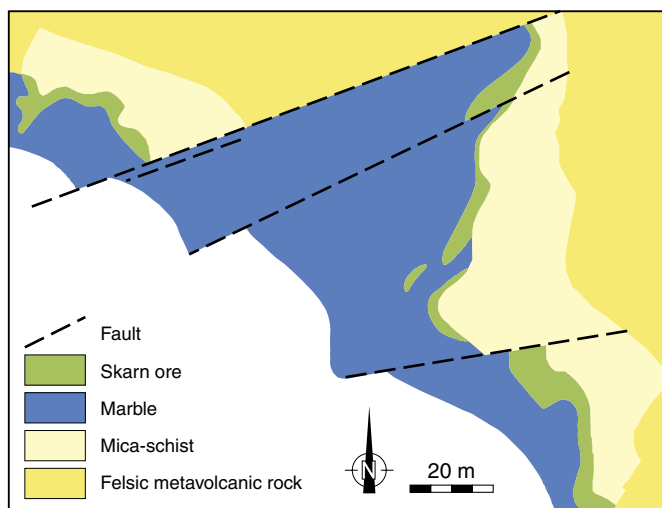
Fig. 10. Geological map of the Malmkärra deposit about the 150-m level (modified from Geijer 1936).

molybdenite) appear locally in intimate association with the skarns. Allanite sensu lato is the most common REE mineral and appears as a mostly microscopic phase scattered in the magnetite-skarn ore. An exceptionally rich, c. 0.5 m wide layer of REE silicates was encountered at the deepest levels of the mine (Lillgruvemalmen at 205 m), in the middle of a transition zone where the skarn ore graded into pure carbonate rock (Geijer 1927).

The Malmkärra mine has a long history– the oldest preserved record is from 1664, when it was noted that the mine had been abandoned temporarily. The amount of ore was found to diminish rapidly with depth, and the mine was finally closed in 1936. During the period 1874–1907, 87 000 tons of ore were mined. The production from 1908 to the cessation of the mining operations corresponded to 58 000 tons of Fe (Geijer & Magnusson 1944). The mine dumps are quite mossy at Malmkärra, but it is still possible to find pieces with dollaseite-(Ce), fluorbritholite-(Ce) etc. with the aid of a hammer. A section with magnetite ore in direct contact with both dolomite marble and the metavolcanic wall rock is visible in the orifice of one of the mine-shafts.

Östanmossa

The Östanmossa deposit (stop 9) belongs to a relatively narrow zone of skarn rocks in association with sporadic carbonate remnants. It appears on the western limb of an extensive synform. Outside the skarn-altered zone, the surrounding rock is a stratified, K-dominant metavolcanic sequence (cf. stop 1) with occasional intercalations of quartz-banded hematite and garnet skarns. Close to the deposit, the metavolcanic rock is to some extent transformed into "quartzite" (Geijer 1936).

The carbonate rock at Östanmossa is more or less totally enclosed by skarns, and consists either of fine-grained, white dolomite or coarser calcite of a greyish or yellow colour. Well-developed ophicalcite with clinohumite is commonly seen in portions of the dolomite marble.

The skarns are dominated by tremolite–actinolite. The amphibole ranges in colour from dark green to nearly colourless and may be fibrous in habit. Diopside is encountered mostly as microscopic remnants in the amphibole masses. Phlogopitic mica and humite-group minerals belong to the common skarn minerals at the deposit. Östanmossa is the type locality for norbergite, $Mg_3(SiO_4)F_2$ (Geijer 1926), which forms massive aggregates and veins of a purplish pink colour. Brownish garnet (andradite) skarns are locally common. Scheelite is quite abundant within the skarns. The largest concentration of REE silicates was found in the Grodorten drift at the 47-m level (Geijer 1936).

The magnetite ore belongs to the amphibole skarns, and is occasionally massive and fine-grained. Locally, the ore has a layered structure, with up to 1 cm thick iron oxide bands alternating with

Fig. 11. Private photo postcard from the early 1930s, showing the large open pit and the head frame at the Östanmossa mine. Photo most probably by Per Geijer (1886–1976). Collection of Jörgen Langhof.

amphibole. Sulphide mineralisation is generally rare, but as the mine originally opened as a copper mine, chalcopyrite was probably locally common. It may be noted that bismuthinite is said to have been found here, albeit in very minor quantities.

The mining operations were conducted in an open pit as well as in underground workings (Fig. 11). The maximum depth of the mine, at the time of its closing in 1931, was 115 m. The total production was estimated at c. 78 000 tons of Fe metal (Geijer & Magnusson 1944). Apparently the mine was reopened at some point because the dumps are still quite fresh.

REE mineral assemblages

Allanite-(Ce) is relatively common in the skarns of these deposits. Its modal abundance may reach a few percent. It is non-metamict, unaltered and strongly pleochroic in thin section. Larger, cm-sized crystals are locally encountered, e.g. at Östanmossa, in cases when the amphibole skarns are in direct contact with coarse-grained calcite. Allanite-(Ce) is often associated with tremolite, magnetite and chondrodite.

Dollaseite-(Ce) is an important mineral for the sequestration of REE in the Norberg district. This mineral was first described from Östanmossa under the name of "magnesium orthite" by Geijer

(1927). Peacor & Dunn (1988) renamed it dollaseite-(Ce), and demonstrated that the mineral was in fact not the simple Mg analogue of allanite ("orthite"), but another member of the epidote group related through a charge-coupled substitution involving both cations and anions: $Mg^{2+} + F^- = (Fe, Al)^{3+} + O^{2-}$. Recent analyses (Holtstam & Andersson, in prep.) have shown that chemical variations exist, and some samples from Malmkärra tend to lie closer to **dissakisite-(Ce)**, the true Mg analogue of allanite.

Dollaseite-(Ce) typically occurs in dark brown, several cm wide aggregates in dolomite-tremolite rock. The mineral grains are <0.5 mm wide and normally irregular in outline, but subhedral crystals have locally also formed in direct contact with carbonate. Occasionally dollaseite-(Ce) occurs as radiating, twinned crystals. It is commonly associated with magnetite and norbergite. The mineral has also been observed as a microscopic phase with fluorbritholite-(Ce), västmanlandite-(Ce) etc.

Västmanlandite-(Ce) is a new mineral species, structurally and chemically related to dollaseite-(Ce), törnebohmite-(Ce) and most closely to gatelite-(Ce) (Holtstam et al. 2005, in press). Malmkärra is the type locality, but it has recently been detected also at S. Hackspikgruvan and Johannagruvan. Västmanlandite-(Ce) is black to dark brown in colour, translucent with a vitreous lustre, and its streak is yellowish grey. It occurs as essentially anhedral grains 0.1–2 mm across. Cleavage is good along {001}, and fracture is uneven to conchoidal. The Mohs hardness is approximately 6. Optically, it is biaxial negative with $\alpha = 1.781(4)$, $\beta = 1.792$(calc.), $\gamma = 1.810(4)$ and $2V_\alpha = 75(5)°$. The dispersion is strong with r > v. The mineral is strongly pleochroic, with X pale yellow, Y reddish brown, Z dark brown, and absorption $Z \approx Y > X$ (orientation unknown). In general, västmanlandite-(Ce) is very similar in its macroscopic and microscopic character to allanite-dollaseite, therefore chemical and diffraction analysis will be necessary in most cases for a confirmation. Associated minerals are commonly fluorbritholite-(Ce), tremolite, magnetite, dollaseite-(Ce), and dolomite. The petrographic data indicate that västmanlandite-(Ce) formed in secondary reactions involving fluorbritholite-(Ce) and tremolite as the principal reactants (Holtstam et al. 2005).

Fluorbritholite-(Ce) appears as the paragenetically oldest REE mineral in these deposits. The colour varies from greyish pink to brownish red. The mineral commonly appears in medium-grained aggregates that may reach several cm across, in association with the other principal REE silicates that, in part, may have formed at the expense of fluorbritholite-(Ce). Geijer (1927) reported the occurrence of conspicuous aggregates of "cerite" in a dolomite vein transecting tremolite skarn. This material has recently been shown to be a Y-dominant analogue to fluorbritholite-(Ce).

Cerite-(Ce) is megascopically and paragenetically similar to fluorbritholite-(Ce). This fact explains why the two minerals were never distinguished in earlier descriptions of the deposits (e.g. Geijer 1927). In a few cases, cerite-(Ce) has been observed coexisting with fluorbritholite-(Ce).

Gadolinite-(Ce) and **gadolinite-(Y)** have been observed mainly in thin sections. They form greenish, irregular grains in association with fluorbritholite-(Ce), dollaseite-(Ce) etc. The individual crystals are often chemically zoned with respect to the REE and Y.

Törnebohmite-(Ce) is said to have been found in relatively large quantities at S. Hackspikgruvan (Geijer 1936). The presence of this mineral seems not to have been confirmed in modern investigations.

Bastnäsite-(Ce) and other REE-bearing fluorocarbonates are relatively uncommon in the Norberg district. They are mostly found as microscopic minerals in close association with the main REE minerals. Visible aggregates (up to 1 cm) of pale red bastnäsite in association with fluorite have been found in amphibole skarns from S. Hackspikgruvan.

Parisite-(Ce) has been observed in microscopic amounts in samples from Östanmossa, as an alteration product of fluorbritholite, and in regular intergrowths with bastnäsite-(Ce).

Genetic considerations

As concluded by Geijer (1927, 1961), the Bastnäs-type mineralisations have formed epigenetically, through reactions between high-temperature fluids and pre-existing carbonate rocks. The spatial relation to Mg-enriched country rocks suggested a genetic link to extensive metasomatic alterations, in his view driven by the emplacement of the early (1.9 Ga) granitoids, that have affected the felsic volcanic successions. According to contemporary knowledge this type of Mg metasomatism is, however, related to synvolcanic alteration and circulation of seawater-dominated fluids (e.g. Trägårdh 1988, 1991, Ripa 1994).

Preliminary microthermometric data for fluid inclusions in bastnäsite from Nya Bastnäs have shown that the mineral was deposited at approximately 400 °C from a CO_2-rich aqueous fluid with a moderate salinity (Holtstam & Broman 2002). Bastnäsite is secondary in relation to cerite-(Ce) and ferriallanite-(Ce), suggesting that the initial temperatures during the mineralisation process was even higher.

The carbon isotope values ($\delta^{13}C_{PDB}$) for mineralised carbonate samples (−4.4 to −6.7 per mil) are within the expected range for a magmatic or mantle source of CO_2. Host marble values group tightly around −2.4 per mil (Holtstam & Broman 2002). These new data suggest that the hydrothermal fluids responsible for the mineralisation were largely of magmatic origin. The development of contrasting mineral assemblages and compositions in the two types of deposits is probably mainly related to different fluid/rock ratios and variations in F concentration of the fluids.

The formulation of a genetic model was for a long time hampered by the lack of geochronological data, but recent Re–Os dating of molybdenite grains extracted from REE-mineralised samples have given crystallization ages in the range 1.85–1.89 Ga (Holtstam 2004, and unpubl.). The Cu-Mo-Bi-W-Be-F association in the deposits indicates a petrogenetic link to granitic magmatism. Granites belonging to the younger suite are at some locations in Bergslagen clearly associated with W-Mo mineralisation. Molybdenite ages from such intrusive rocks and adjacent skarn assemblages fall in the time span 1.78–1.80 Ga (Sundblad et al. 1996). The new Re–Os dates, however, overlap with the early orogenic period in this part of Bergslagen, and suggest that the formation of Bastnäs-type deposits is related to either a waning stage of the early Svecofennian magmatic phase (cf. Hellingwerf & Baker 1985, Baker & Hellingwerf 1988), or to an undisclosed magmatic system in the area.

Many of the world's REE deposits containing bastnäsite, fluorbritholite and cerite are associated with alkaline intrusive rocks (cf. Jones et al. 1996). The lack of minerals bearing significant amounts of elements like Na, Sr, Ba, Th and Nb makes the involvement of a carbonatitic fluid less likely in the case of the Bastnäs-type deposits. Rather, the Bastnäs-type deposits share many characteristics with the genetically diversified, intrusion-related Fe oxide-Cu-Au-REE deposits (Olympic Dam type; Hitzman et al. 1992).

HISTORY OF THE MINERAL AND ELEMENT DISCOVERIES AT BASTNÄS
J. Langhof

It is not really known when the peculiar red heavy stone of Bastnäs was first noticed in the mine Sankt Göransgruvan. The chemist and assayer Axel Fredrik Cronstedt (1722–1765) probably became aware of its existence as early as the 1740s and the name "tungsten" appears on a specimen label in 1746 (Fig. 12) (Nordenskiöld 1873). In 1750, Cronstedt reports the presence of a "dense reddish rather heavy ironstone" and describes also a "black wolfram" containing iron (Tideström 1890). These are probably the first notes on cerite and allanite from Bastnäs.

The red mineral was described by Cronstedt (1751) under the name of "tungsten" (heavy stone) together with another heavy, but white, mineral, from Bispberg further east in Bergslagen. The latter
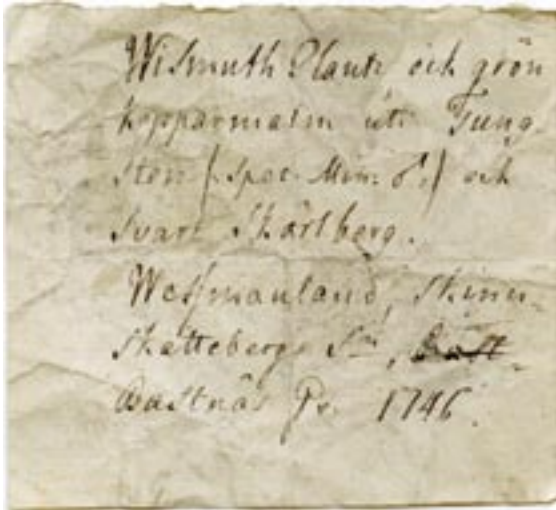
Fig. 12. Label belonging to the oldest known specimen of cerite-(Ce), labelled "tungsten". The specimen was collected in 1746 by Samuel Schröderstierna (1720–1779), and contains the only (?) known specimen with cerite-(Ce) showing crystal faces. Naturhistoriska riksmuseet collection, no. 57:1236–45).

Fig. 13. Wilhelm Hisinger. After a wax medallion made by L. Posch in Berlin in 1821 (Heijkenskjöld 1934).

turned out to be scheelite, containing the new element tungsten. The red mineral became known as "Bastnäs tungsten" (the heavy stone of Bastnäs or Reddish tungsten).

In 1782, the then mere 15 years old Wilhelm Hisinger (Hising before his ennoblement in 1787) sent a piece of the Bastnäs tungsten to the famous chemist Carl Wilhelm Scheele (1742–1786) in Köping, Sweden. In spite of his well-known analytical skills, Scheele could not find anything except silica, alumina, a little iron and no tungsten.

In 1787, the artillery officer Carl Axel Arrhenius (1757–1824) found a black mineral in the quartz and feldspar quarry at Ytterby, north-east of Stockholm. It was shown by the chemist Johan Gadolin in Åbo (Turku), Finland, to contain a new "earth" – yttria. This was later to become yttrium and marked the beginning of more than a century of research on the rare earth elements. The black mineral was later named gadolinite.

With this information Hisinger returned to his mineral collection, which he housed in one of the two wings of his castle-like mansion in Skinnskatteberg (now a school for forest engineers; Skogsmästarskolan) c. 5 kilometres east of the Riddarhyttan ore district. Wilhelm Hisinger (1766–1852) was a wealthy foundry proprietor (Fig. 13) who had studied natural sciences at Uppsala University under famous teachers such as Torbern Bergman (Heijkensköld 1934). His wide range of interests included chemistry, mineralogy, geology, palaeontology, botany, meteorology, and topography. His economical independence provided him with opportunities to travel and to spend comparatively large amounts of money on his spare time occupations. He published several books on mineralogical, geological and palaeontological subjects and they were to a great extent printed at his own expense (Regnéll 1990). He also had a well-equipped laboratory where he performed analyses of various minerals, rocks, ores, and foundry products.

Fig. 14. Jacob Berzelius. Lithographed portrait. Collection of the Hagströmer Medico-Historical Library.

Fig. 15. Carl Gustaf Mosander with his blow-pipe equipment. Lithographed portrait. Collection of the Hagströmer Medico-Historical Library.

Hisinger speculated whether yttria could be found also in the red mineral from Bastnäs. He obtained promising results and when the 23-year-old Jacob Berzelius visited him in the spring of 1803, mineralogical and chemical subjects were discussed and these of course included the problematic "Bastnäs tungsten".

Jacob Berzelius (1779–1848) is, together with Carl von Linné, the most famous Swedish scientist of all time and one of the most renowned chemists in history (Fig. 14). In 1802 he had moved from Uppsala to Stockholm where he soon came in contact with the wealthy Hisinger, sharing the same love for the natural sciences. For Berzelius this was a very fortunate friendship, because Hisinger not only became a life-long friend but also in the beginning an important benefactor for the young scientist. In 1814, Berzelius among others introduced the new chemical classification system for minerals, and also gave the elements new chemical symbols that are still in use. His efforts and contributions to science cannot be overestimated, and the interested reader is referred to articles by Jorpes (1966), Melhado (1981) and Moore (1988).

Hisinger and Berzelius made new analyses of both gadolinite and the red Bastnäs mineral and came to the conclusion that a previously unknown chemical element, with several characteristics in common with yttria, was present in the "Bastnäs tungsten". Further analyses undertaken during the winter 1803–1804 confirmed this conclusion. Berzelius gave this new element the preliminary name "bastium", after the locality and observed that it occurred in two oxidation states. The name "bastium" was changed to cerium (Ce), this name being derived from the discovery of the asteroid Ceres by the Italian astronomer Giuseppe Piazzi in 1801, and the mineral was hence named cerite. See Trofast (1996) for a detailed description of the discovery of Ce.

The discovery was revealed to Berzelius's former teacher in chemistry at Uppsala University, professor Johan Afzelius (1753–1837), who together with other colleagues speculated in Berzelius's ability to make reliable chemical analyses. On the basis of a few test analyses they thought that cerium was a mixture of yttria and iron or something similar. Discussions between leading men of chemistry in Sweden were held and renowned chemists including Anders Gustaf Ekeberg (1767–1813) and Johan

Gottlieb Gahn (1745–1818) were involved. Berzelius and Hisinger won this battle, but a new, much more prestigious event was ahead.

Berzelius's and Hisinger's paper on the discovery of cerium had been approved by the German chemist Adolph Ferdinand Gehlen (1775–1815) for immediate publication in his journal. However, in the third issue of the same journal, which was just printed, Gehlen had a report dealing with the discovery of a new "earth" from the same mineral, written by the German chemist Martin Heinrich Klaproth (1743–1817) in Berlin (Trofast 1996). Klaproth called the new "earth" ochroite (terre ochroite), due to the light brown colour of the pure substance. This news was very disappointing for Berzelius and Hisinger, but Hisinger, at his own expenses, had their Swedish version of the paper, a small pamphlet of 24 pages, printed in 50 copies in May 1804, to be distributed among their mutual scientific friends. When the paper appeared in Gehlen's journal (Hisinger and Berzelius 1804b) it attracted much attention among the chemists of Europe. It was published in a number of other journals around Europe in different languages and the news spread quickly. Due to the simultaneous publication of the discovery, a priority dispute began between Berzelius/Hisinger and Klaproth. This led to disappointment and strange rumours spread among all three of them. After many letters, explanations and controls of analyses where the French scientist Louis Nicolas Vauquelin (1763–1829) and Gehlen played important roles, Berzelius's and Hisinger's discovery won priority. This was eventually also accepted by Klaproth (Trofast 1996). Klaproth did, however, advocate that the name could as well, or better, be derived from the Greek word "cera", meaning wax, thereby implying that the names should be "cererum" for the element and "cererite" for the mineral (Klaproth 1807). Berzelius, only 25 years old at the time, had shown little respect for the scientific establishment in Europe, and that a new era was about to be established. The discovery of cerium was followed by more attention and controversy in Sweden and abroad, than any other discovery made by a Swedish scientist since the days of Carl Wilhelm Scheele and the great controversy on oxygen (Jorpes 1966).

In the 1820s, Carl Gustaf Mosander (1797–1858), a chemist, surgeon and mineralogist (Fig. 15), continued the investigation of cerite from Bastnäs. Mosander was one of Berzelius's numerous pupils and he ended up as curator of minerals at Naturhistoriska riksmuseet. Before that he succeeded Berzelius as professor at Karolinska Institutet where he taught chemistry, pharmacy and mineralogy. During his work with the cerium oxides, "Pater Moses", as his nickname was, had become increasingly suspicious regarding their true nature. He obtained results indicating a mixture of rare earths. But it was not until 1839, after much persuasion by Berzelius, that he published the discovery of the new element lanthanum (La), from the Greek word "lantánein", being hidden. In the same year, the Swedish mineralogist and geologist Axel Erdmann (1814–1869) also discovered lanthanum in a mineral from Norway that he named mosandrite in honour of Mosander's discovery (Lundgren 1987). Four years later, Mosander discovered another new element from the red Bastnäs mineral, and named this new element didymium (Greek for twin) because, as he said, it seemed to be "an inseparable twin brother of lanthanum" (Weeks & Leicester 1968). Didymia itself was further separated into neodymium (Nd) and praseodymium (Pr) in 1885 by the Austrian chemist Karl Auer von Welsbach (1858–1929). See compilation of Öhman et al. (2004).

LOCALITY DESCRIPTIONS
U.B. Andersson, P. Nysten, I. Lundström & D. Holtstam

For locations, see Figures 7 and 9. Coordinates are given in the Swedish national grid, RT90.

Stop 1. Viken, Klackberg (6660844/1505641). Fresh roadcut along the road Klackberg–Norberg, west of lake Noren. Felsic, quartz-porphyritic, massive, but foliated metavolcanic rock (a possible, pyroclastic mass flow deposit?), interbedded with fine-grained, even-grained, bedded metavolcanic rocks, probably originally volcanic ash–siltstones and exhalites. Gradual shifts between red and grey varieties. Fairly well-preserved with limited deformation. Scattered signs of incipient Mg-alteration seen in the

surrounding outcrops are missing here. Nevertheless, the rocks may well have undergone previous alkali metasomatic Na- or K-enrichment, which unfortunately is difficult to discern macroscopically. Skarn and magnetite horizons (Fig. 3). Phenocryst-bearing metabasite, that partly has taken up the deformation.

Stop 2. Road outcrop on northern side of road 68, 200 m west of side road to Bäckegruvan. (6634750/1485580). Heavily Mg-altered, felsic metavolcanic rock, interpreted to have undergone earlier K-metasomatism. K-rich metavolcanic rocks crop out south of the road and possibly occur as relict fragments in this outcrop, see also locality 10 (Malmkärragruvan). The Mg-metasomatically altered matrix consists of biotite, muscovite, quartz, cordierite, and magnetite, possibly also with andalusite. The feldspar content is very low, which is typical for rocks having undergone Mg-metasomatism, the main effect of which was feldspar breakdown (Lagerblad et al. 1987, Trägårdh 1988, 1989, 1990, 1991).

Stop 3. Bastnäs mine area (663636/148781). Large mine dumps of magnetite skarn ore (possibly also quartz-banded hematite ore may be found), locally associated with REE mineralization, as described in detail above. Country rocks of skarn-banded, altered volcanic rocks can be observed in outcrop. In places, within the horizontal adit (Nya Bastnässtollen), cerite ore (Fig. 16) and small occurrences of microscopic uraninite associated with solid hydrocarbons ("thucholite") may be observed.
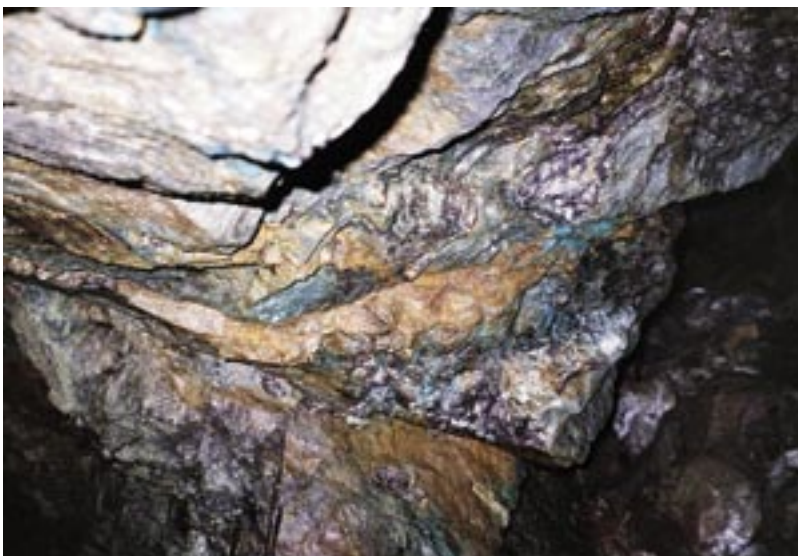

Fig. 16. Cerite ore (reddish violet lumps) within amphibole-skarn. In situ occurrence in horizontal adit (Nya Bastnässtollen) at Bastnäs (see stop 3). Width of photograph approximately 50 cm. Photo: Per Nysten.
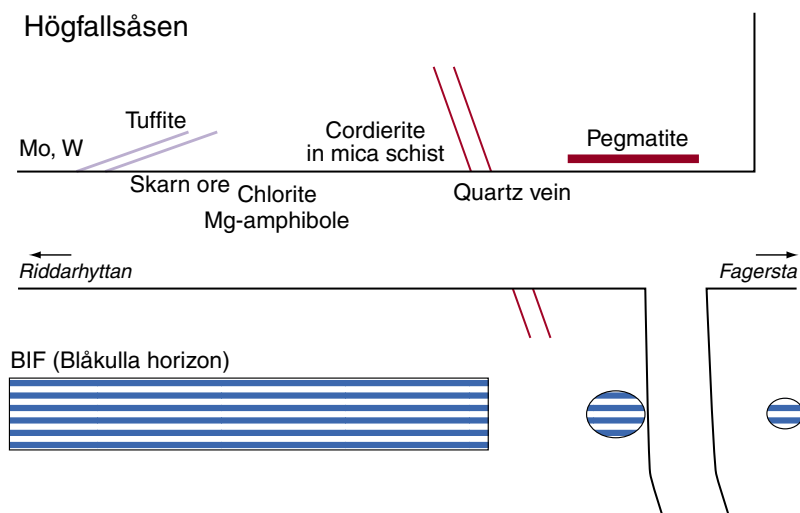

Fig. 17. Schematic overview of stop 4 at Högfallsåsen.

Stop 4. The Högfallsåsen roadcut (6637740/1487982). This, relatively fresh outcrop is more than 100 m long, and occurs on both sides of road 68 between Fagersta and Riddarhyttan (the north-west side yields the best information). It shows metasomatically altered felsic volcanic rocks, skarn iron ore, quartz veins of several generations, and pegmatites (Fig. 17). A few 10's of m to the south-east of the roadcut, exhalative BIF-horizons (Blåkulla formation; Geijer 1923) may be studied. A good starting point is at the southernmost part of the outcrop. Steeply folded banded tuffite alternates with sections consisting of epidote, dark brown andradite, minor hornblende, and diopside (Fig. 18). This skarn locally carries magnetite, molybdenite and Mo-scheelite. Further to the north, grey mica schist spotted with cm-sized cordierite (Fig. 4), and locally andalusite, alternates with sections rich in chlorite with large aggregates of radiating Mg-amphibole (gedrite–anthophyllite, Fig. 5). Although clearly post-deformational in age, the crystallization of these radiating orthoamphiboles was probably much favoured by the much earlier, hydrothermal Mg-enrichment of the originally potassium-rich volcanic rock. This schistose rock dominates the rest of the section going northwards. It also shows a steep lineation. Deformed quartz pods, as well as vertical, up to 3 dm wide quartz veins cut the cordierite mica schist. At the contact between these rocks accumulations of black tourmaline are common. In the northernmost part of the outcrop, a horizontal pegmatite has intruded into a system of subparallel fractures. This dyke is 2–3 dm wide and consists of quartz, white feldspar(s), muscovite, and minor small spots of black REE phases(?). Anhedral green chrysoberyl (max. 10 mm) has been verified by X-ray diffraction. From road 68, follow the crossing small forest road c. 30 m to the south-east and study the blasted outcrop on the right hand side. Boulders of banded hematite-quartz-epidote-spessartine-(rhodonite) stems from the exhalative Blåkulla formation which can be seen in several forest outcrops nearby and used as a marker horizon over a long distance (Källfallet–Gamla Bastnäs–Älgtorp).

Fig. 18. Skarn-banded, felsic metavolcanic rock. Dark, reddish-brown, andradite-rich skarn horizon to the right. Roadcut along road 68 at Högfallsåsen (stop 4). Photo: Dan Holtstam.

Stop 5. Skinnskatteberg (6634683/1493469). Roadcut of greyish red, coarsely medium-grained, somewhat deformed granite, mapped as belonging to the older, early Svecofennian (c. 1.89 Ga, although not dated in this area) generation. Contains large quartz veins and common small micaceous enclaves. Some workers have associated W-Mo occurrences with this generation of granite (e.g. Baker & Hellingwerf 1988).

Stop 6. Small roadcut of greyish white, medium-grained granite to (albite?) tonalite (663380/149145). This granitoid may be an example of an early granitoid that was subject to the same regional Na-metasomatism as the volcanic rocks. It shows diffuse borders towards the altered metavolcanic rocks (Ambros 1983b). Baker (1985) describes a case of alteration and Na-enrichment in an older Svecofennian granite further west in Bergslagen, where also the REE have been highly mobile.

Stop 7. South of Uvberget (662980/148340). Outcrops of red, porphyritic, massive biotite granite with c. 0.5 × 2 cm tabular K-feldspars (petrographic description is given in Geijer 1923). It is strongly radioactive (Ambros 1983b) and contains frequent enclaves of metavolcanic rocks. This granite belongs to the youngest generation in the area, expected to be c. 1.80 Ga. However, no age determination exists on this pluton. It is probable that it formed in conjunction with the late Svecofennian regional metamorphism and pegmatite formation in the area. Granites of this generation are related to W-Mo-deposits elsewhere in Bergslagen (cf. Sundblad & Bergman 1996).

Stop 8. Quarry in pegmatite at Hultebo/Godkärra (663880/149090). This dyke was originally worked by yeomen from Godkärra during the 18th and 19th centuries. In the year 1927, 300 tons of good quality feldspar and 100 tons of quartz were quarried. The outcropping dyke occurs on a small hill and is surrounded by "Mg-metasomatic" mica schist. The quarried part is water-filled and not accessible, but pegmatite outcrops can be found in the vicinity. The main minerals of the pegmatite are white albite, grey quartz, white muscovite in aggregates up to 10 × 30 cm, minor biotite, and euhedral, up to 10 cm long andalusite prisms. The andalusite often occurs in fine-grained greenish yellow muscovite. Locally, cm-sized light brown monazite (xenotime?) crystals occur associated with albite and quartz. The phosphate is also accompanied by dark brown, anhedral crystals of polycrase-(Y). Whether K-feldspar is present is uncertain, although graphic feldspar-quartz has been noted. The age of this and similar pegmatites in the area have not been determined, but most are probably related to the late Svecofennian (c. 1.80 Ga) regional metamorphism and granite formation.

Stop 9. Östanmossa mine (666225/150692). Mine dumps, close to the large open pit, can be studied. Actinolite-dominated skarns, with magnetite ore, and dolomitic marble, containing portions of 'ophicalcite' associated with humite minerals, as well as a variety of REE-minerals may be found (as detailed above).

Stop 10. Malmkärra mine (666006/150227). Several small pits of skarn iron ore within dolomitic marble, in contact with Mg-altered metavolcanic rocks. REE-mineral assemblages (as described above) may be observed in the dumps in association with the skarn ore. In one place (at the margin of a pit), ore and host carbonate can be observed in contact with the volcanic rocks. Nearby, typical mica schistose, heavily Mg-altered, felsic metavolcanic rock, in the approximate strike direction from Stop 1 can be observed. The rocks at that locality (Stop 1) could well be the precursor rocks to this Mg-altered variety.

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