

Structure, stratigraphy and ore-forming processes in Bergslagen: implications for the development of the Svecofennian of the Baltic Shield



James H. Baker,¹ Rob H. Hellingwerf¹ & I.S. Oen²

¹ *Geological Museum, University of Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands; Present address: Instituut voor Aardwetenschappen, Rijks Universiteit Utrecht, P.O. Box 80-021, 3508 TA Utrecht, The Netherlands*

² *Geological Institute, University of Amsterdam, Nieuwe Prinsengracht 130, 1018 VZ Amsterdam, The Netherlands*

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Abstract

Bergslagen is the ore-bearing part of the 1.9–1.86 Ga Svecofennian of central Sweden, characterized by large thicknesses of felsic metavolcanics and sediments, with an intricate association of local and regional hydrothermal alterations and mineralizations related to the development of mostly submarine rift basins. Mineralization types show a change with time in response to the evolving geotectonic setting. The change in lithology from predominantly volcanic Bergslagen to more sedimentary in the easterly Stockholm region is accompanied by an increase in metamorphic grade and change in deformational style.

The main geological features of the three granitoid magmatic regions, and intervening sedimentary areas of the Svecofennian are summarized and related to the processes affecting the northern Archean block during Proterozoic times. A two stage model for the evolution of the 1.9–1.86 Ga Svecofennian of the Baltic Shield is proposed. New crust of felsic to intermediate composition was generated in the period 2.6–2.1 Ga by multiple subduction from the SSE. In this period the Archean block underwent deformation as an active margin. Accretion of the newly formed crust occurred during a collision type orogeny with the Archean block in the period 2.1–2.0 Ga. Reworking of the accreted crust in Central Finland, Skellefteå-Kiruna and Bergslagen occurred in the period 1.9–1.86 Ga, with elongate volcanic basins developing in transtensional strike slip zones, where deep faulting penetrated to the lower crust.

Introduction

The Bergslagen district of central Sweden comprises a number of long, narrow synformal sediment-filled basins flanked by large thicknesses of felsic supracrustal rocks, developed in a continental rift setting (Oen et al., 1982; Vivallo & Rickard, 1984; Baker, 1985a; Oen, 1987; De Groot et al., 1988).

The presence of discontinuous iron formations, which define stratigraphic zones traceable for hundreds of km characterize the West Bergslagen ore province as an iron formation basin (Oen, 1987). Bergslagen was formerly the ore-bearing part of central Sweden, where both oxide and sulphide deposits were exploited. This paper reviews some of the current ideas on the stratigraphy, alteration

geochemistry and ore-forming processes, as well as considering the tectonic setting of Bergslagen and its relationship to the development of the Svecofennian of the Baltic Shield.

General geological and geochronological relationships in the West Bergslagen ore province

The West Bergslagen ore province forms the westernmost part of the South Svecofennian Volcanic Belt (Gaál & Gorbatshev, 1987), cut off in the west by the Transscandinavian Granite-Porphry Belt, and bordered to the east by a block of granitoids with inliers of felsic supracrustals. The felsic metavolcanics and metasediments which predominate in the West Bergslagen ore province comprise the Bergslagen Supracrustal Sequence (Oen et al., 1982; Oen, 1987). The felsic metavolcanics have high silica contents, with phenocrysts of relict high temperature quartz and feldspar, and minor (<3%) chloritized biotite. Mafic rocks form a very minor phase intrusive in the lower felsic units and co-magmatic with the upper felsic units, forming part of a bimodal suite (Van der Velden et al., 1982; Vivallo & Rickard, 1984; Lagerblad & Gorbatshev, 1985).

The felsic metavolcanics are constrained by U–Pb zircon ages of 1.90 and 1.86 Ga (Welin et al., 1980; Åberg et al., 1983b). Rb–Sr whole rock determinations usually give younger metamorphic resetting ages but one age of 1.80 Ga is recorded from a felsic metavolcanic (Oen & Verschure, 1985). Syn-volcanic biotite granites in the age range 1.84–1.9 Ga (Welin et al., 1980; Åberg et al., 1983a; Oen et al., 1984) are intrusive in the supracrustal sequence.

Metamorphic mineral ages of about 1.84 Ga (Rb–Sr; K–Ar) have been obtained from mafic dykes in the Hjulsjö area (Moorman et al., 1982), comparable to the whole rock Rb–Sr age of 1.84 Ga for the Hyttsjö diorite and hybrid granite (Oen & Wiklander, 1982). A phase of younger granitic magmatism (Welin et al., 1977; Oen 1982, 1983; Åberg & Fredriksson, 1984) in the age range 1.6–1.78 Ga post-dates the development of the Bergslagen Supracrustal Sequence, the older granites,

and mafic rocks, while younger, unmetamorphosed dolerite dykes of presumed Sveconorwegian age (Oen & Verschure, 1982) cut through the whole sequence.

Stratigraphic relationships in the felsic supracrustal sequence

The general geological relationships of western Bergslagen were originally described in such Swedish classics as Sundius (1923), Magnusson (1925) and Geijer & Magnusson (1944). More recent descriptions include those of Oen et al. (1982), Van der Velden et al. (1982), Lundström (1983, 1985), Baker (1985a), Björk (1986) Hellingwerf (1986), Oen (1987), Kuipers (1987), Van Meerten (1988) and Parr (1988). The 1.8–1.9 Ga Bergslagen Supracrustal Sequence (BSS) of western Bergslagen comprises a <10 km thick pile of felsic, predominantly volcanic supracrustal rocks. In the Hällefors-Hjulsjö area (Fig. 1) three lithostratigraphic groups of the BSS are recognised; these show an upward transition from units produced by explosive volcanism, with thick ignimbrites and minor airfall deposits, to units formed by less explosive regimes marked by fewer pyroclastic flows and more tuffitic rocks, with ± 2 km of metasediments, including greywackes, shales and mass flow deposits forming the upper part of the sequence deposited in graben basins. Polymict conglomerates present in the upper units mark local unconformities (Sundius, 1923; Kuipers, 1987), related to rift basin development (Oen, 1987). The presence of shallow water (<150 m) conditions, at least locally, is confirmed by stromatolitic limestones (Boekschoten et al., 1988). Descriptions of the volcanic and sedimentary stratigraphy to the NE and E are given by Lundström (1983, 1985) and Parr (1988), who find a similar vertical transition from lower units of explosive volcanism to upper tuffitic and sedimentary units (see also Lundström, 1987). Evidence of some subaerial volcanism in the higher stratigraphic units of the Kopparberg area is given by Parr & Rickard (1987) and Parr (1988), and has also been identified further NE, in the Norberg region (Ambros, 1983). The synformal, supracrustal enclave

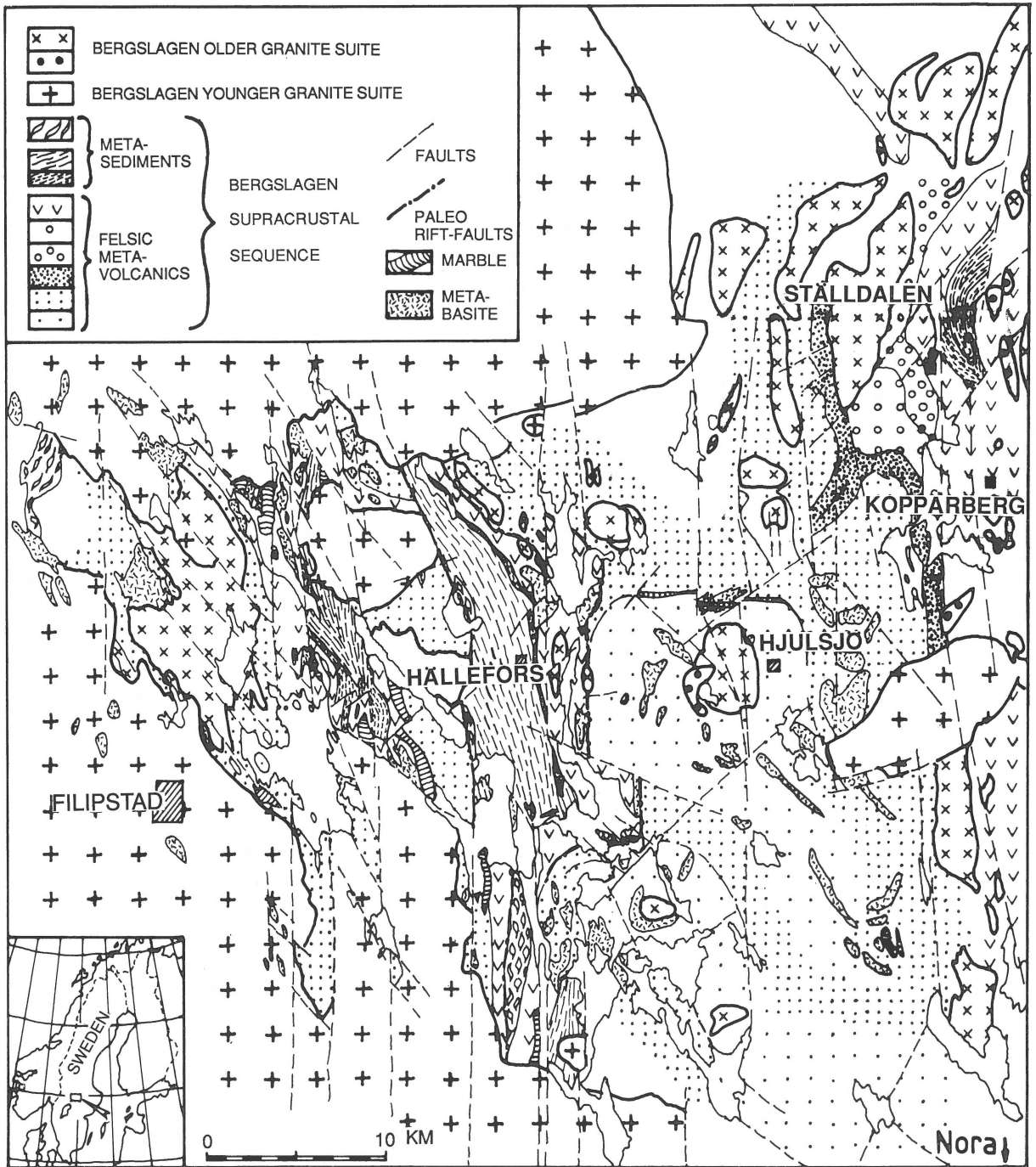


Fig. 1. Geological sketch map of the Filipstad-Kopparberg-Nora region, modified from Oen et al. (1982), Baker (1985a) and De Groot et al. (1988).

120 km NNE of Filipstad which contains the Falun polymetallic sulphide ore in one of the highest units is located along strike from the Filipstad-Hällefors area, and shows a ± 5 km thick sequence from metarhyolites to mixed metasediments and metatuffites (e.g. Bromley-Challenor, 1988). Approximately 50 km across strike, to the SE, Vivallo (1984) describes a similar sequence, though a higher metamorphic grade prevents a detailed stratigraphic interpretation.

Lithostratigraphic correlations between the BSS in western Bergslagen and comparable Svecofennian sequences in areas to the east have been made by Lundström (1987, 1988), who demonstrates a lateral variation from the predominantly volcanogenic BSS to the predominantly sedimentary sequences in the eastern areas. The more than 10 km thick pile of felsic metavolcanics of the BSS thins to about 900 m in the Uppsala-Stockholm region (Lundström, pers. comm.), where less felsic compositions are also found (Lundström, 1987). A major difference is that the eastern volcanics are underlain by a thick sequence of greywackes and sub-greywackes. This pre-volcanic level can only be traced west as far as Norberg or Zinkgruvan (Ambros, 1983; Lundström, 1987), where a thin basal sedimentary unit is found. The metasediments overlying the eastern volcanics are comparable to those forming the upper part of the BSS (Lundström, 1987, 1988). No basement to the BSS or any part of the Svecofennian has been identified, a problem discussed below.

Hydrothermal processes and alteration geochemistry

Regional alteration

It had long been recognised that there was a division within the BSS into a lower, predominantly Na-rich unit, and a higher, predominantly K-rich unit (Sundius, 1923; Magnusson, 1925). Alkali metasomatism as an alternative mechanism to primary chemical variation was proposed by a number of workers (e.g. Lindroth, 1922; Sundius, 1923; Frietsch, 1982). It is now recognised that the Na-K divisions are related to sub-seafloor hydrothermal

processes (Oen et al., 1982; Lagerblad & Gorbatshev, 1985; Baker, 1985a). The alteration process mainly involves phenocryst and matrix feldspars, and in that sense can be called selective pervasive regional alteration. Thermodynamic calculations (e.g. Jasiński et al., 1985) indicate that in the presence of a seawater type fluid, below about 140°C K-feldspar is stable, while at higher temperatures K-feldspar alters to albite. Similarly the albitization seen in a number of high level older granites possibly resulted from sub-seafloor alteration processes (Baker, 1985b). Vivallo & Rickard (1984) and Parr & Rickard (1987) suggested the Na-K variation may also relate to the presence of non-marine surface conditions. While non-marine lithologies have been locally identified in the Kopparberg area, (Parr & Rickard, 1987; Parr, 1988), stable isotope (C & O) ratios in Bergslagen marbles are all compatible with a marine environment (De Groot & Sheppard, 1988).

Local alteration

The relationship between alteration and mineralization in Bergslagen has been discussed mainly with respect to regional Na and K alteration (e.g. Frietsch, 1982; Lagerblad & Gorbatshev, 1985). Some recent papers stress the importance of localized alteration systems superimposed on the regional Na-K alteration pattern and genetically related to different mineralizations (Baker, 1985a; Hellingwerf, 1986, 1988a; Outhuis & Van Berkel, 1988; Valbracht & Helmers, 1988). The sedimentary-exhalative magnetite ore of Ösjöberg-Sirsjöberg near Hjulsjö, for example, is underlain by discordant zones of Mg-chlorite-quartz sericite schists developed during sub-seafloor alteration (Baker & De Groot, 1983a, b). In some cases these Mg-rich alteration zones are so large they assume the dimensions of the regional alterations discussed above (e.g. Ambros, 1983; Trägårdh, 1988). Local tourmalization, phlogopitization and calc-silicate alteration is present below the Älvsängen-Vikern stratiform Zn-Pb mineralization (Hellingwerf et al., 1988). Local microclinization of metatuffites, metacherts, marbles and meta-basites has been observed around the Cu-Zn-Fe-Pb-As sulphide

mineralization at Gruvåsen (Hellingwerf, 1984, 1987), whereas sericitization, K–Mg- and Mg–Fe alteration has been reported in the footwalls and host rocks of the Cu–Co–As–Sb–Au deposit of Håkansboda (Carlson & Bleeker, 1988). In the sense that a wide range of mineralogies, irrespective of rock types, are induced to alter to new parageneses, the process can be called non-selective.

Regional versus local alteration

The regional and local alteration types differ in mineralogy, texture, litho-geochemistry and scale (Hellingwerf, 1988a). The higher temperature of local hydrothermal systems, restricted to narrow, structurally controlled zones of high fluid flow, enhance the mobility of elements such as Ti, Zr, Y, Hf and REE (Baker & De Groot, 1983a; Hellingwerf, 1988a; Outhuis & Van Berkel, 1988). This contrasts with seawater dominated fluids that reacted with the felsic volcanites on a regional scale in the diagenetic/sub-seafloor situation where only minor trace element mobility accompanies the alkali exchange (e.g. Baker, 1985a).

Mineralizations

The majority of mineralizations in West Bergslagen comprise iron ores. Discontinuous banded iron formations can be followed for hundreds of km along strike, forming a marker zone in the middle of the stratigraphic sequence, characterizing the West Bergslagen ore province as an SSW–NNE trending iron formation basin, discordant with respect to the more general E–W trend of the non-ore bearing Svecofennian successions to the east.

There appears to be a broad stratigraphic control on the different types of mineralization in Bergslagen. Fe-oxide mineralizations occur mainly in the lower stratigraphic levels, while Fe–Mn oxide and polymetallic sulphide mineralizations are located in the upper levels (Magnusson, 1925; Oen et al., 1982). W–Mo–(Au) mineralizations are genetically linked to a suite of anorogenic high silica microgranites (Baker, 1985a; Hellingwerf & Baker, 1985). The distribution of rock, alteration and ore types relative to an idealized Bergslagen rift is shown in Fig. 2.

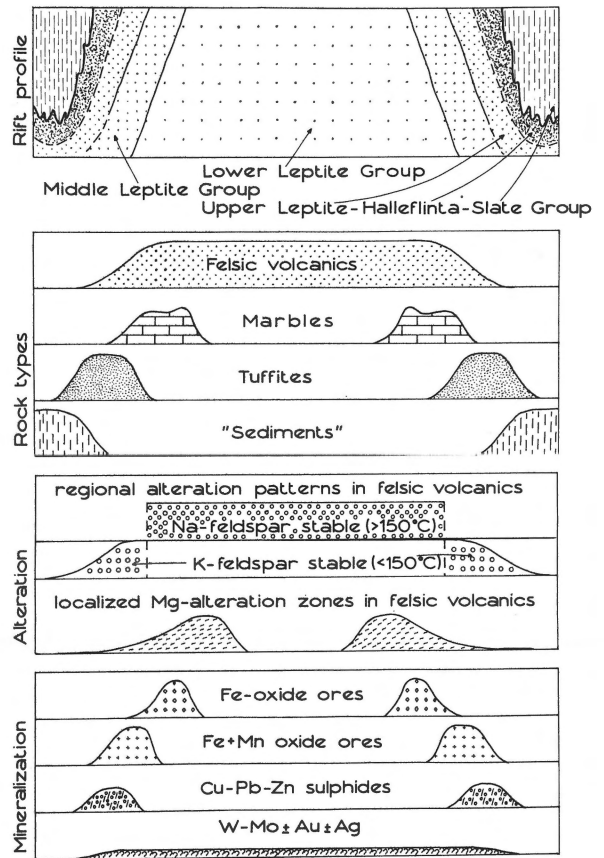


Fig. 2. Relative distribution of mineralizations, alterations and rock types in the three lithostratigraphic divisions of Oen et al. (1982), relative to an idealized W. Bergslagen rift.

Oxide-sulphide mineralizations

The stratiform Fe and Fe–Mn oxide deposits are generally considered to be the products of sedimentary-exhalative processes (e.g. Långban type Fe–Mn ores: Boström et al., 1979; Hjulsjö Fe ores: Baker & De Groot, 1983b). The largest iron ore of Bergslagen, the Grängesberg magnetite-apatite ore may have developed in the exhalative-sedimentary environment, but clearly intrusive relationships are visible in the underground workings. The oxide and silicate facies Fe–Mn mineralizations show local transitions along strike into sulphide facies mineralizations (e.g. the Älvsjö-Vikern Zn–Pb–Fe–Mn mineralization (Hellingwerf et al., 1988); the Håkansboda Cu–Co–As–Sb–Bi–Au mineralization (Carlson & Bleeker, 1988);

and the Stollberget Fe–Pb–Zn–Mn–(Ag) deposit (Ripa, 1988). A facies model predicting changes from oxide to sulphide ores was proposed by Zakrzewski (1982) and Frietsch (1982). Where data is available, polymetallic sulphide (Gruvåsen; Hellingwerf, 1984, 1988a) and Fe–Mn oxide (Gåsborn; Damman, 1988) mineralizations show zonation of trace elements. Early ideas on the genesis of Bergslagen sulphide mineralizations involved fluid fronts emanating from granites (Geijer, 1917; Magnusson, 1925). Later a sedimentary-exhalative origin was proposed for deposits such as the Falun massive sulphide and Långban Fe–Mn ore (e.g. Koark, 1962; Boström et al., 1979). More recently the role of sub-seafloor hydrothermal cells developing metalliferous brines through leaching of felsic and mafic rocks to form exhalative-sedimentary as well as epigenetic sub-seafloor mineralizations has been emphasised (e.g. Oen et al., 1982; Oen et al., 1986; Oen, 1987; Hellingwerf, 1984, 1986; Vivallo, 1984; Lagerblad & Gorbatshev, 1985). The localized alterations described above in many cases underlie these mineralizations. Mine records often describe several cross cutting zones of hydrothermal Mg minerals, related to a single Fe oxide deposit (e.g. Geijer & Magnusson, 1944). This relates to cyclic or repeated phases of alteration during ore genesis. Although a seawater derivation is now generally accepted for the hydrothermal fluids, the relatively high contents of B and Cl in the Älvlängen mineralization (Hellingwerf et al., 1988) together with significant quantities of W, Mo, Sn and Bi, as well as $\delta^{34}\text{S}$ values between -3 and $+7\%$ for sulphide phases in the Gruvåsen mineralization (Hellingwerf, 1984; Hellingwerf & Van Raaphorst, 1988) possibly indicate a magmatic contribution to the ore fluid. Plimer (1986) considered mantle devolatilization to provide an important component of the Australian Broken Hill sulphide deposit, associated with early Proterozoic bimodal rift-related volcanism. In view of the high metal, B and Cl contents in active geothermal areas, (e.g. Ellis, 1979; Haymon & Kastner, 1981; Pottorf & Barnes, 1983), the role of magmatic derived fluids in Bergslagen ore genesis needs further investigation. Calc-silicate (skarn) parageneses are commonly found associated with oxide and/or sulphide

mineralizations in Bergslagen. They occur intimately associated with both silicate alteration and the ore-forming processes, and a genetic link is indicated. It is suggested that these skarn minerals form from ore-brine precipitates through diagenesis or low grade metamorphism (e.g. Parr & Rickard, 1987; Oen & Hellingwerf, 1988), in a manner comparable to that described by Vaughan & Stanton (1986). In epigenetic mineralizations (e.g. Gruvåsen, Hellingwerf, 1984), skarn parageneses are developed by replacement through a process of infiltration and metasomatic reactions.

W–Mo–(Au) granite and skarn mineralizations

The granite-related character of the W–Mo mineralizations in Bergslagen (e.g. Hübner, 1971) is generally accepted and a model relating intragranitic mineralizations to high and low temperature, mineralized, replacement skarns and cross cutting molybdenite-biotite zones (sköls) has been developed (Hellingwerf & Baker, 1985; Baker & Hellingwerf, 1988; see Fig. 3d). In a review of stratiform tungsten mineralizations, Cheilletz (1988) also supported a replacement origin for the Yxsjöberg type of tungsten skarn mineralization. The age of the granites responsible for the mineralizations has been debated, Hellingwerf & Baker (1985) arguing for a genetic link with the older generation of 1.9–1.8 Ga syn-volcanic granites, rather than the younger Fellingbro-Mallingsbo granites. However, a U–Pb zircon age of 1.78 Ga has now been obtained for the molybdenite-bearing Pingstaberget granite (Billström et al., 1988). While the intragranitic mineralizations of Pingstaberget and V. Gråshöjden, and the major replacement W-skarn ore body of Yxsjöberg contain only a minor base metal sulphide component (Baker et al., 1987; Baker & Hellingwerf, 1988), a minor W–Mo–Sn–Bi component is present in several base metal sulphide deposits of exhalative-sedimentary or feeder pipe origin (e.g. Carlon & Bleeker, 1988; Hellingwerf, 1984). There is an apparent mixing line or gradual transition between 1) syn-volcanic exhalative-sedimentary W–Mo-bearing base metal sulphide deposits and 2) post volcanic, magmatic derived W–Mo–(Au) granite and skarn mineralizations. The significance of this apparent evolution in the development of the ore province has yet to be evaluated.

Metamorphism and the development of the West Bergslagen ore province

The first of the three metamorphic events in W. Bergslagen described by Lundström (1983, 1985, 1988) and Helmers (1984), is broadly coeval with the volcanic development of the BSS. This first phase low grade hydrothermal metamorphism is related to sub-seafloor alteration processes, initiated by the heat of cooling intrusions (Oen et al., 1982). This resulted in the metasomatic changes discussed above and a widespread annealing recrystallization (Oen, 1987). The presence of prograde Fe-silicates such as greenalite and Mg minnesotaite (Baker, 1985c), diagenetic and fossiliferous Mn-bearing horizons (Oen et al., 1986), fine scale preservation of organic textures in stromatolites (Boekschoten et al., 1988), and the soft rock and diagenetic replacement textures in a Pb–Zn exhalative-sedimentary horizon (Oen & Hellingwerf, 1988) testify to the low grade of metamorphism. Skarn parageneses showing an apparent disequilibrium with respect to their surroundings were developed by infiltration metasomatism at high temperature but low pressures. The range in metamorphic conditions from diagenetic to greenschist facies burial metamorphism encountered in western Bergslagen, with amphibolite facies only locally developed, is considered characteristic for extensional settings, where maximum temperatures of 300–400°C can be attained in the early material accumulated in rapidly subsiding basins (Robinson, 1987). Estimates of geothermal gradients in Bergslagen during this hydrothermal metamorphic event vary from 50 to 75°C (Baker, 1985a; Rickard, 1988). This first metamorphic phase did not last more than 20 Ma (Rickard, 1988). Later, post-volcanic metamorphism includes a phase related to younger granite intrusion, and a retrogressive phase (Lundström, 1983, 1985; Helmers, 1984).

Tectonic evolution of western Bergslagen

The Bergslagen Supracrustal Sequence, with related felsic and mafic intrusives, and various ore de-

posits has been interpreted in terms of a continental rifting event, in which the stratigraphically highest metavolcanics and sediments are contained in rift grabens (Oen et al., 1982). Vivallo & Rickard (1984) suggested that Andinotype alternate subsidence-rifting and compression occurred in an active continental margin setting. Previous models suggesting a volcanic arc setting for Bergslagen (e.g. Hietanen, 1975; Löfgren, 1979; Loberg, 1980; Park, 1985) are not consistent with the regional geology, structure, or geochemistry of the region, often being based on a non-recognition of the alteration geochemistry of the supracrustals (e.g. Baker, 1985a; Parr & Rickard, 1987; Rickard, 1988; Plimer, 1988), which can result in a pseudo-calcalkaline trend (e.g. MacGeehan & Maclean, 1980). While most workers now accept rifting of some sort, the nature of the pre-BSS basement, nowhere exposed, remains to be fully established. In fact the absence of an exposed basement has been taken as implicit evidence for mantle derivation of the BSS (e.g. Patchett et al., 1987). Several lines of evidence point to a felsic to intermediate precursor to the BSS (see Baker, 1985a; De Groot et al., 1988). The 1.9–1.8 Ga intrusives and extrusives are predominantly felsic, with calc-alkaline tendencies found in only a few restricted areas (e.g. Vivallo & Rickard, 1984; Lagerblad & Gorbatshev, 1985). The region is characterized by a homogeneity in lead isotope compositions (μ -values ≈ 10), indicative of a crustal source for the lead (e.g. Rickard, 1978; Johansson & Rickard, 1985; Åberg & Charalampides, 1986). The least altered felsic intrusives and extrusives show a similarity in major and less mobile (Nb, Y, Ta, REE) elements from Falun to Västervik (Baker, 1988 and in preparation cf. Bromley-Challenor, 1988), indicating the lack of significant geochemical trends on a regional scale. There is a marked absence of andesitic rocks of any importance (e.g. Vivallo & Rickard, 1984), and ophiolites and high pressure metamorphism are absent. While mafic rocks become volumetrically more important towards the east, no relict oceanic crust has been found. On the contrary, the mafic rocks are continental tholeiites (Hellingwerf & Oen, 1986; Baker, 1985a), displaying a strong bimodality with the felsic rocks (Van

der Velden et al., 1982; Vivallo & Rickard, 1984; Lagerblad & Gorbatshev, 1985). Petrographic and geochemical evidence suggests that the felsic rocks originated by anatexis of a felsic to intermediate precursor (Baker, 1985a; Baker & Drucker, 1988). The felsic rocks cannot be satisfactorily classified as I- or S-type since they contain features of both types (see Baker, 1985a). Oxygen isotope studies on quartz (De Groot, unpubl. data) indicate the precursor did not contain a significant sedimentary component. This means anatexis of a pre-existing intermediate igneous basement was likely. Nd-Sm data from the region (Beunk et al., 1985; Miller et al., 1986; Patchett et al., 1987) shows a short residence time, suggesting that the crustal precursor to the 1.8–1.9 Ga BSS had an age of 2.4–2.1 Ga. Detrital zircons from the Västervik quartzite (Åberg, 1978), the Vetlanda metasediments (Åberg & Persson, 1984), and metaquartzites from the Tampere district of Finland (Huhma, 1987) are derived from a 2.3–2.2 Ga precursor, with a provenance area to the SE (Lundström, 1987, 1988).

The petrography and geochemistry of the syn-volcanic biotite granites (Baker, 1985a) and an estimate on the depth at which melting can occur, given the high geothermal gradient thought to be operating during the Svecofennian (Rickard, 1988) suggest the precursor to the BSS during the volcanic stage not more than 12–15 km thick. A mechanism involving rifting of a 2.1 Ga basement and encompassing the whole BSS was suggested by Baker (1985a).

A four stage tectonic evolution for western Bergslagen has been proposed by De Groot et al. (1988); an initial crust forming event at about 2.1 Ga was followed in a second stage by crustal attenuation and rifting, accompanied by the main phase of extrusive felsic magmatism and syn-volcanic granite intrusion. The heat source for anatexis was most likely underplated mafic material. Felsic volcanics accumulated mainly in the rift grabens. The syn-volcanic granites cut their own extrusiva. These granites formed the proto-diapirs of a gravity tectonic system, initiated in the second stage, and developed in the third stage of uplift, sedimentation and gravity subsidence. What were

originally felsic volcanite filled grabens became, in a period of inversion, the horsts between newly forming, sediment filled grabens. Granite diapirs were simultaneously emplaced to higher levels, accounting for the current structural configuration of western Bergslagen (De Groot et al., 1988). Mafic magmatism coincides approximately with this inversion. Metamorphic mineral ages of 1.84 Ga (Moorman et al., 1982) mark the end of this third stage, which is followed by a fourth stage with renewed large scale granitic magmatism in the period 1.78–1.6 Ga.

In a consideration of the tectonic setting of the region it should be remembered that the geological relationships of western Bergslagen, with abundant felsic volcanics and high level silicic intrusives clearly demonstrate that the region never underwent any significant uplift, but remained a region of subsidence, probably at or close to sea level. In this respect the term Svecofennian orogenesis (mountain building) is inappropriate as applied to central Sweden. Rather the 1.9–1.7 Svecofennian event records a period of crustal stabilization.

Tectonics and ore formation

The relationship of the ore deposits to the tectonic system described above are shown in Fig. 3. Fe-oxide deposits formed during the main stages of felsic magmatism are primarily sedimentary-exhalative, in which syn-volcanic felsic intrusives served as the heat sources to the sub-seafloor hydrothermal systems (Fig. 3a). As the rift grabens evolved, volcanism became less explosive, sediments became more frequent, and polymetallic epigenetic, stratiform and massive sulphide mineralizations, and minor Fe-Mn oxide mineralizations were formed (Fig. 3b). Ore brines originated primarily through leaching during water-rock interaction in a sub-seafloor environment, producing the widespread and diversified hydrothermal alteration described above. Ascent of the metalliferous brines to, or just under, the seafloor was along structurally controlled zones, possibly triggered by movements on rift faults as a result of structural readjustment in periods of quiescence following the

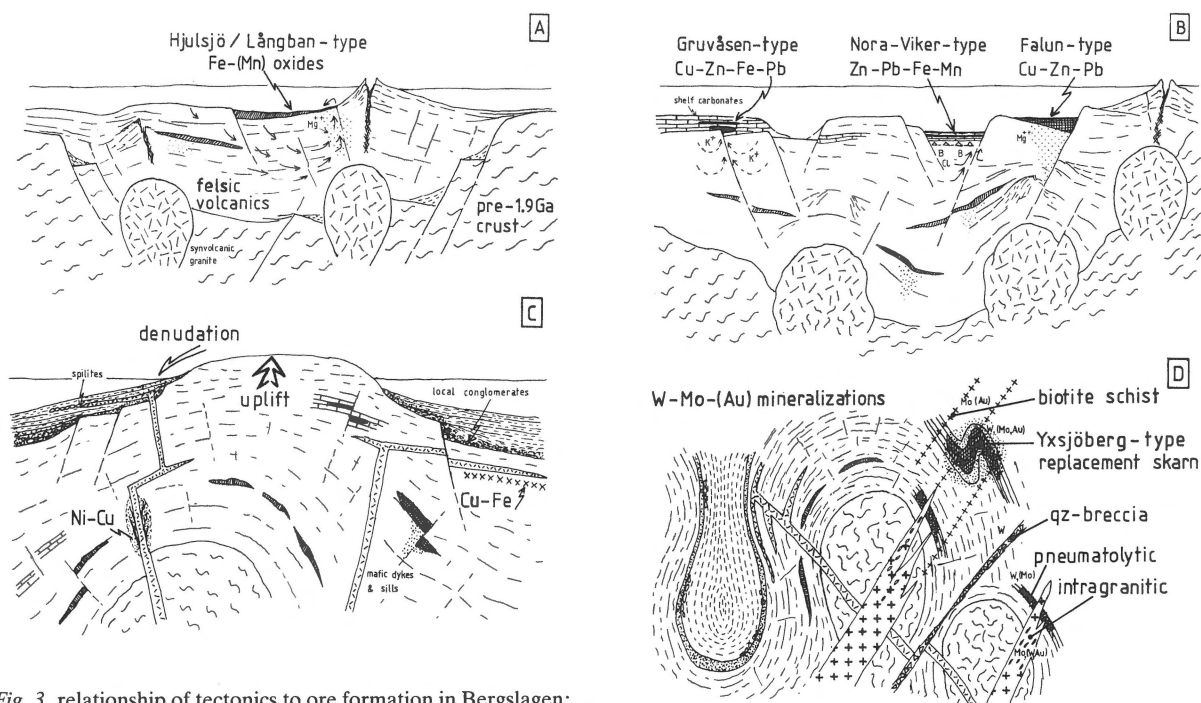


Fig. 3. relationship of tectonics to ore formation in Bergslagen; a) Submarine volcanism and sub-seafloor plutonism during rifting of a felsic crust generated hydrothermal cells leading to the development of exhalative Fe-Mn oxide ores. b) In an advanced stage of rifting polymetallic massive sulphide, epigenetic and exhalative mineralizations develop, sometimes accompanied by tourmalinites. c) Tectonic inversion produced sediment filled grabens, while minor Ni-Cu-Fe mineralization accompanied mafic magmatism. d) Anorogenic granites developed a series of W-Mo-(Au) mineralizations, from intragranitic to high and low temperature replacement skarns.

venting of felsic magma. Plimer (1988) compares and contrasts Bergslagen and Broken Hill noting that while bimodal magmatism is present in both rift systems, Bergslagen comprises a series of small basins with proximal, mostly volcanic infill, while Broken Hill comprises a very large single rift basin with distal, mainly sedimentary infill. In Broken Hill ore brines developed in a long lived geothermal system operating in wet sediments sustained by the intrusion of mafic sills (Plimer, 1988). The mechanism of ore deposition is similar in both areas. Exhalation was triggered by movement on rift faults which probably also served as fluid conduits; ore deposition was rapid, occurring between fault triggered mass flow sedimentary deposits (Plimer, 1988). The rhyolite-hosted nature of the Bergslagen mineralizations is in itself an additional

argument for extensional tectonics (Sillitoe, 1982).

Some minor intramagmatic or marginal Ni-Cu mineralizations are directly related to the emplacement of mafic rocks during the tectonic phase of inversion (Fig. 3c), when graben floors were uplifted (Zakrzewski, 1988; Baker et al., 1988).

The W-Mo-(Au) mineralization developed after the gravity tectonic stage of western Bergslagen (Fig. 3d), and is not restricted to any specific stratigraphic level (Hellingwerf & Baker, 1985; Baker & Hellingwerf, 1988).

Western Bergslagen and the southern part of the Svecofennian

Correlations made across the ± 300 km from western Bergslagen to the east have demonstrated the variation from a predominantly volcanic sequence to a sedimentary sequence (Fig. 4). Rickard (1988) demonstrates the change in metamorphism from extremely low grade in the volcanic western sequence to upper amphibolite in the more sedimentary eastern sequence, where veined gneisses are developed. Deformation styles also vary from

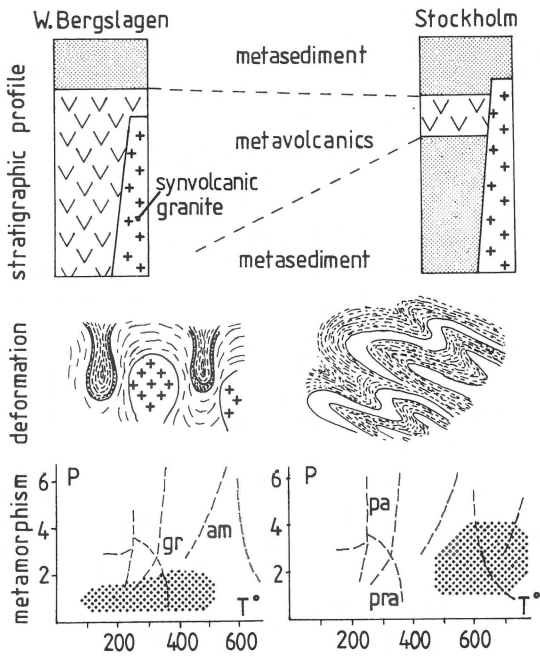


Fig. 4. Comparison of lithology, metamorphism and deformation in W. Bergslagen and the Stockholm region. gr: green schist, Am: amphibolite, Pa: pumpellyite-actinolite, pra: prehnite actinolite.

W to E (Fig. 4), with diapirism and gravity tectonics important in the W (De Groot et al., 1988), and west verging recumbent folds in the E (Stålhös, 1984). The style of diapiric deformation in W. Bergslagen is also found in the margin of the Archean craton NE of Outokumpu (Brun et al., 1981) and to the N of the Skellefteå district, again closely linked to the Archean craton (Witschard, 1984), thought to result from basement reactivation. The relationships shown in Fig. 4 are consistent with a model of an ensialic basin development, with the deepest part of the basin in the Stockholm area coinciding with the highest metamorphic grade (Rickard, 1988). Gorbatshev (1969) also indicates a deepening of the basin to the east. The eastern volcanics occur at a high stratigraphic level, demonstrating that sedimentation and basin development were already operating in the E before tensional processes initiated volcanism and ore deposition in the discordant NNE–SSW trending West Bergslagen iron formation basin. Granites which are syn-volcanic in western Bergslagen cross cut the lower

sediments in the east supporting this idea. As Rickard (1988) pointed out, sediments *underlying* the volcanics cannot easily be explained by simplistic volcanic arc models. Taken in the context of the overall geology, with the predominance of felsic intrusive and extrusive rocks *across the whole province*, the most viable model for the formation of the felsic igneous suite is a fairly rapid recycling of a felsic to intermediate precursor during ensialic rifting. The discordant nature of the iron formation basin, overlying the E–W trending more sedimentary belt to the E indicates that the Southern part of the Svecofennian comprises a series of overlapping basins rather than a single magmatic arc.

Following the E–W striking sedimentary sequence of Central Sweden across to southern Finland, there is a tendency for the felsic igneous rocks to become intermediate to mafic (e.g. Font & Nurmi, 1987; Gaál & Gorbatshev, 1987). The supracrustal sequence comprise lower units of submarine mafic-intermediate flows followed by turbiditic metasediments, with felsic volcanics again at higher stratigraphic levels (e.g. Colley & Westra, 1987). It could be that basin development here involved sufficient attenuation to allow mafic magma to be emplaced at an early stage.

Bergslagen in relation to the evolution of the Baltic Shield

Early Proterozoic development of the Archean Block

The development of the West Bergslagen ore province and ensialic basin must be considered in the context of the overall evolution of the Baltic Shield. Two major structurally coherent pre-1.7 Ga blocks are present in the Baltic (Fig. 5), bounded to the W by the Caledonides and the Transscandinavian Granite-Porphry Belt and coeval Fellingsbro-type granites (e.g. Öhlander & Zuber, 1988). The Archean block which was affected to different degrees during the Proterozoic occupies the NE part of the Baltic Shield, and has a NW–SE contact with the post-Archean Svecofennian. The general geological relationships and evolution of the Archean have been summarized by

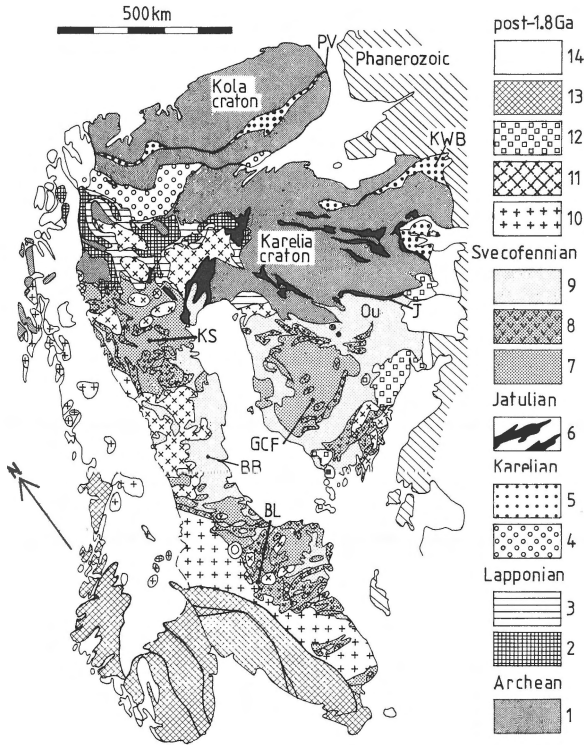


Fig. 5. Simplified geological map of the Baltic Shield. 1) pre-2.6 Ga granite gneisses and greenstones, 2) mafic volcanics, 3) metasediments, 4) Lapland granulites, 5) epicontinental sediments and volcanics, 6) metasediments, 7) granitoids, coeval with 8, 8) metavolcanics, 9) metasediments, 10) Transscandinavian Granite Porphyry Group, 11) Fellingsbro-type granites, 12) Rapakivi granites, 13) Post-1.8 Ga supracrustals, 14) Caledonian cover. PV: Pechanga-Varzuga rift, KWB: Kuolajärvi-Windy Belt rift, J: Janisjärvi rift, Ou: Outokumpu, KS: Kiruna-Skellefteå, GCF: Granitoid belt of Central Finland, BL: Bergslagen, BB: Bothnian basin.

Gaál & Gorbatshev (1987) and are not considered here. The Archean block can be divided into the Kola craton and Karelia craton (Fig. 5), separated by an axial zone containing the lapland granulite belt (Barbey et al., 1984; Barbey & Martin, 1987). Ages for Archean units range from 3.1 to 2.8 Ga (see Gaál & Gorbatshev, 1987). Several early Proterozoic (Lapponian, Karelian & Jatulian; approx 2.6–2.1 Ga) rift zones run through the Archean block, approximately parallel to the contact with the Svecofennian. In the NE the Pechanga-Varzuga rift is filled with continental to epicontinental sediments overlain by alkali volcanics followed by

shallow water sediments and mafic flows. To the SW, in the axial zone, the granulite (including Tana) belt represents early volcanic activity associated with continental rifting and deformed turbidites formed on a shallow shelf (Barbey et al., 1984; Barbey & Martin, 1987). To the SE of the axial zone the Jatulian was deposited on a continental platform and in several rift structures, including the Kuolajärvi-Windy belt and Janisjärvi rifts (Fig. 5). Barbey et al. (1984) and Barbey & Martin (1987) suggest that an initial stage of continental rifting and spreading, with possible ocean basin development represented by the Belmorian basin, accompanied by denudation and sedimentation in the period 2.4–2.0 Ga, was followed by compression as a result of collisional orogenesis in the period 2.0–1.9 Ga. The position of the approx. 2.6–2.3 Ga Lapponian supergroup in this scenario, developed on the western part of the Archean block is unclear. The Lapponian comprises a lower sequence of ultramafic volcanics followed by shallow water mainly continental sediments, with some minor felsic and intermediate volcanics. As Gaál & Gorbatshev (1987) point out, volcanism follows the NW trend seen in the Granulite belt and other rifts. It is our contention that the Lapponian, occurring between masses of Archean gneisses, records a more evolved ensialic rifting event than that recorded during Jatulian, to the SE. In all, rifting and opening was better developed in the NW part of the Archean block than in the SE.

Inter-relationships in the Svecofennian of the Baltic

From the NW trending contact between the Archean block and the Svecofennian domain to Bergslagen in the SW is approximately 800 km, and including the Svecofennian exposed in windows through the Transscandinavian Granite-Porphyry Belt down to Bornholm, gives about 1200 km of Svecofennian supracrustals (Fig. 5). In general terms, three granitoid magmatic areas can be distinguished; Bergslagen, Kiruna-Skellefteå, and the granitoid complex of central Finland. The ensialic development of Bergslagen, including the discordant West Bergslagen iron formation basin has been discussed above. On its own Bergslagen shows some of the characteristics of an ensialic

back arc basin, with sedimentation preceding volcanism. In the Kiruna-Skellefteå area (Fig. 5) the oldest mafic rocks yield ages of about 2.2 Ga (see Skiöld, 1987), comparable to some Jatulian ages from mafic intrusives. However, the Lapponian is not necessarily continuous into the Svecofennian as Fig. 5 suggests, the younger felsic metavolcanics of Kiruna-Skellefteå having an age range of about 1.9–1.86 Ga, which covers the age range of early coeval, possibly syn-genetic granitoids (Skiöld, 1987). Skiöld (1987) quoted Sm–Nd evidence for a major Archean component in early granitoids in the Vittangi area, E of Kiruna, which supports the basement reactivation and ensialic orogeny model of Witschard (1984). Rickard & Zweifel (1975) suggested the Skellefteå ore district, located some 250 km to the SW, represents a rifted volcanic arc, though Pharoah & Pearce (1984) noted the chemistry is also compatible with a back arc setting. The granitoid complex of central Finland (Fig. 5) comprises mainly intrusives with some volcanic rocks preserved along the margin of the complex (Gaál & Gorbatshev, 1987). The granitoids are coeval, but not comagmatic with mafic plutons, derived by anatexis of an igneous precursor (Font & Nurmi, 1987). A model involving first the generation of island arcs through continuous mantle magmatism, followed by a recycling of thickened, newly formed crust to generate the granitoid complex has been proposed (Font & Nurmi, 1987).

The magmatic areas described above interfinger with, and are surrounded by areas of metasedimentary rocks. The change in sedimentary regime across the Archean-Svecofennian boundary has been documented from the Outokumpu area by Ward (1987). A series of ensialic *en echelon* basins developed in the margin of the Karelian craton through transtensional stress related to NW shearing (Ward, 1987). The Jatulian represents a transgressive facies across the continental margin, feeding Archean and early Proterozoic debris into these basins at about 2.1 Ga (Ward, 1987; Gaál & Gorbatshev, 1987). The unconformably overlying Karelian (2.0–1.9 Ga) marks the transition to marine facies with turbiditic sequences of metagreywackes marking a change from near shelf to distal facies, passing into the marine sediments of the Svecofennian proper.

The Kalevian metasediments have model ages T_{DM} of 2.4 Ga, substantially more than the model ages for sediments from the Tampere area ($T_{DM} \approx 2.2$ Ga), consistent with an older source area in the east, with a substantial contribution from 2.2 Ga crust (Huhma, 1987).

In Sweden the Bothnian basin, located between Bergslagen and the Kiruna-Skellefteå areas contains a thickness of at least 10 km of metasediments, with a transition from marine to near shore facies to the SW, marked by an increasing importance of meta-quartzites and arkoses, taken by Lundqvist (1987) to indicate a pre-Svecofennian continental provenance area to the SW. Claesson (1987) gave model ages T_{DM} of 2.4 for metasediments from the central part of the basin, with $\epsilon_{Nd} -2.4$ to -3.1 , higher than the range of -3.2 to -4.4 given by Patchett et al. (1987) for basin metasediments collected more to the west. Some felsic metavolcanics are present in the upper part of the stratigraphy, while mafic rocks are only a minor component in the sequence (Lundqvist, 1987; Claesson, 1987).

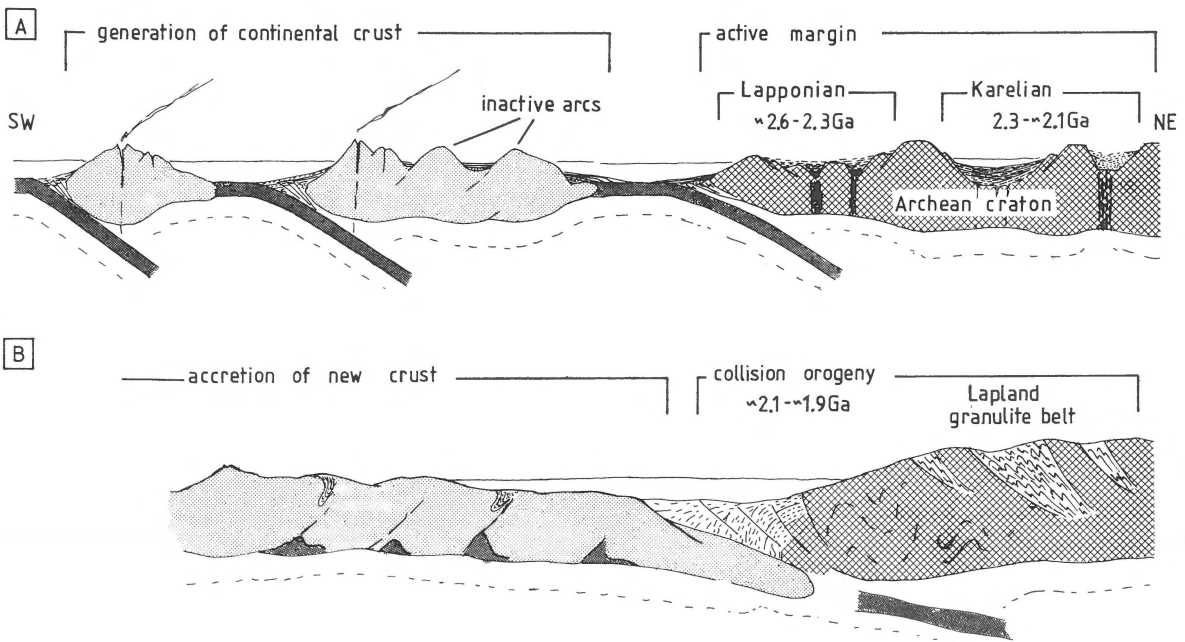
Evolution of the Svecofennian

The intracratonic rifting phase (2.6–2.1 Ga) affecting the Archean was followed by a collision type orogeny recorded in the Lapland granulite belt (Barbey et al., 1984), after which the E part of the Karelian craton from about 2.0 Ga acted as a passive margin with denudation and sediment transport to the S to SW (Gaál & Gorbatshev, 1987). This 2.6–2.1 Ga rifting phase corresponds with the model ages for Svecofennian sediments and volcanics, giving a time span of about 0.4 Ga to develop at least 1200 km of new crust prior to the Svecofennian. Two possibilities present themselves. Either the pre-Svecofennian represents an accreted exotic microcontinent, or new crust was generated in a series island arcs possibly during a phase of multiple subduction. In either case the amount of crust generated is very large. Accretion of an exotic terrain is less likely since such a crust has also to be generated in the period 2.6–2.1 Ga. In the period 2.6–2.1 Ga the Archean acted as an active margin, developing a series of back arc rifts during subduction (Fig. 6a). This was followed by colli-

sional tectonics and uplift to form the Lapland granulite belt (Fig. 6b). The direction of subduction and collision can be inferred to be from the SSE, based on the N-NE vergence of thrust sheets in Outokumpu (Bowes et al., 1984; Ward, 1987), and W vergence in the Stockholm area (Stålhös, 1984), resolved to a NW component, and the presence of major NW shears in the Karelian craton, parallel to Jatulian and other rifts and mafic dyke swarms (e.g. Gaál & Gorbatshev, 1987). Pre-collision oblique subduction probably started in the N part of the craton, evidenced by the greater amount of rifting and spreading (Fig. 5), and during initial collision denudation and sedimentation occurred across the continental margin in the Outokumpu area (Fig. 6c). The volcanism and related plutonism at Outokumpu can be traced into the larger zone of crustal reworking in the Granitoid belt of Central Finland, and resulted from rifting in a transtensional system where deep faults penetrated to sub-crustal layers where anatexis was responsible for the magmatism. The pre-Svecofennian crust underwent large scale reworking in the period 1.9–1.86 Ga. In Bergslagen, initial sedimentation in response to crustal sagging was followed by mag-

matism and subsequent deformation culminating in a peak of metamorphism at 1.84 Ga. The felsic volcanics developed during crustal attenuation define linear structures, and in Bergslagen at least, rift grabens (Fig. 6d), running up towards the Archean-Svecofennian contact. This suggests a large scale structural control on the Svecofennian rifting. Transtensional strike slip faulting across the Archean-pre-Svecofennian boundary caused crustal reworking to form the 250 km wide Skellefteå-Kiruna area. Some sort of strike slip movement is likely with transtensional stresses to produce the *en echelon* volcanic structures seen in the Svecofennian domain (see also Berthelson & Marker, 1986).

The felsic-intermediate magmatism was apparently initiated by underplating of the pre-Svecofennian crust in Bergslagen by mafic material during attenuation, evidenced by coeval, but not co-magmatic mafic magmatism in Bergslagen and the granitoid complex of central Finland. The underplating could be the result of low angle subduction under the Svecofennian, again from the SSE (Fig. 6d).



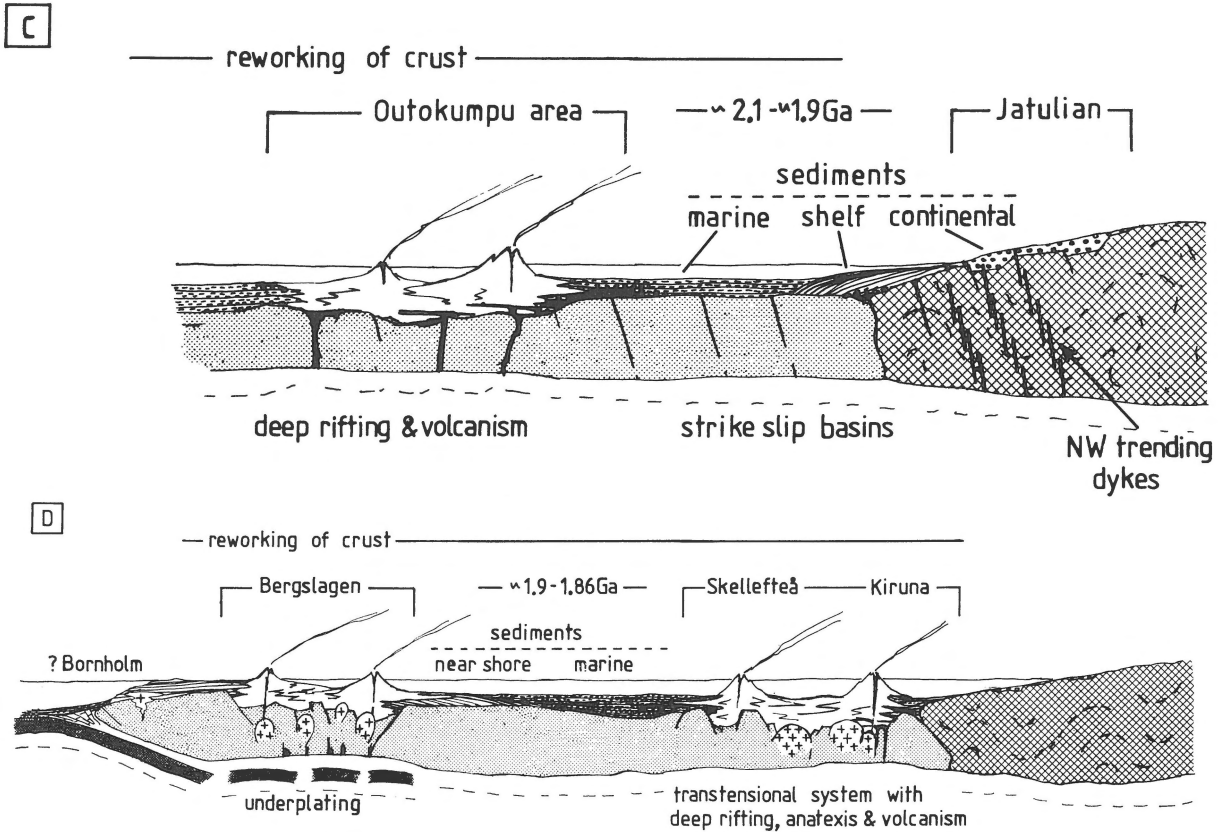


Fig. 6. Simplified model for the development of the Svecofennian of the Baltic Shield; a) precursor to the Svecofennian formed by multiple subduction in the period 2.6–2.1 Ga, accompanied by back arc rifting of the Archean block. b) Accretion of newly formed crust during collision orogeny to the Archean block. c) sedimentation across passive margin situation at Outokumpu. Volcanics generated by anatexis during transtensional strike slip movements and deep rifting which penetrated lower crust. d) tensional system in Bergslagen with the heat for anatexis probably provided by underplated mafic material. Transtensional system in the Skellefteå-Kiruna produces magmatism, while sedimentation in the intervening region covers the older crust

Conclusions

The stratigraphy, alteration processes, and mineralizations in Bergslagen are summarized. The variation in lithology, metamorphism and deformational style from the West Bergslagen ore province to Stockholm allow the paleo-reconstruction of the area. The identification of a felsic to intermediate continental precursor to the region of central Sweden has profound implications for the development of the Svecofennian. Prior to and during Svecofennian times the NE Archean block acted first as an active margin (2.6–2.1 Ga), developing rift basins and continental sediments followed by Andean type uplift; later it became a passive margin (2.0–

1.9 Ga), best seen N of Outokumpu. The pre-Svecofennian crust originated in the period 2.6–2.1 Ga. Multiple subduction probably generated new crust, and preceded by oblique subduction, was accreted onto the Archean. Transtensional stresses during plate movement developed elongate, *en echelon* volcanic rift basins with associated plutonism, driven by underplated mafic material. In Bergslagen crustal sagging and sedimentation preceded volcanism.

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References

- Åberg, G. 1978 Precambrian geochronology of south-eastern Sweden – *Geol. För. Förh.* 100: 125–154
- Åberg, G. & Charalampides, G. 1986 New lead isotope data from the Långban mineralization, central Sweden – *Geol. För. Förh.* 108: 243–250
- Åberg, G. & Fredriksson, G. 1984 Radiometric dating of the post orogenic Järna granite, South Central Sweden – *Geol. För. Förh.* 106: 171–174
- Åberg, G. & Persson, L. 1984 Radiometric dating of Precambrian rocks in Småland, southeastern Sweden – *Geol. För. Förh.* 106: 319–325
- Åberg, G., Bollmark, B., Björk, L. & Wiklander, U. 1983a Radiometric dating of Horrsjö granite, South Central Sweden – *Geol. För. Förh.* 105: 78–81
- Åberg, G., Levi, B. & Fredriksson, G. 1983b Zircon ages of metalvolcanic and synorogenic granitic rocks from the Svärdsjö and Yxsjöberg area, south central Sweden – *Geol. För. Förh.* 105: 199–203
- Ambros, M. 1983 *Beskrivning till berggrundskartan Lindesberg NO – Sver. Geol. Unders. Ser. Af 141: 75 pp*
- Baker, J.H. 1985a The petrology and geochemistry of 1.8–1.9 Ga granitic magmatism and related sub-seafloor hydrothermal alteration and ore-forming processes, W. Bergslagen, Sweden – *GUA Pap. Geol. Ser. 1, 21: 204 pp*
- Baker, J.H. 1985b Rare earth and other trace element mobility accompanying albitization in a Proterozoic granite, W. Bergslagen, Sweden – *Mineral. Mag.* 49: 107–115
- Baker, J.H. 1985c Greenalite, Mg-rich minnesotaite and stilpnomelane from the Ösjöberg and Sirsjöberg iron-ore mines, Hjulsjö, W. Bergslagen, Sweden – *Mineral. Mag.* 49: 611–613
- Baker, J.H. 1988 Primary geochemical features of 1.95–1.88 Ga Co-magmatic granites and felsic volcanics from the Falun-Filipstad-Västervik supracrustal belt, Sweden. In: 18 *Nordiske Geoliske Vintermøde-Danske. Geol. Unders. (Abstract): 38*
- Baker, J.H. & De Groot, P.A. 1983a Proterozoic seawater – felsic volcanics interaction W. Bergslagen, Sweden. Evidence for high REE mobility and implications for 1.8 Ga seawater compositions – *Contrib. Mineral. Petrol.* 82: 119–130
- Baker, J.H. & De Groot, P.A. 1983b Proterozoic submarine exhalative iron ores from Hjulsjö, leached from felsic volcanics by modified seawater – (Abstract) *Terra Cognita* 3: 167
- Baker, J.H. & Hellingwerf, R.H. 1988 Rare earth element geochemistry of W–Mo–(Au) skarns and granites from W. Bergslagen, Central Sweden – *Mineral. Petrol.:* (in press).
- Baker, J.H. & Drucker, W.H. 1988 Major element geochemistry of the 1.9–1.86 Ga Bergslagen Older granite Suite, (W. Bergslagen, Central Sweden). In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 227–237 (this issue)*
- Baker, J.H., Hellingwerf, R.H. & Hammergren, P. 1987 Geochemistry of a Proterozoic high silica W–Mo granite from Västra Gråshöjden, Central Sweden – *Geol. För. Förh.* 109: 111–121
- Baker, J.H., Andersson, L-G. & Marinou, A. 1988 Geochemical variation in a hydrothermal mafic breccia dyke and skarn related to Ni–Cu–Fe mineralization at Annehill, Bergslagen, Sweden – *Geol. Mijnbouw 67: 000–000 (this issue)*
- Barbey, P. & Martin, H. 1987 The role of komatiites in plate tectonics. Evidence from the Archean and early Proterozoic crust in the eastern Baltic Shield – *Precamb. Res.:* 35: 1–14
- Barbey, P., Convert, J., Moreau, B., Capdevila, R. & Hammeurt, J. 1984 Petrogenesis and evolution of an early Proterozoic collisional orogenic belt: the granulite belt of Lapland and the Belmorides (Fennoscandia) – *Bull. Geol. Soc. Finland* 56: 161–188
- Berthelsen, A. & Marker, M. 1986 1.9–1.8 Ga old strike-slip megashears in the Baltic shield, and their plate tectonic implications – *Tectonophysics* 128: 163–181
- Beunk, F.F., Baker, J.H. & Van Raaphorst, J.G. 1985 A Sm–Nd isotope study of the 1.85 Ga Hjulsjö volcano-plutonic complex, W Bergslagen, south central Sweden – (Abstract) *Terra Cognita* 5: 278
- Billström, K., Åberg, G. & Öhlander, B. 1988 Isotopic and geochemical data on the Pingstaberget Mo-bearing granite, Bergslagen, south central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 255–263 (this issue)*
- Björk, L. 1986 *Beskrivning til kartbladet Filipstad NV – Sver. Geol. Unders. Ser. Af 147: 110 pp*
- Boeschoten, G.J., Van der Raad, A.C., Kenter, J.A.M. & Reijmer, J.J.G. 1988 Note on a mid-Proterozoic stromatolite limestone, South of Grythyttan, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 467–469 (this issue)*
- Boström, K., Rydell, H. & Joensuu, O. 1979 Långban – an exhalative sedimentary deposit? – *Econ. Geol.* 74: 1002–1011
- Bowes, D.R., Halden, N.M., Koistinen, T.J. & Park, A.F. 1984 Structural features of basement and cover rocks in the eastern Svecokarelikes, Finland. In: Kröner, A. & Greilings, R. (eds): *Precambrian tectonics illustrated – Schweizerbart'sche Verlagsbuch. (Stuttgart): 147–171*
- Bromley-Challenor, M.D. 1988 The Falun Supracrustal Belt: Part 1. Primary geochemical features of the felsic metavolcanics and associated granites. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 239–253 (this issue)*
- Brun, J.-P., Gapais, D. & Le Theoff, B. 1981 The mantled gneiss domes of Kuopio (Finland): interfering diapirs – *Tectonophysics* 73: 288–304
- Carlson, C.J. & Bleeker, W. 1988 The geology and structural

- setting of the Håkansboda Cu–Co–As–Sb–Bi–Au deposit and associated Pb–Zn–Cu–Ag mineralization, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 279–292 (this issue)
- Cheilletz, A. 1988 Stratiform tungsten deposits: A review, with some implications for the Yxsjöberg – Sandudden deposits of Central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 293–311 (this issue)
- Claesson, S. 1987 Nd isotope data on 1.9–1.2 Ga-old basic rocks and metasediments from the Bothnian basin, central Sweden – Precamb. Res. 35: 115–126
- Colley, II. & Westra, L. 1987 The volcano tectonic setting and mineralization of the early Proterozoic Kemiö-Orijärvi-Lohja belt, SW Finland. In: Pharoah, T.C., Beckinsale, R.D. & Rickard, D. (eds): Geochemistry and mineralization of Proterozoic volcanic suites – Geol. Soc. Spec. Publ. 33: 95–107
- Damman, A. 1988 Exhalative-sedimentary manganiferous iron ores from the Gåsborn area, W. Bergslagen, Central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 433–442 (this issue)
- De Groot, P.A. & Sheppard, S.M.F. 1988 Carbonate rocks from W. Bergslagen, Central Sweden. Isotopic (C, O, H) evidence for marine deposition and alteration by hydrothermal processes. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 177–188 (this issue)
- De Groot, P.A., Baker, J.H. & Oen, I.S. 1988 Evidence for gravity subsidence and granite diapirism in the 1.8–1.9 Ga Proterozoic succession of W. Bergslagen, Sweden. – Geol. Mijnbouw 67: 19–29
- Ellis, A.J. 1979 Explored geothermal systems. In: Barnes, H.L. (ed.): Geochemistry of hydrothermal ore deposits – Wiley, (New York): 632–683
- Frietsch, R. 1982 A model for the formation of the iron manganese and sulphide ores of central Sweden – Geol. Rundsch. 71: 206–212
- Front, K. & Nurmi, P.A. 1987 Characteristics and geological setting of synkinematic Svecofennian granitoids in southern Finland – Precamb. Res. 35: 207–224
- Gaál, G. & Gorbatshev, R. 1987 An outline of the Precambrian evolution of the Baltic Shield – Precamb. Res. 35: 15–52
- Geijer, P. 1917 Falutraktens berggrund och malmyndigheter – Sver. Geol. Unders. Ser. C275: 316 pp
- Geijer, P. & Magnusson, N.H. 1944 De mellansvenska järnmalmernas geologi – Sver. Geol. Unders. Ser. Ca 35: 654 pp
- Gorbatshev, R. 1969 A study of Svecofennian supracrustal rocks in central Sweden: lithological association, stratigraphy and petrology in the northwestern part of the Mälaren-Hjälmaren basin – Geol. För. Förh. 91: 479–535
- Haymon, R.M. & Kastner, M. 1981 Hot spring deposits on the East Pacific Rise at 21° C N: Preliminary description of mineralogy and genesis – Earth Planet. Sci. Lett. 53: 363–381
- Hellingwerf, R.H. 1984 Paragenetic zoning and genesis of Cu–Zn–Fe–Pb–As sulfide skarn ores in a Proterozoic rift basin, Gruvåsen, Western Bergslagen, Sweden – Econ. Geol. 79: 696–715
- Hellingwerf, R.H. 1986a Contributions to the geology and ore genesis of western Bergslagen, Sweden – GUA Pap. Geology 25: 260 pp
- Hellingwerf, R.H. 1987 Spilitization and potassic alteration of Proterozoic metabasites and formation of sulfide deposits in the Saxå rift basin, Bergslagen, Sweden – Mineral. Deposita 22: 53–63
- Hellingwerf, R.H. 1988a Regional and Local potassic alterations in western Bergslagen and their relation to sulphide mineralizations: Proc. 7th IAGOD-Schweizerbart'sche Verlagsbuch. (in press)
- Hellingwerf, R.H. 1988b Local scale zoning patterns of trace and rare earth elements in marbles from Gruvåsen, Sweden: implications for mobility and precipitation – J. Geochem. Expl. (in press)
- Hellingwerf, R.H. & Baker, J.H. 1985 Wall-rock alteration and Tungsten and Molybdenum mineralizations associated with older granites in western Bergslagen, Sweden – Econ. Geol. 80: 479–487
- Hellingwerf, R.H. & Van Raaphorst, J.G. 1988 Sulphur isotope data of sulphides from Gruvåsen, Bergslagen, Sweden – Mineral. Petrol. (in press)
- Hellingwerf, R.H. & Oen, I.S. 1986 Some geochemical aspects of altered and least altered metabasic rocks in the Saxå area, Bergslagen, Sweden – N. Jb. Miner. Mh. 2: 65–81
- Hellingwerf, R.H., Lilljequist, R. & Ljung, S. 1988 Stratiform Zn–Pb–Fe–Mn mineralization in the Ävlången – Vikern area, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw 67: 313–332 (this issue)
- Helmers, H. 1984 Stages of granite intrusion and regional metamorphism in the Proterozoic rocks of Western Bergslagen, C. Sweden, as exemplified in the Grängen area – N. Jb. Miner. Mh. 150: 307–324
- Hietanen, A. 1975 Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian of Finland – J. Res. U.S. Geol. Surv. 3: 631–645
- Hübner, H. 1971 Molybdenum and tungsten occurrences in Sweden – Sver. Geol. Unders. Ser. Ca 46: 29 pp
- Huhma, H. 1987 Provenance of early Proterozoic and Archaean metasediments in Finland: a Sm–Nd isotopic study – Precamb. Res. 35: 127–144
- Jasiński, A.W., Baker, J.H. & De Groot, P.A. 1985 Thermodynamic aspects of the Mg-chlorite-alkali feldspar-sericite-kaolinite system: applications to the fossil sub-seafloor hydrothermal system at Hjulsjö, Bergslagen, Sweden GUA Pap. Geology 21: 159–188

- Johansson, Å. & Rickard, D. 1985 Some new lead isotope determinations from the Proterozoic sulfide ores of central Sweden – *Mineral. Deposita* 20: 1–7
- Koark, H.J. 1962 Zur Altersstellung und Entstehung der Sulfiderze von Typus Falun – *Geol. Rundsch.* 52: 123–146
- Kuipers, G. 1987 Volcanic facies associations in the mid-Proterozoic Grythyttan rift-basin and their lithostratigraphic relationship, west-Bergslagen, central Sweden – *GUA Pap. Geology* 28: 162 pp
- Lagerblad B. & Gorbatshev, R. 1985 Hydrothermal alteration as a control of regional geochemistry and ore formation in the Central Baltic shield – *Geol. Rundsch.* 74: 33–49
- Loberg, B.E.H. 1980 A Proterozoic subduction zone in southern Sweden – *Earth Planet. Sci. Lett.* 46: 287–294
- Löfgren, C. 1979 Do leptytes represent Precambrian island arc rocks? – *Lithos* 12: 149–165
- Lindroth, G.T. 1922 Studier over Yxsjöfältets geologi och petrografi – *Geol. För. Förh.* 44: 20–123
- Lundqvist, Th. 1987 Early Svecofennian stratigraphy of southern and central Norrland, Sweden, and the possible existence of an Archaean basement west of the Svecokareliides – *Precamb. Res.* 35: 343–352
- Lundström, I. 1983 Beskrivning till berggrundskartan Lindesberg SV – *Sver. Geol. Unders. Ser. Af* 126: 140 pp
- Lundström, I. 1985 Beskrivning till berggrundskartan Lindesberg NV – *Sver. Geol. Unders. Ser. Af* 140: 131 pp
- Lundström, I. 1987 Lateral variations in supracrustal geology within the Swedish part of the Southern Svecokarelian Volcanic Belt – *Precamb. Res.* 35: 353–365
- Lundström, I. 1988 Regional interrelationships in the Proterozoic geology of Bergslagen and SE central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 157–164 (this issue)
- MacGeehan, P.J. & Maclean, W.H. 1980 An Archean sub-seafloor geothermal system, 'calc-alkali' trends and massive sulphide genesis – *Nature* 286: 767–771
- Magnusson, N.H. 1925 Persbergs malmtrakt och berggrunden i de centrala delarna av Filipstads bergslag i Värmlands län – *Kungl. Kommerskollegium, Beskrivning over mineralfyndigheter, Stockholm*, 2: 231 pp
- Miller, R.G., O'Nions, R.K., Hamilton, P.J. & Welin E. 1986 Crustal residence ages of clastic sediments, orogeny and continental evolution – *Chem. Geol.* 57: 87–99
- Moorman, A.C., Andriessen, P.A.M., Boelrijk, M.A.I.M., Hebeda, E.H. Oen, I.S., Priem, H.N.A., Verdurmen, E.A.T., Verschure, R.H. & Wiklander, U. 1982 K–Ar and Rb–Sr mineral ages of skarns and associated metabasites and leptytes in the Hjulsjö area of the Bergslagen ore province, Central Sweden – *Geol. För. Förh.* 104: 1–9
- Oen, I.S. 1982 Isotopic age determinations in Bergslagen, Sweden: II The Filipstad-type granite of Rockesholm, Grythyttan area. – *Geol. Mijnbouw* 61: 305–307
- Oen, I.S. 1983 isotopic age determinations in Bergslagen, Sweden: IV Granites of the Grängen area, East of Hjulsjö – *Geol. Mijnbouw* 62: 301–303
- Oen, I.S. 1987 Rift related igneous activity and metallogenesis in SW Bergslagen, Sweden – *Precamb. Res.* 35: 367–382
- Oen, I.S. & Verschure, R.H. 1982 Isotopic age determinations in Bergslagen, Sweden: I Introduction – *Geol. Mijnbouw* 61: 301–304
- Oen, I.S. & Wiklander, U. 1982 Isotopic age determinations in Bergslagen, Sweden: III The Hjuttjö suite of gabbro-diorites and tonalite-granites, Filipstad area – *Geol. Mijnbouw* 61: 309–312
- Oen, I.S. & Verschure, R.H. 1985 Isotopic age determinations in Bergslagen, Sweden: VI Acid metavolcanics of the Bergslagen Supracrustal Series, Grythyttan-Hjulsjö area – *Geol. Mijnbouw* 64: 175–179
- Oen, I.S. & Hellingwerf, R.H. 1988 Structural evidence for seafloor, soft rock hydrothermal metamorphism in a garnet-skapolite bearing metatuffite-exhalite-skarn-sphalerite ore sequence, Nora, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 333–348 (this issue)
- Oen, I.S. Verschure, R.H. & Wiklander, U. 1984 Isotopic age determinations in Bergslagen, Sweden: V The Horrsjö granite, Filipstad area – *Geol. Mijnbouw* 63: 85–88
- Oen, I.S., De Maesschalck, A.A. & Lustenhower, W.J. 1986 Mid-Proterozoic exhalative-sedimentary Mn-skarns containing possible microbial fossils, Grythyttan, Bergslagen, Sweden – *Econ. Geol.* 81: 1533–1543
- Oen, I.S., Helmers, H., Verschure, R.H. & Wiklander, U. 1982 Ore deposition in a Proterozoic incipient rift zone environment: A tentative model for the Filipstad-Grythyttan-Hjulsjö region, Bergslagen, Sweden – *Geol. Rundsch.* 71: 182–194
- Öhlander, B. & Zuber, J. 1988 Geochemistry of Fellingsbro type granites, south central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 213–225 (this issue)
- Outhuis, J. & Van Berkel, J.T. 1988 Petrographic and geochemical evidence for major and trace element metasomatism in recrystallized felsic metavolcanics from the Persberg area, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 411–424 (this issue)
- Park, A. 1985 Accretion tectonism in the Proterozoic Svecokareliides of the Baltic shield – *Geology* 13: 725–729
- Parr, J. 1988 Metasediments associated with base metal mineralization, Ljusnarsberg district, Central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 189–202 (this issue)
- Parr, J. & Rickard, D. 1987 Early Proterozoic subaerial volcanism and its relationship to Broken Hill-type volcanism in Central Sweden. In: Pharoah, T.C., Beckinsale, R.D. & Rickard, D. (eds): *Geochemistry and Mineralization of Proterozoic volcanic suites – Geol. Soc. Spec. Publ.* 33: 81–93

- Patchett, P.J., Todt, W. & Gorbatshev, R. 1987 Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes in the Svecofennian orogenic terrains of Sweden – *Precamb. Res.* 35: 145–160
- Pharoah, T.C. & Pearce, J.A. 1984 Geochemical evidence for the geochemical setting of early Proterozoic metalvolcanic sequences in Lapland – *Precamb. Res.* 25: 283–308
- Plimer, I.R. 1986 Sediment hosted exhalative Pb–Zn deposits-products of contrasting ensialic rifting – *Trans. Geol. Soc. S. Africa* 89: 57–73
- Plimer, I.R. 1988 Broken Hill, Australia and Bergslagen, Sweden – Why God and Mammon bless the Antipodes! In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 265–278 (this issue)
- Pottorf, R.J. & Barnes, H.L. 1983 Mineralogy, Geochemistry and ore genesis of hydrothermal sediments from the Atlantis II deep, Red Sea – *Econ. Geol. Monogr.* 5: 198–223
- Rickard, D. 1978 The Svecofennian anomalous ore lead line – *Geol. För. Förh.* 100: 19–29
- Rickard, D. 1988 Regional metamorphism in the Bergslagen Province, south central Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 139–155 (this issue)
- Rickard, D.T. & Zweifel, H. 1975 Genesis of Precambrian sulfide ores, Skellefte district, Sweden – *Econ. Geol.* 70: 255–274
- Ripa, M. 1988 Geochemistry of wall rock alteration and of mixed volcanic-exhalative facies at the Proterozoic Stollberget Fe–Pb–Zn–Mn–(Ag) deposit, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 443–457 (this issue)
- Robinson, D. 1987 Transition from diagenesis to metamorphism in extensional and collision settings – *Geology* 15: 866–869
- Skiöld, T. 1987 Aspects of the Proterozoic geochronology of northern Sweden – *Precamb. Res.* 35: 161–168
- Sillitoe, R.H. 1982 Extensional habitats of rhyolite-hosted massive sulfide deposits – *Geology* 10: 403–407
- Stålhös, G. 1984 Svecofennian folding and interfering macrostructures in eastern Central Sweden. In: Kröner, A. & Greiling, R.E. (eds): *Precambrian Tectonics Illustrated*, Schweizerbart'sche Verlagsbuch. (Stuttgart): 369–379
- Sundius, N.L. 1923 Grythyttfältets geologi – *Sver. Geol. Unders. Ser. C312*: 354 pp
- Trägårdh, J. 1988 Cordierite-mica-quartz schists in a Proterozoic volcanic iron ore-bearing terrain, Riddarhyttan area, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 000–000 (this issue)
- Valbracht, P. & Helmers, H. 1988 metasomatic alteration of a felsic volcanite to an actinolite skarn, Stållbergstorp, Bergslagen, Sweden: evidence for high LREE mobility. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 425–432 (this issue)
- Van der Velden, J.W., Baker, J.H., De Maesschalck, A.A. & Van Meerten, T. 1982 Bimodal early Proterozoic volcanism in the Grythyttte field and associated volcano-plutonic complexes, Bergslagen, Central Sweden – *Geol. Rundsch.* 71: 171–181
- Van Meerten, Th. 1988 Lithostratigraphic correlations in an asymmetrical rift-basin, the Grythyttan area, W. Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 203–212 (this issue)
- Vaughan, J.P. & Stanton, R.L. 1986 Sedimentary and metamorphic factors in the development of the Pegmont stratiform Pb–Zn deposit, Queensland, Australia – *Trans. Inst. Min. Metal. Sect. B* 95: 94–121
- Vivallo, W. 1984 The origin of the early Proterozoic supracrustal rocks in the Garpenberg district of south central Sweden – *Geol. För. Förh.* 106: 131–149
- Vivallo, W. & Rickard, D. 1984 Early Proterozoic ensialic spreading-subsidence. Evidence from the Garpenberg enclave, Central Sweden – *Precamb. Res.* 26: 203–211
- Ward, P. 1987 Early Proterozoic deposition and deformation at the Karelian margin craton margin in southeastern Finland – *Precamb. Res.* 35: 71–94
- Welin, E., Gorbatshev, R. & Lundegårdh, P.H. 1977 Rb–Sr dating of rocks in the Värmland granite group in Sweden – *Geol. För. Förh.* 99: 363–367
- Welin, E., Wiklander, U. & Kahr, A.M. 1980 Radiometric dating of a quartz-porphiritic potassium rhyolite at Hällefors, South Central Sweden – *Geol. För. Förh.* 102: 269–272
- Witschard, F. 1984 The geological and tectonic evolution of the Precambrian of Northern Sweden – a case for basement reactivation? – *Precamb. Res.* 23: 273–315
- Zakrzewski, M.A. 1982 Geochemical facies model of ore formation in the Grythyttan-Hällefors area, Bergslagen, central Sweden – *Geol. Rundsch.* 71: 195–205
- Zakrzewski, M.A. 1988 Mineral parageneses of the sulphide ore deposits of Bergslagen metallogenic province: 1. Ni–Cu deposits of southern Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): *The Bergslagen Province, Central Sweden: structure, stratigraphy and ore-forming processes – IGCP Project 247 – Geol. Mijnbouw* 67: 357–362 (this issue)