

## Evolution and tectonic history of the Bergslagen volcano-plutonic complex, central Sweden

Björn Lagerblad  
*Dept. of Geology, Lund University, Sölvegatan 13, 22362, Lund, Sweden*

Received 6 August 1987; accepted in revised form 28 January 1988

*Key words:* Bergslagen, geochemistry, magmatic arc, Proterozoic, structures, Sweden

### Abstract

The Proterozoic Svecofennian volcano-plutonic rocks in Bergslagen, central Sweden, exhibit changes in both geochemistry, grade of deformation and metamorphism going from the west toward the eastern and more interior parts of the south Svecofennian volcanic belt. In the west geochemically homogeneous rhyolitic volcanic rocks cover vast areas while towards the east the magmatic variation is larger, and dacitic volcanic rocks become increasingly common. Andesites are locally present. Similarly coeval granitoids in western Bergslagen are granitic, while granodiorite and tonalite plutonic complexes are more common to the east. A change in the magmatic character of the rocks is substantiated by their trace element signatures.

The rocks in the westernmost parts of Bergslagen have characteristics similar to modern continental within-plate settings, while those in the easternmost parts of Bergslagen have characteristics similar to volcanic arcs. The change in magmatic character is successive, and resembles the compositional polarity across a Phanerozoic magmatic arc at a destructive plate margin.

The more continental character of the Svecofennian rocks in western Bergslagen implies thicker crust. This is substantiated by the more homogeneous magmatic character of the volcanic rocks which can be taken to imply larger magma chambers.

Thus, when the Svecofennian crust, shortly after its consolidation, was subjected to an E-W compression, the crust in western Bergslagen acted as a more competent block relative to the thinner more 'primitive' crust in east. This resulted in stronger compression of the crust to the east, which in turn explains more intense folding and higher grades of regional metamorphism in these areas.

### Introduction

When the geology of the western part of Bergslagen is compared to the geology of the areas to the east, considerable differences can be found. Interpretations of these separate areas has produced conflicting models for an origin of the region as a whole.

In the west the geological picture is given by a relatively thick volcano-sedimentary sequence in-

errupted by faults and updoming synvolcanic plutons, while in the east the picture is given by large plutonic complexes separated by volcano-sedimentary rocks in long synformal troughs. This change of geological framework is coupled to an increase in the intensity of deformation and grade of metamorphism from the west towards the east.

With the exception of subordinate amounts of late basaltic eruptives, all the volcanic rocks in the west are rhyolitic. Furthermore, all the Svecofen-



nian plutonics are either gabbroic or granitic. Based on rift tectonics and a bimodal geochemistry, the Svecofennian rocks in western Bergslagen have been interpreted as having been formed in a continental rift environment (Oen et al., 1982).

Towards the east dacitic and occasionally andesitic volcanic rocks, and granodioritic to tonalitic intrusives become increasingly common. Based on geochemical evidence and other related data, the Svecofennian rocks in the Falun area (Kresten, 1986) and the Garpenberg area (Vivallo, 1984; Vivallo & Richard, 1985) have been interpreted as having been formed at a destructive plate margin.

Both these interpretations make sense if the two areas are investigated separately as isolated domains. However, isotopic data and other geological criteria (see below) indicate a common origin. The material upon which this paper is based covers the whole of Bergslagen and therefore can cast light on the whole province. Furthermore there is a clear connection between the changing magmatic type and the change in deformative style. By connecting the magmatic and deformative style on a regional basis a model can be constructed.

#### *The Svecofennian domain*

The Bergslagen province, treated in this paper, forms only a minor part of a large Svecofennian domain covering major parts of the central Baltic Shield (Fig. 1a). To the east the Svecofennian domain is bound to an Archean-early Proterozoic (Karelian) craton, while the rocks to the west of it are younger.

In the Svecofennian domain proper, most of the continental crust was formed during a relatively short time period between 1.90 and 1.87 Ga (Wilson et al., 1985; Huhma, 1986; Gaal & Gorbatshev, 1987; Welin, 1987).

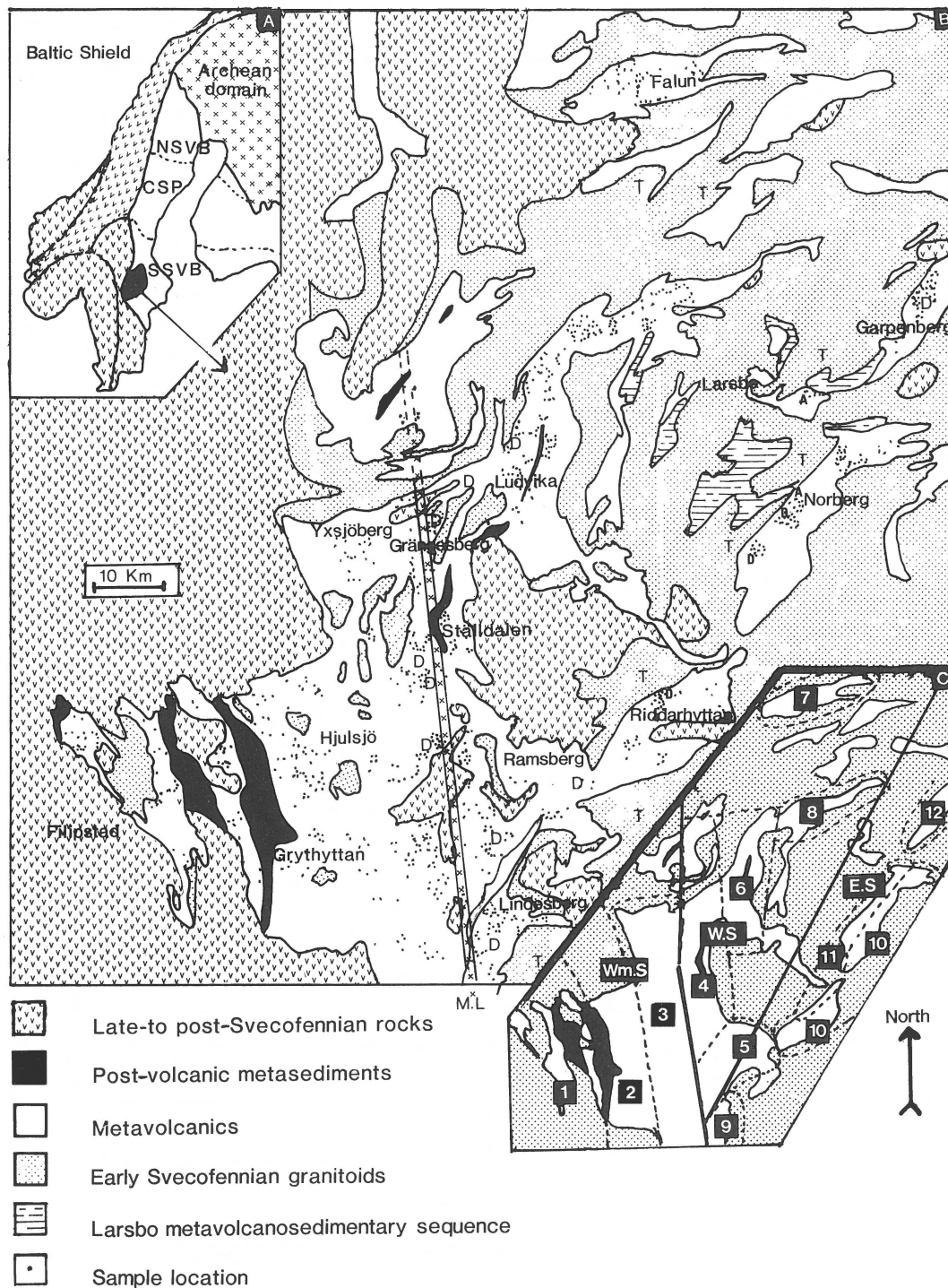
Except in, or close to, the Archean craton, most Svecofennian rocks are characterized by low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios (Welin, 1987) and positive epsilon-Nd values indicating little contamination of the newly formed Proterozoic crust by Archean material (Beunk et al., 1985; Huhma, 1986; Patchet & Kouvo, 1986; Patchet et al., 1987). The Bergslagen province (cf. Fig. 1b) covers the western part of a volcano-plutonic complex which runs

from the central part of Sweden over the Baltic sea into the southern part of Finland. To differentiate this volcano-plutonic belt from the other rock provinces of the Svecofennian domain, Gaal and Gorbatshev (1987) named it the southern Svecofennian volcanic belt (SSVB). Bergslagen is defined as the ore-bearing part of the Swedish sector of the SSVB. The investigated area covers most of the major ore districts, and in this paper is referred to as the Bergslagen province.

#### *South Svecofennian Volcanic Belt (SSVB)*

Supracrustal rocks are the oldest components of the entire SSVB. In Bergslagen volcanites dominate, while sedimentary rocks become more common towards the east (cf. Lundström, 1987). Soon after the extrusion of the volcanics and the deposition of the overlying sediments, the volcano-sedimentary complex was intruded by a sequence of granitoids. With the exception of western Bergslagen, the early Svecofennian granitoid sequence forms a differentiated suite of calc-alkaline intrusives ranging from gabbro and diorite through tonalite and granodiorite to granites (Lundqvist, 1979; Nurmi & Haapala, 1986; Front & Nurmi, 1987; Gaal & Gorbatshev, 1987). In general the more basic plutonics intruded prior to those more acid (Lundqvist, 1979). In the SSVB as a whole, tonalitic to granodioritic plutonic complexes cover the largest areas. Granites can, however, be found everywhere. The age difference between the early Svecofennian granitoids and volcanics is so small that it lies within the uncertainty limits (Welin, 1987).

Later, after a period of orogenic deformation, the newly consolidated Svecofennian crust was intruded by a set of 'post-orogenic' granitoids. No volcanism was attached to this plutonic event. The first of these post-orogenic granitoids intruded at around 1.83 Ga ago and granitoids belonging to this group continued to intrude until 1.77 Ga (Wilson et al., 1985; Patchet et al., 1987). Like the early granitoids these mostly granitic plutonic rocks have positive epsilon-Nd values indicating a short crustal residence age and remobilization of early Svecofennian material (Patchet et al., 1987). This 'late' Svecofennian period of orogenic activity coincided



*Fig. 1a.* Map showing the main subdivisions of the Baltic Shield. The area in white shows the Svecofennian domain. Abbrev; NSVB = northern Svecofennian volcanic belt. CSP = Central Svecofennian province. SSVB = Southern Svecofennian volcanic belt; *1b.* Map showing the investigated part of the SSVB (Bergslagen province). Abbrev; M.L. = Magnetic lineament. D = Dacitic volcanic rocks. A = Andesitic volcanic rocks. T = Tonalitic to granodioritic plutonic complexes; *1c.* Sketch map of the Bergslagen province showing the different subareas and the division in segments used in the text. Abbrev; Wm.S = Westernmost segment. W.S. = Western segment. E.S. = Eastern segment.

broadly with the initial stages of Gothian crust formation in areas to the west of the Svecofennian domain (Wilson et al., 1986; Patchet et al., 1987).

### Deformation and metamorphism in Bergslagen

The geological map (Fig. 1b) shows considerable differences between the western and eastern parts of Bergslagen. The volcano-sedimentary sequences are contained in N-S to NE-SW trending troughs, separated by granitoids of early to late Svecofennian age. The stratigraphic order and the secondary chemical alteration patterns (e.g. Sundius, 1923; Lagerblad & Gorbatshev, 1985), indicate that the volcano-sedimentary formations lie in synformal positions between granitoids in antiformal positions.

Several phases of deformation can be distinguished. However, one of them, very strong, transposed all the other phases and gave rise in the synforms to an isoclinal folding with horizontal to sub-horizontal fold axes. The associated cleavage, which can be correlated with the regional foliation, dips steeply in the synforms. Formerly rounded fragments like volcanic pebbles are strongly elongated and flattened, and like all other linear elements dip steeply down the regional foliation, indicating stretching in the direction of the fold limbs. The strong deformation has destroyed most volcanic structures making detailed stratigraphic and structural interpretations difficult in most areas. The strong deformational phase was caused by a regional E-W compression while the present configurations result from interference between updoming diapiric granitoids and less competent volcano-sedimentary rocks (Stephansson, 1975; Stålhös, 1984). The eastern part of Bergslagen is dominated by amphibolite facies metamorphism. The metamorphism was of a high T-low P type, indicated by parageneses including andalusite, sillimanite and cordierite. The peak of metamorphism was syn to post the major deformational event. In the western part of Bergslagen the intensity of deformation and grade of thermal metamorphism was significantly lower than in the eastern part, and in most other parts of the SSVB. A different tec-

tonic regime can also be noticed on geological (cf. Fig. 1b) and geomagnetic compilation maps (not published), revealing rounded structures and faults. In the westernmost parts of Bergslagen, in the Filipstad-Grythyttan area, the geological configuration is dominated by grabens containing syn- to post-volcanic sediments (Oen et al., 1982). Further to the east in the Hjulsjö-Yxsjöberg area rounded structures are given by subvolcanic granitic intrusives doming up in older volcanic strata (Baker & Drucker, 1985). Most of the geological configurations seem to have resulted from vertical movements associated with the updoming of the syn-volcanic plutons and rifting giving rise to late basic volcanism (Oen et al., 1982). After rifting and updoming, the western part of Bergslagen was, like the eastern, affected by an E-W compression (Oen et al., 1982; Helmers, 1984; Björk, 1986). However, it was less intense and only of local importance. The grade of regional metamorphism was within greenschist facies, increasing eastwards (Helmers, 1984).

The Svecofennian rocks were being folded as late as 1.85 Ga (Welin & Stålhös 1986). The orogenesis giving rise to the penetrative foliation must, however, have ended before 1.84 Ga because of intrusions of post-deformative granitoids of this age (Oen & Wiklander, 1982).

The change of structural style and metamorphic grade between the western and eastern part of Bergslagen is rather sudden and is manifested on aeromagnetic compilation maps as a N-S trending magnetic lineament (Fig. 1b). The lineament itself is not caused by a sudden change in volcanic lithology, but to later intruding granites and pegmatites, indicating a zone of weakness. Svecofennian and later reactivation of the zone has resulted in small scale thrusting and local deformational rock fabrics.

### Magmatic geochemical patterns in Bergslagen

#### *Sampling and analytical techniques*

Volcanic rocks were sampled on a regional scale (Fig. 1b). In order to avoid the effects of secondary alteration, preferably undeformed and seemingly

unaltered porphyritic rocks from non-mineralized strata were sampled. Altogether, over 1200 rocks were analysed. Of these 300 were omitted from the data set due to signs of re-deposition and/or chemical precipitation. (called tuffite in Table 1). The chemical analyses were performed on fresh samples of more than 1 kilogram, collected at single spots in homogeneous rock layers. After crushing and grinding, a large proportion of the samples were analysed by proton-induced, simultaneous X-ray (PIXE) and gamma-ray (PIGE) techniques at the Dept. of Nuclear Physics, Lund institute of technology. The method and its accuracy have been described by Carlsson (1984). In addition, 400 samples were analysed or re-analysed by conventional X-ray fluorescence. These samples gave the same results and indicate the same geochemical

pattern as those analysed by the PIXE-PIGE method.

### Geochemistry

Three different types of hydrothermal alteration affecting the chemistry of the volcanics can be distinguished, manifested by a magmatically unrealistic increase in Na, K or Mg (Lagerblad & Gorbatshev, 1985). Table 1 shows the chemistry of 370 volcanic rock samples from the western part of Bergslagen when subdivided into groups defined by these alteration types. From this Table it can be noted that, as expected, elements with high ionic potentials such as Ti, Al, Ga, Th, Nb, Y and Zr occur with similar contents and ratios in all the groups, while all other elements vary according to the alteration type. Furthermore, even tuffites (Ta-

*Table 1.* Compilation of chemical data from acid ( $\text{SiO}_2 < 70$  wt. %) volcanic rock samples from subareas 2–5 (cf. Fig. 1c). The potassium- and sodium-rich types are selected on the basis of a  $\text{Na}_2\text{O}/(\text{Na}_2\text{O} + \text{K}_2\text{O})$  ratio of below and above 0.2 and 0.8 respectively. All the other are regarded as alkali intermediate (Alk.-int.). All samples with higher contents of MgO than  $\text{Fe}_2\text{O}_3$  are excluded from the alkali-defined types and if the samples have a content of MgO higher than 2 wt. % they are regarded as Mg-enriched. Tuffite = redeposited volcanic rock.  $\text{Fe}_2\text{O}_3$  = total iron. Alk. mol = The sum of alkalis in mol. Oxides are given in wt. %, elements in ppm. Standard deviations are indicated in parenthesis.

Type	Alk.-int.	K-enriched	Na-enriched	Mg-enriched	Tuffite
$\text{SiO}_2$	75.43 (5.28)	74.03 (2.03)	77.27 (1.85)	76.96 (1.98)	75.46 (2.28)
$\text{TiO}_2$	0.20 (0.12)	0.23 (0.11)	0.17 (0.09)	0.13 (0.04)	0.17 (0.12)
$\text{Al}_2\text{O}_3$	12.31 (0.81)	12.51 (0.99)	12.05 (0.96)	11.87 (1.13)	12.27 (1.08)
$\text{Fe}_2\text{O}_3$	2.18 (1.07)	2.64 (1.18)	1.24 (0.96)	1.05 (0.88)	2.34 (1.65)
MnO	0.02 (0.03)	0.05 (0.05)	0.01 (0.03)	0.01 (0.01)	0.06 (0.10)
CaO	0.74 (0.73)	0.78 (0.83)	0.54 (0.49)	0.21 (0.23)	1.11 (1.15)
MgO	0.85 (0.71)	0.90 (0.76)	0.76 (0.66)	3.47 (1.20)	1.13 (0.87)
$\text{Na}_2\text{O}$	3.37 (1.04)	0.86 (0.44)	6.10 (0.91)	1.93 (1.86)	3.15 (1.87)
$\text{K}_2\text{O}$	3.60 (1.28)	6.93 (1.23)	0.51 (0.33)	2.57 (1.16)	3.17 (1.90)
Rb	93 (54)	140 (43)	21 (17)	74 (35)	103 (70)
Ba	797 (475)	1317 (675)	48 (122)	266 (242)	570 (506)
Sr	41 (28)	27 (22)	33 (28)	16 (16)	34 (30)
Y	44 (13)	43 (11)	47 (16)	45 (16)	44 (14)
Nb	14 (4)	16 (3)	14 (4)	15 (4)	16 (4)
Zr	225 (70)	255 (54)	224 (73)	183 (52)	215 (71)
Ga	18 (3)	17 (3)	17 (3)	18 (4)	18 (4)
Th	15 (3)	15 (2)	16 (4)	16 (3)	17 (4)
Ga/Al	2.74 (0.39)	2.62 (0.43)	2.76 (0.51)	2.89 (0.70)	2.73 (0.61)
Alk. mol.	0.19 (0.02)	0.17 (0.03)	0.21 (0.03)	0.11 (0.05)	0.17 (0.05)
Nb/Y	0.36 (0.20)	0.38 (0.10)	0.34 (0.13)	0.42 (0.37)	0.38 (0.12)
Zr/TiO <sub>2</sub>	0.13 (0.04)	0.13 (0.04)	0.16 (0.05)	0.14 (0.03)	0.15 (0.04)
Numer of anal.	149	43	96	30	51

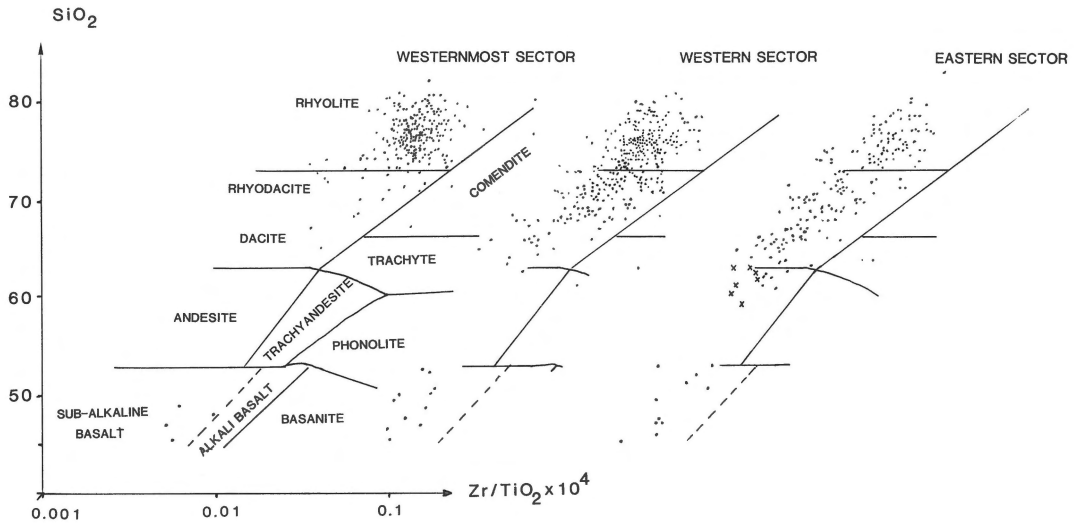


Fig. 2. Diagrams showing the  $\text{SiO}_2$ - $\text{Zr}/\text{TiO}_2$  variation in the volcanic rocks from the three segments (sectors) of the Bergslagen province marked on Fig. 1c. Fields of common volcanic rocks are drawn according to Winchester & Floyd (1976). Each dot mark the position of one chemical analysis. The crosses mark the position of the andesitic volcanic rocks from the Larbo metavolcanosedimentary sequence. Tuffites and Mg-enriched samples are excluded. The diagrams from westernmost, western and eastern sector contains 246, 371 and 215 analyses respectively.

ble 1) and rocks extremely enriched in Mg (Baker & De Groot, 1983; Lagerblad & Gorbatshev, 1985), have similar contents and ratios between these apparently immobile elements. These samples were, however, not included in the following plots.

Thus, the 'immobile' elements must be used to identify the magmatic character of the volcanites. However, as silica is generally mobile in hydrothermal fluids this element must be examined first in order to prove that the regional variation is primary feature. If the samples from Bergslagen are plotted in the  $\text{Ti}/\text{Zr}$  versus  $\text{SiO}_2$  diagram compiled by Winchester & Floyd (1976), all the samples plot along a typical subalkaline magmatic trend (Fig. 2). A subalkaline geochemistry is also indicated by relatively low Nb/Y ratios. However, from Table 1 it can be concluded that the Na-enrichment process is coupled to an enrichment of  $\text{SiO}_2$  (relative to the other elements). This effect is, however, not large enough to explain the regional differences. This indicates that although variations in the silica content occur, the Si-content accurately reflects the primary magmatic composition of the original volcanic rocks.

Furthermore, the dacitic character of the samples from eastern parts of Bergslagen is reflected in their mineralogy (cf. Lundström, 1983). The plagioclase phenocrysts in the dacitic samples range in composition from andesine to oligoclase while those in the rhyolites range in composition from oligoclase to albite. The andesitic volcanic rocks from the Grängesberg area (Magnusson, 1938) and the northeastern parts of Bergslagen (Hjelmqvist, 1966) contain andesine phenocrysts.

#### Regional variation

The most obvious indication of magmatic variation is the very acid character of both the volcanites and granitoids in western Bergslagen and the less acid rocks towards the east and more interior parts of the SSVB. The first dacitic volcanites (63–73 wt. %  $\text{SiO}_2$ ) do not appear until close to or east of the magnetic lineament marked on Fig. 1b. Here the intermediate volcanics (except in area 9, west of Lindsberg) appear as distinct volcanic complexes surrounded by rhyolitic volcanites (> 73 wt. %  $\text{SiO}_2$ ). One set of intermediate volcanic units can be followed along a line parallel to the magnetic lineament from southwest of Ställdalen over Grängesb-

erg up to the eastern part of the Ludvika area (cf. Fig. 1b). In general these volcanites are dacitic. However, andesitic lavas and feeder dykes appear in the Grängesberg area (Magnusson, 1938). Furthermore dacitic complexes are common in the Ramsberg area (Lundström, 1983, 1985). Dacitic to andesitic volcanites, in part intrusive, have also been identified in the Falun area (Kulling & Hjelmqvist, 1948).

In the Lindesberg (the Storsjö Formation, Lundström, 1983) and more easterly areas (Hjelmqvist, 1966) the intermediate volcanics do not appear as separate complexes, but as distinct formations. In the Garpenberg area dacitic volcanic rocks dominate. In the Norberg-Riddarhyttan area a formation characterized by dacites overlies a rhyolitic formation (Geijer, 1923, 1936). Furthermore, in this area andesites (< 63 wt. % SiO<sub>2</sub>) occur in close association with the Larsbo sedimentary sequence. The exact relationship between these andesites and the other volcanics is, however, unclear.

In general the intermediate volcanic rocks appear to have extruded later than the acid (Geijer, 1967; Sundius, 1968). The same compositional variation can be noticed among the old granitoids. West of the magnetic lineament all the old granitoids are granitic (Baker, 1985; Baker & Drucker, 1985). However, east of the magnetic lineament in the Lindesberg area granodioritic and tonalitic granitoids start to appear (Lundström, 1983, 1985). Grey, relatively mafic granitoid complexes are also common close to dacites at Grängesberg and west of Ludvika, but the majority of these complexes are granitic (Magnusson & Lundqvist, 1933; Strömberg pers. comm. 1987). Further to the east in the district between Ludvika and Norberg-Riddarhyttan (Strömberg, 1983) the old granitoid complexes contain both granites, granodiorites and tonalites. Tonalitic complexes lie closest to the andesite and dacite formations in the Norberg area, while granites dominate in the areas close to the rhyolites of the Ludvika area. This spatial and compositional relationship between the early granitoids and volcanic rocks, which was pointed out by Hjelmqvist (1966), implies a genetic link. Bergslagen has been divided into three segments, based on the relative abundance of intermediate granitoids

and volcanics (cf. Fig. 1c). Apart from the general change in the contents of SiO<sub>2</sub> in the metavolcanics, a magmatic variation can be seen in the contents of the immobile elements, especially Nb, Y and Zr. To show this the investigated part of Bergslagen has been divided on geographical or geological grounds into 12 distinct sub-areas (Fig. 1c). Plotting Y, Nb and Zr contents in histograms for the 12 sub-areas (Fig. 3) shows there is a general decrease from the westernmost part of Bergslagen towards the eastern and more interior parts of the SSVB. The difference is most pronounced and significant when the westernmost (Filipstad area) and easternmost (Garpenberg area) parts of Bergslagen are compared, whereas the difference is less pronounced when adjacent areas are compared. The dacitic and rhyolitic volcanites within each sub-area and/or geological formation always have the same high or low contents of Nb, Y and Zr. This indicates that the variation in general is due to regional rather than local magmatic variation. Based on the contents of Nb, Y and Zr, the intermediate volcanic complexes close to the magnetic lineament (western segment) can be distinguished from the intermediate complexes further to the east (eastern segment; Fig. 3). Furthermore, if the least altered volcanic rocks from the eastern and western sector of Bergslagen are compared, the dacitic rocks from the western sector contain more Ti, Fe and Th, while those from the eastern sector contain more Ca, Al and Sr (Lagerblad, unpubl. data). This indicates that the eastern part of the Bergslagen province has a more 'primitive' calc-alkaline character than the western part.

## Discussion

### *Volcanic type*

In the western part of Bergslagen, from the Grythyttan syncline to the magnetic lineament (sub-areas 2 and 3, Fig. 1c, Table 1), the trace element (Nb, Y, Zr) chemistry of the rhyolitic volcanics is very uniform. Furthermore, apart from the appearance of dacites, the chemistry of the volcanic rocks from sub-areas 4 and 5 is very similar. No regional variation can be noticed between the basal volcanic

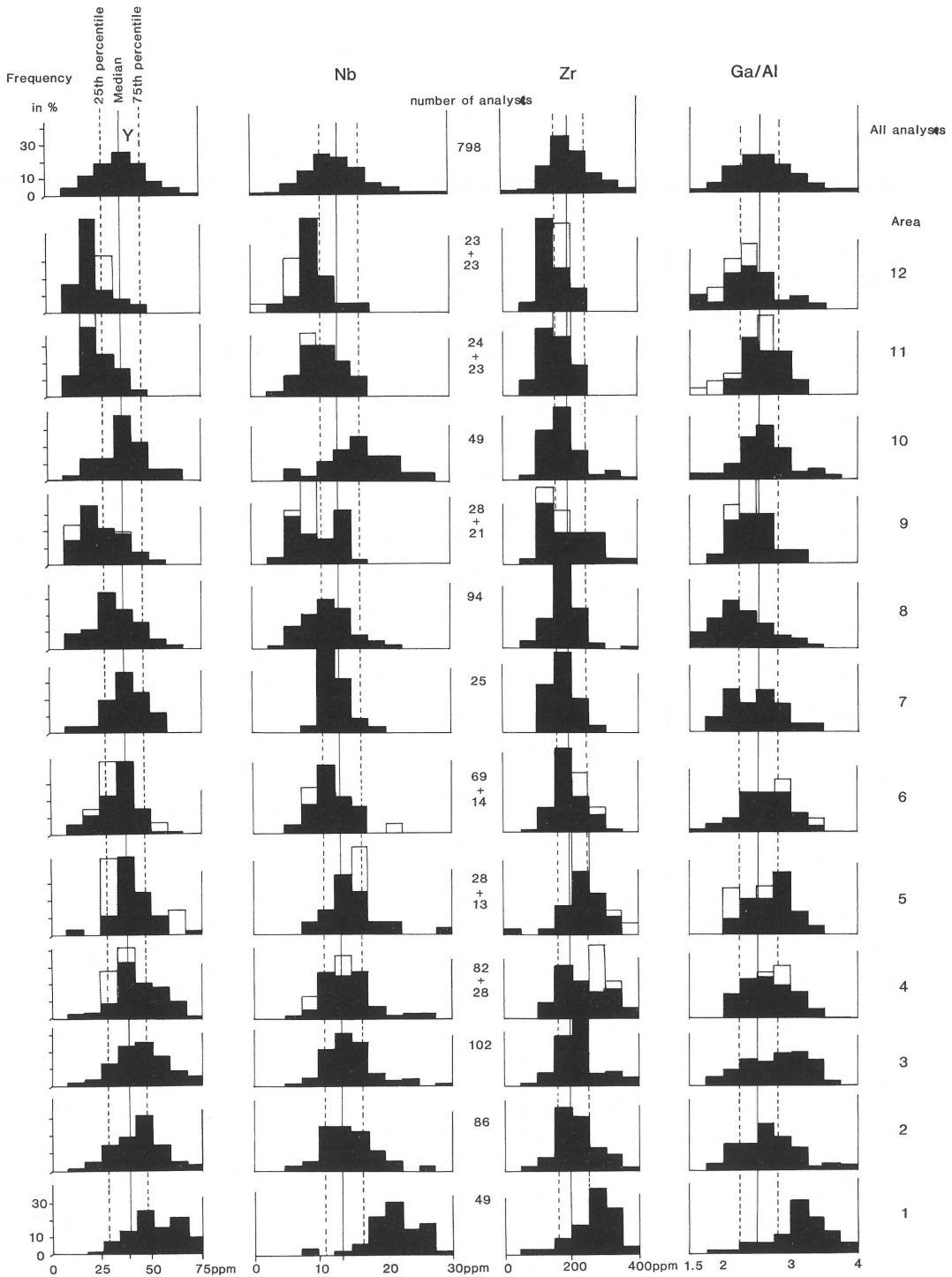


Fig. 3. Frequency distribution in % of Y, Nb, Zr and  $(\text{Ga}/\text{Al}) \times 10000$  from the different subareas marked on Fig. 1c. Black staples shows distribution of samples with more than 70 wt.  $\text{SiO}_2$ . Grey marks the distribution of intermediate volcanic rocks samples (63 and 70 wt. %  $\text{SiO}_2$ ) when frequency in the intervall is higher than that of the acid volcanic rocks. No staples with intermediate samples are plotted when the number of analyses from the subarea is less than 10. The lower number in 'number of analyses' marks the intermediate samples. The lines marked median and percentiles refer to all analyses (contents of  $\text{SiO}_2$  more than 63 wt. %). Tuffites and Mg-enriched samples are excluded.

formations or those at the top of the volcanic pile. This area covers more than 1000 km<sup>2</sup> (cf. Fig. 1b). If a depth of 2 km. of extruded rhyolitic volcanics is assumed, then 2000 km<sup>3</sup> of geochemically homogeneous material was extruded. Baker (1985) suggests the volcanic pile was more than 7 km thick, while Beunk et al. (1987) estimate 10000 km<sup>3</sup> of rhyolitic material. Such large volumes of rhyolitic extrusives can today only be produced in very large magmatic systems (Smith, 1979) associated with very large calderas such as Valles, Long Valley and Yellowstone, or in volcanic tectonic depressions such as Tobe in Sumatra, or San Juan Mountains in Colorado (Smith, 1979; Fisher & Schminke, 1984).

Only smaller proportions of the upper part of the magma chamber are extruded (Smith, 1979). This seems to support the idea implied by the similarity in chemical and isotopic characteristics, that the oldest generation of granitoids are subvolcanic, relict magma chambers (Baker, 1985).

In the eastern part of Bergslagen the geochemical pattern is less homogeneous. The geochemical subdivision in the Norberg-Riddarhyttan area, with a dacitic formation on top of a rhyolitic one indicates either two volcanic systems separated in space and time, or differentiation within a smaller magma chamber. Geochemical studies have shown that early eruption products from relatively large magma chambers (but smaller than those implied for the western part of Bergslagen) are rhyolitic, while volcanics with more intermediate compositions erupted later (Smith, 1979). Simultaneously the contents of Nb and Y decrease while that of Zr increases (Hildreth, 1979, 1981). This geochemical variation is found in the Norberg sub-area, where the contents of Zr do not follow those of Y and Nb. This model of differentiation in a magma chamber can, however, only be applied to the stratification in the Norberg-Riddarhyttan area. Elsewhere, the ratios between the three immobile elements Nb, Y and Zr remain the same.

#### *Modern analogies and conclusions*

As a whole the SSVB is characterized by I-type, calc-alkaline tonalitic to granodioritic plutons often of batholith size (Wilson, 1982; Front & Nurmi, 1987; Gaal & Gorbatshev, 1987). Likewise, with

the exception of western Bergslagen, the volcanites form a differentiated calc-alkaline suite ranging from basalt to rhyolites (Frietsch, 1982; Kähkönen, 1987). This, and the isotopic data indicating material newly separated from the mantle (Pachet & Kouvo, 1986; Huhma, 1986; Pachet et al., 1987), suggest that subduction-related differentiation produced the bulk of the Svecofennian rocks in the SSVB. Today similar types of rocks are common at destructive plate margins.

Western Bergslagen, however, does not fit into models employing compressional tectonics. The bimodal distribution and very large masses of often extremely acid volcanics suggest crustal extension (Oen et al., 1982). Bimodal volcanic suites can, however, be found today in back-arc spreading positions on the continental side of magmatic arcs (cf. p. 386–413 in Hughes 1982).

No lithological break can be found between western and eastern Bergslagen. Furthermore, all the volcanics of Bergslagen are sub-alkaline and changes in chemistry successive. Thus, to explain the change of igneous rock types in Bergslagen magmatic polarity across a magmatic arc is suggested:

Such a polarity is also indicated by the trace element (Nb, Y, Zr) pattern. If the granitoid and volcanic rock samples from Bergslagen are plotted in the Nb-Y diagram compiled by Pearce et al. (1984) the rocks from the western part of Bergslagen plot in the within-plate field, while those from the eastern parts of Bergslagen plot in the volcanic arc or syn-collision field (Fig. 4). Furthermore, if the analyses from Bergslagen are plotted in the Ga/Al versus Nb (Fig. 5), Y or Zr diagrams compiled by Whalen et al. 1987, the samples from western Bergslagen plot in the field of anorogenic igneous rocks while the samples from eastern Bergslagen plot in the field of orogenic rocks. Assuming a similar process of crust formation in the Proterozoic as in the Phanerozoic, it is suggested that the rocks in eastern Bergslagen were formed by magmatic processes closer to a subduction zone, while the rocks in the western parts of Bergslagen were formed further from the subducting plate in a 'continental' back arc spreading position. Such a polarity across a magmatic arc requires involvement of

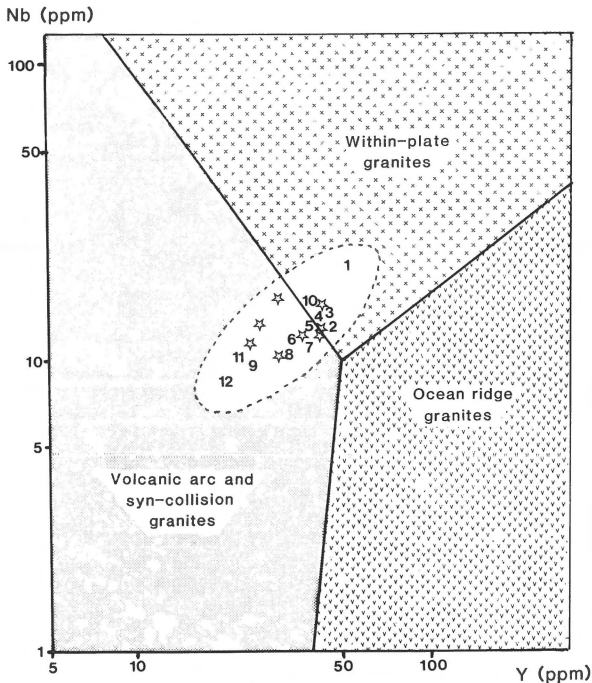


Fig. 4. Diagram showing the Nb vs. Y variation in the felsic Svecofennian rocks (contents of  $\text{SiO}_2$  more than 63 wt %) from the Bergslagen province. The white field marks where the majority the Bergslagen volcanics plot. The numbers mark the position of the median value of the volcanic rocks from the different subareas (cf. Fig. 1c). The stars marks the position of some granitic early Svecofennian plutonics from the western segment. Fields are drawn according to Pearce et al. (1984).

continental crust. Thus it is suggested that the present Svecofennian igneous rocks had a prehistory involving eroded, 'continentalized', more primitive island arcs (Lagerblad in prep). During pre-Svecofennian times thicker continental crust was generated in the west than in the east.

A thicker continental crust containing larger magma chambers in the western part of Bergslagen could explain the structural differences with the eastern part. During the E-W compression following the development of the Svecofennian rocks, the thick continental crust in western Bergslagen acted as a competent mass relative to the thinner continental crust further to the east. The rocks to the east would be intensely folded due to competence differences. The magnetic lineament (Fig. 1) was thus probably the result of a weakness zone formed at the interface between more and less competent

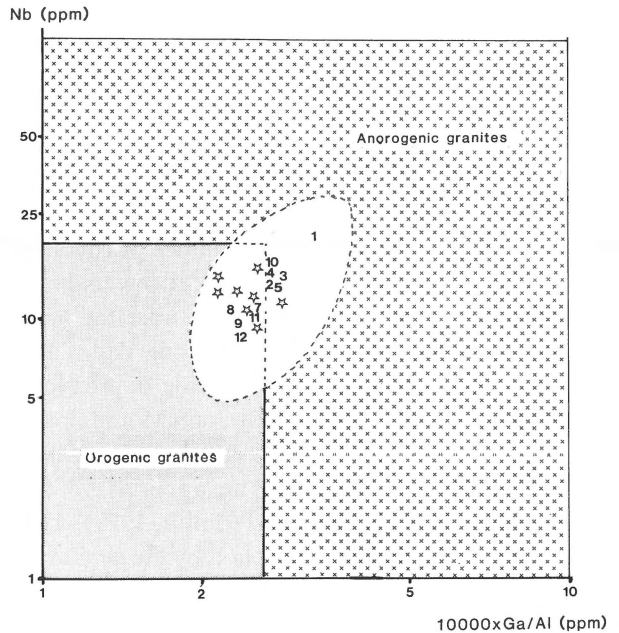


Fig. 5. Diagram showing the Nb vs. Ga/Al variation in the felsic Svecofennian rocks (contents of  $\text{SiO}_2$  more than 63 wt %) from the Bergslagen province. The white field marks where the majority the Bergslagen volcanics plot. The numbers mark the position of the median value of the volcanic rocks from the different subareas (cf. Fig. 1c). The stars mark the position of some granitic early Svecofennian plutonics from the western segment. The fields are drawn according to Whalen et al. (1987).

crust. Later, granites and pegmatites would preferably intrude into this tectonic zone.

The E-W compression did not result in extensive overthrusting or high-P metamorphic parageneses. This indicates that the folding was not due to any continent-continent collision. Instead it seems like there was a steady compression, in which the western volcano-plutonic complex was pushed eastward. This could be explained by a reversal of a subducting plate. Shortly after Svecofennian orogenesis the deformed crust was intruded by another set of late Svecofennian granitic plutons. Similar types of granites can be found in the transscandinavian granite-porphyry belt west of the Svecofennian domain. Assuming that these granitoids also were formed in a continental magmatic arc environment (Nyström, 1982; Wilson et al., 1986) this would imply eastward subduction of an oceanic

plate. Reversal of a subducting ocean plate could explain the E-W compression in Bergslagen.

### Acknowledgements

This paper is based on the results of a geochemical study supported by the Swedish Board for Technical Development (STU). The author wishes to thank P.A. Floyd and C. Crow for comments on an earlier draft of this paper, and L.-G. Andersson (LKAB-prospecting) for showing the magnetic lineament.

### References

- Baker, J.H. 1985 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, Thesis Univ. Amsterdam – GUA Papers of Geology 1–21: 204 pp
- Baker, J.H. & De Groot, P.A. 1983. Proterozoic seawater-felsic volcanics interaction, W. Bergslagen, Sweden: Evidence for high REE mobility and implications for 1.8 Ga seawater composition – *Contrib. Mineral. Petrol.* 82: 119–130
- Baker, J.H. & Drucker, W.H. 1985. Proterozoic 1.8–1.9 Ga S-type granites from W. Bergslagen, central Sweden – GUA Papers of Geology 1–21: 89–122
- Beunk, F.F., Baker, J.H. & Van Raaphorst, J.G. 1985. A Sm–Nd study of the 1.85 Ga Hjulsjö volcano-plutonic complex, W. Bergslagen, south central Sweden – *Terra Cognita* 5: 278
- Beunk, F.F., Helmers, H. & Valbracht, P.J. 1987. Geochemistry, geology and tectonic setting of the bimodal 1.9. By W. Bergslagen volcanic and intrusive suite, C. Sweden, Abstract–Congr. IGCP 217 Lund Sweden:
- Björk, L. 1986. Description to the map of solid rocks, Filipstad NW (Swedish with English summary) – *Sver. Geol. Unders. Ser. Af* 147: 1–110
- Carlsson, L.-E. 1984. Accuracy and precision in thick target PIXE-PIGE analysis determined with geological standards – *Nucl. Instr. Meth. in Phys. Res.* 231:
- Fisher, R.V. & Schminke H.-U. 1984 *Pyroclastic rocks*. Springer (Berlin, Heidelberg, New York, Tokyo): 472 pp
- Frietsch, R. 1982. Alkali metasomatism in the ore-bearing metavolcanics of central Sweden – *Sver. Geol. Unders. Ser. C* 791: 1–54
- Front, K. & Nurmi, P.A. 1987 Characteristics and geological setting of synkinematic Svecokarelian granitoids in southern Finland – *Precamb. Res.* 35: 195–207
- Gaal, G. & Gorbatshev, R. 1987. An outline of the Precambrian evolution of the Baltic Shield – *Precamb. Res.* 35: 15–52
- Geijer, P. 1923. Ridrarhytte malmfält (English summary) – *Beskrivningar av mineralfyndigheter 1, Kungl. Kommerskollegium*: 1–342
- Geijer, P. 1936. Norbergs berggrund och malmfyndigheter (English summary): *Geology and ore deposits of Norberg – Sver. Geol. Unders. Ser. Ca* 24: 1–162
- Geijer, P. 1967. The Precambrian quartzite in the Norberg district, Central Sweden, and its iron-sand beds – *Sver. Geol. Unders. Ser. C* 619: 1–36
- Geijer, P. & Magnusson, N.H. 1944. De mellansvenska malmernas geologi – *Sver. Geol. Unders. Ser. Ca* 35: 1–655
- Helmers, H. 1984. Stages of granite intrusions and regional metamorphism in the Proterozoic rocks of western Bergslagen, C. Sweden, as exemplified in the Grängen area – *N. Jahrb. Mineral.* 150: 307–324
- Hildreth, W. 1979. The Bishoff tuff: evidence for the origin of compositional zonation in magma chambers – *Geol. Soc. Am. Spec. Pap.* 180: 43–75
- Hildreth, W. 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism – *J. Geophys. Res.* 86: 10153–10192
- Hjelmqvist, S. 1966. Beskrivning till Berggrundskarta över Kopparbergs län. (English summary) – *Sver. Geol. Unders. Ser. Ca* 40: 1–217
- Hughes, C.J. 1982. *Igneous Petrology, Developments in Petrology 7 – Elsevier (Amsterdam-Oxford-New York)*: 551 pp
- Huhma, H. 1986. Sm–Nd, U–Pb and Pb–Pb isotope evidence for the origin of the early Proterozoic Svecokarelian crust in Finland – *Geol. Surv. Finland. Bull.* 337: 1–48
- Kresten, P. 1986. Geochemistry and tectonic setting of metavolcanics and granitoids from the Falun area, south central Sweden – *Geol. Förh.* 107: 275–285
- Kulling, O. & Hjelmqvist, S. 1948. Beskrivning till kartbladet Falun – *Sver. Geol. Unders. Ser. Aa* 189: 1–185
- Kähkönen, Y. 1987. Geochemistry and tectonomagmatic affinities of the metavolcanic rocks of the early Proterozoic Tampere Schist belt, southern Finland – *Precamb. Res.* 35: 295–313
- Lagerblad, B. & Gorbatshev, R. 1985. Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic Shield – *Geol. Rundsch.* 74, 1: 33–49
- Lundström, I. 1983. Description to the map of solid rocks, Lindsberg SW. (Swedish with English summary) – *Sver. Geol. Unders. Ser. Af* 126: 1–140
- Lundström, I. 1985. Description to the map of solid rocks, Lindsberg NW. (Swedish with English summary) – *Sver. Geol. Unders. Ser. Af* 140: 1–128
- Lundström, I. 1987. Lateral variations in the supracrustal geology within the Swedish part of the southern Svecokarelian volcanic belt – *Precamb. Res.* 35: 353–366
- Lundqvist, Th. 1979. The Precambrian of Sweden – *Sver. Geol. Unders. Ser. C* 768: 1–87
- Magnusson, N.H. & Lundqvist, G. 1933. Beskrivning till kartbladet Grängesberg – *Sver. Geol. Unders. Ser. Aa* 177: 1–133
- Magnusson, N.H. 1938. Neue Untersuchungen innerhalb des Grängesbergfeldes. Mit eine Karte – *Sver. Geol. Unders. Ser. C* 418: 1–44

- Nurmi, P.A. & Haapala, I. 1986. The Proterozoic granitoids of Finland: Granite types, metallogeny and relation to crustal evolution – *Bull. Geol. Soc. Finland* 58, 1: 203–233
- Nyström, J.O. 1982. PostSvecokarelian Andinotype evolution in central Sweden – *Geol. Rundsch.* 71: 141–157
- 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
- Oen, I.S. & Wiklander, U. 1982. Isotopic age determinations in Bergslagen, Sweden III. The Hyttsjö suite of gabbro-diorites and tonalites-granites, Filipstad area – *Geol. Mijnbouw* 61: 309–312
- Patchett, J. & Kouvo, O. 1986. Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes and U-Zr ages in the Svecokarelian terrain of South Finland – *Contrib. Mineral. Petrol.* 92: 1–12
- Patchett, J., Gorbatshev, R. & Todt, W. 1987. Origin of continental crust of 1.9–1.7 Ga age: Nd isotope in the Svecokarelian orogenic terrain of Sweden – *Precamb. Res.* 35: 145–161
- Pearce, J.A., Harris, N.B.W. & Tindle, A.G. 1984. Trace element discrimination for the tectonic interpretation of granitic rocks – *J. Petrology* 25: 956–983
- Smith, R.L. 1979. Ash-flow magmatism – *Geol. Soc. Am. Spec. Pap.* 180: 5–27
- Stephansson, O. 1975. Polydiapirism of granitic rocks in the Svecofennian of central Sweden – *Precamb. Res.* 2: 189–214
- Strömberg, A. 1983. Description to the map of solid rocks, Ludvika SO (Swedish with English summary) – *Sver. Geol. Unders. Ser. Af* 128: 1–100
- Stålhös, G. 1948. Svecokarelian folding and interfering macrostructures in eastern central Sweden – In: Kroner, A & Greiling, R. (eds.): *Precambrian Tectonics Illustrated* – Schweizerbartsche Verlagsbuchhandlung, (Stuttgart): 369–381
- Sundius, N. 1923. Grythyttfältets geology – *Sver. Geol. Unders. Ser. C* 312: 1–354
- Sundius, N. 1968. En kvartsporfyritformation av post-leptitålder i mellersta och södra Sverige – *Geol. För. Förh.* 90: 267–291
- Vivallo, W. 1984. The origin of the early Proterozoic supracrustal rocks in the Garpenberg district, south central Sweden – *Geol. För. Förh.* 106: 131–149
- Vivallo, W. & Richard, D. 1985. Early Proterozoic ensialic spreading-subsidence: evidence from the Garpenberg enclave, central Sweden – *Precamb. Res.* 26: 203–221
- Van der Velden, J.W., Baker, J.H., De Maesschalck, A.A. & Van Merten, Th.G. 1982. Bimodal volcanism in the Grythyttte field and associated volcano-plutonic complexes, Bergslagen, central Sweden – *Geol. Rundsch.* 71: 171–181
- Welin, E. 1987. The depositional environment of the Svecofennian supracrustal sequence in Finland and Sweden. – *Precamb. Res.* 35: 95–115
- Welin, E. & Stålhös, G. 1986. Maximum age of the synmetamorphic Svecokarelian fold phases in south central Sweden – *Geol. För. Förh.* 108: 31–34
- Whalen, J.B., Currie, K.L. & Chappel, B.W. 1987. Geochemical characteristics, discrimination and petrogenesis – *Contrib. Mineral. Petrol.* 95: 407–419
- Wilson, M.R. 1982. Magma types and the tectonic evolution of the Swedish Proterozoic – *Geol. Rundsch.* 71: 120–129
- Wilson, M.R., Hamilton, P.J., Fallick, A.E., Åftalion, M. & Michard, A. 1985. Granites and Early Proterozoic crustal evolution in Sweden: evidence from Sm-Nd, U-Pb and O isotope systematics – *Earth Planet. Sci. Lett.* 72: 376–388
- Wilson, M.R., Fallick, A.E., Hamilton, P.J. & Persson, L. 1986. Magma sources for some mid-Proterozoic granitoids in the SE Sweden: Geochemical and isotopic constraints – *Geol. För. Förh.* 108: 79–93
- Winchester, J.A. & Floyd, P.A. 1976. Geochemical magma type discrimination – *Earth Planet. Sci. Lett.* 28: 459–469