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Cover: The Exportfältet ore field at Grängesberg. Photo Christer Åkerman.

Preface

The current volume is the second to report on results from the work within the ore documentation programme at the Geological Survey of Sweden (SGU). The first volume reported on results from work performed during 1999 and 2000 (Economic geology research. Volume 1. 1999–2000. P. Weihed (ed.). Sveriges geologiska undersökning C 833, 136 pp.).

The aim is to publish various papers of interest to exploration and mining companies as well as the layman. Most papers result from compilation of data from published papers and from prospecting reports in the archives of SGU. In some cases additional field work and analysing of samples have been performed.

Uppsala, June 2003
Magnus Ripa

Contents

Styles of hydrothermal alteration and accompanying chemical changes in the Sången formation, Bergslagen, Sweden, and adjacent areas

Anders Hallberg

Abstract

The Bergslagen ore district in south-central Sweden is mainly hosted by a belt of Palaeoproterozoic metavolcanic and metasedimentary rocks. In western Bergslagen, the supracrustal rocks have been divided into three principal formations, representing different phases in the volcanic evolution of the area. The lowermost and oldest supracrustal formation, the Sången formation, consists of poorly sorted volcanic sandstones and represents an "intense volcanic stage" characterised by eruptions of enormous volumes of mainly rhyolitic volcanic rocks over large areas. Overlying formations, the Älgen and Torrvarpen formations, represent progressively calmer volcanic activity.

The Zr/TiO_2 ratios of rocks from the Sången formation and from mafic rocks and early orogenic granite intruding the Sången formation divide these rocks into two distinct groups, a mafic group with low ratios and a felsic group, including the metavolcanic rocks and the early orogenic granites, with high ratios. This bimodal distribution is in agreement with previous observations based on different methods (e.g. Allen et al. 1996). The Zr/TiO_2 ratios of the early orogenic intrusions in the area, some of which are suggested to be subvolcanic intrusions, overlap with the ratios for some of the volcanic rocks suggesting that they could be co-magmatic.

A large portion of the rocks in the Sången formation have been affected by one or more episodes of alteration. Using whole-rock geochemistry and a number of classification diagrams, it is possible to discern three principal types of regional alteration in the Sången formation and adjacent areas: Na alteration, K alteration, and Mg (mica) alteration. These types are in general agreement with previous studies in the region. Na alteration affected both early orogenic granites and felsic volcanic rocks. It mainly affects the alkali content, with minor effects on the other major elements. It is characterised by the replacement of K_2O by Na_2O. Na alteration was not restricted to the lower volcanic sequences, the Sången formation, but continued over formation boundaries into the overlying Älgen formation. Some of the Na-altered rock shows a tendency towards Mg alteration. The Na-altered rocks had probably reached equilibrium with the hydrothermal fluids, since identical alteration is found at several localities which represent large areas. It is suggested that high-salinity fluids occurring as groundwater under evaporite-forming sequences, combined with heat from the waning volcanism and channelled by fractures formed by the ongoing extension, provided the fundamental conditions for a long-lived environment in which rocks could be completely Na-altered.

K alteration proper is not found in the Sången formation, but is more common in the overlying Älgen formation.

A more intense form of alteration, probably regional in character, is the Mg alteration observed at several localities in the Sången formation. It is characterised by substantial depletion in alkali – almost all of the Na is leached from the rock and K is strongly depleted – and an addition of MgO to the rock. The feldspars have been destroyed and mica has been formed. Several samples from different localities show a similar style of Mg alteration indicating that the alteration has reached completion and that the Mg-altered rock was in equilibrium with the hydrothermal fluids.

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Introduction

This paper describes a lithogeochemical approach to hydrothermal alteration in western Bergslagen. The aim is to further the understanding of alteration in Bergslagen and to provide a tool to chemically describe and classify different styles of alteration. To this end, 35 rock samples were collected from outcropping metavolcanic rocks in the Sången formation (Lundström 1995), from rocks intruding the Sången formation, and from rocks overlying it. Additional chemical data from published and unpublished papers were recorded in databases and where possible the location from which each sample was taken was given co-ordinates in the Swedish National grid (RT 90).

The well-documented geology of the area (Lundström 1995, Allen et al. 1996 and references therein), with a large number of published works on the geology in general and altered rocks in particular and a large volume of published whole-rock geochemistry for less altered as well as altered rocks, makes the area highly suitable for a study of alteration geochemistry. The area has long been considered a type locality for Bergslagen volcanic-sedimentary stratigraphy (Sundius 1923, Allen et al. 1996).

Geology

Regional geology

The Bergslagen region in south central Sweden consists of a belt of Palaeoproterozoic volcanic and sedimentary rocks intruded by large early- to post-orogenic intrusions. The supracrustal rocks and older intrusions have been folded and faulted in several epochs, metamorphosed from greenschist to amphibolite grade, and affected by hydrothermal alteration (e.g. Lundström & Papunen 1986, Lundqvist 1979). In the western part of the region deformation and metamorphism were locally less intense than in other areas of Bergslagen and the supracrustal rocks are unusually well preserved. This fact has attracted scientists for more than a century.

The bedrock of the most closely studied areas of western Bergslagen has recently been published on 1:50 000 scale maps: 11E Filipstad SO and NO (Lundström 1995), 11F Lindesberg SV (Lundström 1983), 11F Lindesberg NV (Lundström 1985), and 11E Filipstad NV (Björk 1986). The geological map shown in Figure 1, is
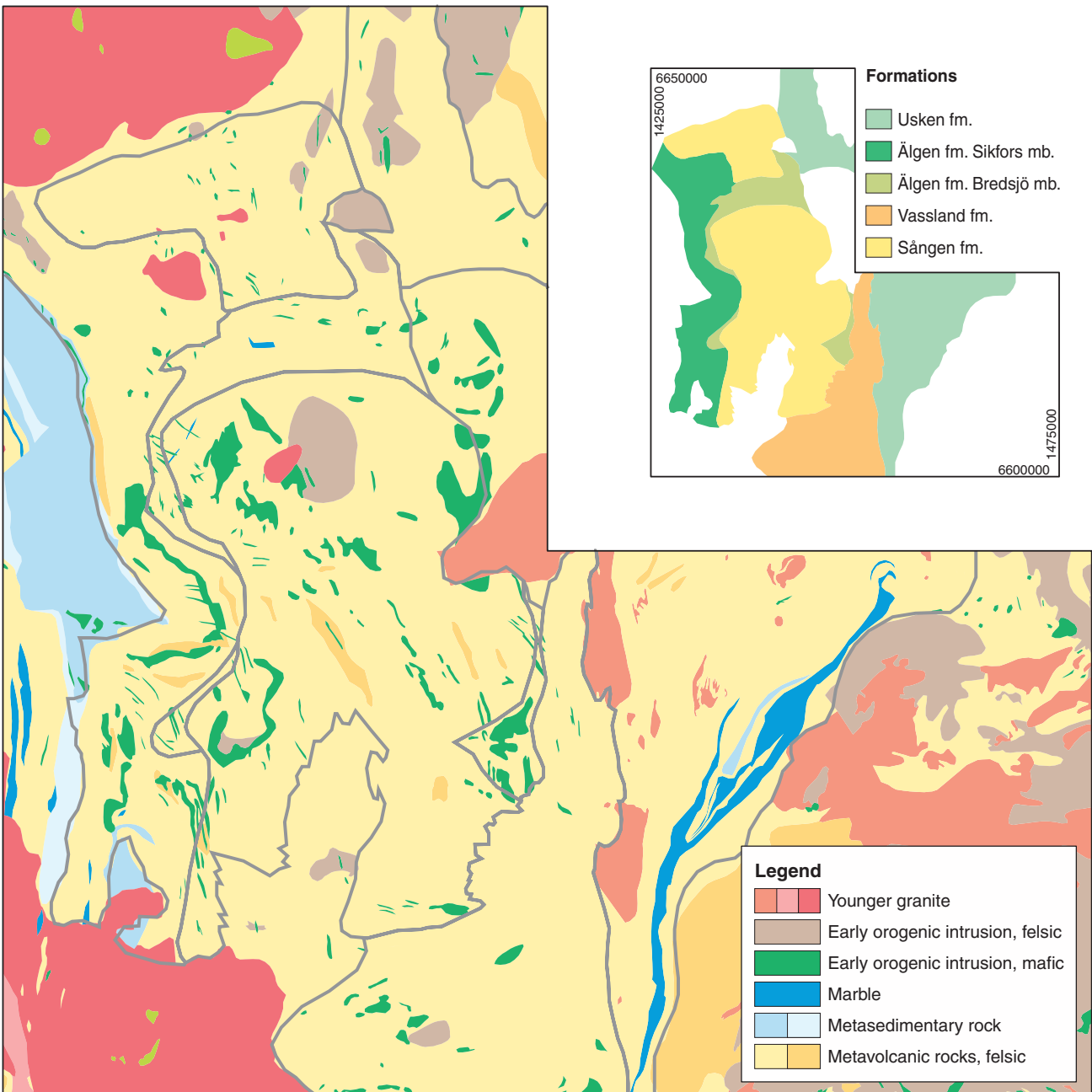

Fig. 1. Geological map of the central parts of western Bergslagen, compiled from Stephens et al. (in prep). Inset map and thick grey lines on the geological map show the extent of different formations (Lundström 1983, 1995). Coordinates given on inset map according to the Swedish grid system RT 90.

simplified from the digital version of the recently completed map of Bergslagen and surrounding areas.

Lundström (1995) subdivided the lithostratigraphy of the central parts of western Bergslagen into three local formations, each of which can be correlated to an older stratigraphical division of Bergslagen, e.g. Oen et al (1982) and Sundius (1923). The stratigraphically lowermost formation is the Sången formation, consisting of poorly sorted volcanic sandstones. This is overlain by the Älgen formation, which mainly consists of better-sorted volcanic siltstones, and the Torrvarpen formation dominated by sedimentary rocks.

It should be noted that this division into local formations in western Bergslagen does not fulfil the criteria of internationally agreed principles of stratigraphical classification as recommended by the IUGS (e.g. Hedberg 1976). Consequently, the words formation and member are written with lower-case letters in this text in order to avoid confusion with a strict stratigraphic classification. Nevertheless, these local formations, and the differences in volcanic environment that they are based on, can be correlated to adjacent, more strongly metamorphosed areas (Lundström 1983, 1985). Together with modern volcano-stratigraphical work in Bergslagen (Allen et al. 1996), in which the local formations in western Bergslagen have their counterparts in the "intense volcanic stage", the "waning volcanic stage", and the "sedimentary stage", respectively, the use of local formations provides an embryo of a unified supracrustal stratigraphy of Bergslagen.

Geology of the Sången formation and surrounding rocks

The lowermost and oldest supracrustal unit in western Bergslagen is the Sången formation which makes up the core of a north–north-west trending anticlinal structure (Fig. 1). Rocks of the Sången formation consist of poorly sorted volcanic metasandstones, locally quartz and feldspar porphyritic and lithic fragment-bearing. Bedding in the volcanic metasandstones is generally very diffuse or absent and intercalations of other rocks such as clastic sediments or limestones are rare.

The rocks of the Sången fm. correspond to the "intense volcanic stage" of Allen et al. (1996), a stage in the volcanic evolution of Bergslagen that is characterised by eruptions of enormous volumes of rhyolitic volcanic rocks over large areas. High-precision U-Pb dating of zircons from a well-defined rock unit at Ekebergshöjden in the Sången fm. gave an age of 1891±4 Ma (Lundström et al 1998). This age is consistent with previous datings, but is more precise. There is no known basement to the Sången formation, but several authors (e.g. Valbracht et al.

1994, Beunk et al. 1985, de Groot et al. 1988) argue for the existence of an older basement in order to explain the large amount of felsic volcanic rocks and the upper crustal signature indicated by the isotopic work. Tentative correlations with the Utö area in eastern Bergslagen, where older volcanic rocks rest on quartzitic greywackes, suggest that Palaeoproterozoic metasedimentary rocks could form a basement to the Sången formation. The Vassland formation, occuring south-east of the Sången formation, consists of rocks that are believed to be stratigraphically equal to the Sången formation, but at a higher metamorphic grade (Lundström 1983, 1995).

The Älgen formation, divided into a lower Bredsjö and an upper Sikfors member, overlies the Sången formation (Lundström 1995). Rocks of the Älgen formation show a more reworked character compared to the Sången fm. and in general the Sikfors member show more reworking than the Bredsjö member (Lundström 1995). The rocks of the Älgen formation represent the "waning volcanic stage" of Allen et al. (1996), a stage during which the products of the first stage of volcanism were reworked and re-deposited, although the volcanism continued at a lower intensity. Carbonates, calc-silicate rocks and mineral deposits are common in the Älgen formation (Lundström 1995).

The Torrvarpen formation is the uppermost and youngest formation in the area (Lundström 1995). Here the rocks are much more reworked and the rock has a clear sedimentary character. The Torrvarpen fm. represents the "sedimentary stage" in Allen et al (1996), a stage characterised by deep-water deposition of argillite-greywacke rocks.

Like the Sången formation, which has its more metamorphosed counterpart in the Vassland fm., the overlying formations have more metamorphosed equivalents in adjacent areas (e.g. Lundström 1983, 1985).

Alteration in Bergslagen

The large variation in the alkali content of felsic volcanic rocks in Bergslagen has been discussed for nearly a century (e.g. Sjögren et al. 1914). It was suggested early on that the anomalous composition of mica-rich volcanic rocks was a result of metasomatic processes and was not a primary feature of the rocks (Sundius 1923). The suggestion that the variation in alkali content was also due to metasomatic processes was put forward by Frietsch (1982) and it was shown that the metasomatism was due to hydrothermal alteration, with seawater as the dominant fluid (e.g. Baker & de Groot 1983, Lagerblad & Gorbatschev 1985). It was observed that some styles of alteration were more common at specific stratigraphic levels (Frietsch 1982), Na-altered volcanic rocks generally occurring below K-altered vol-

canic rocks. Using a thermodynamic approach, Jasinsky (1988) and de Groot (1990) discussed Na-K-Mg changes in altered rocks and attributed most of the variation in alteration to differences in alteration temperature. It has also been shown that both the early orogenic intrusions (Baker 1995a, 1995b) and mafic intrusions (Valbracht et al. 1991) were affected by hydrothermal alteration.

A most important observation discussed in recent years is the division of alteration in Bergslagen into regional-scale alteration and an overprinting local and locally ore-related alteration (Baker et al. 1988a and references therein). Ripa (1994) stressed the importance of distinguishing local from subregional and regional alteration when exploring for ore. De Groot and Baker (1992) divided alteration in western Bergslagen into regional alteration, of a widespread, low-temperature style, and local, intense alteration that strongly affected the rocks. Trägårdh (1991) also applied a clear distinction between regional and local alteration in the Riddarhyttan area.

The lithogeochemical database

The analyses carried out in this study were performed on samples collected by the author in the autumn of 2001. Sample locations were determined by GPS. Generally,

about one kilogram of sample was collected. The samples were analysed at XRAL (Canada) using XRF, ICP, and INAA on crushed and milled powder. Brief descriptions of the samples analysed in this study are found in Appendix 1. The results of the chemical analyses are found in Appendix 2.

During the work on this project it was realised that a large number of whole-rock analyses from western Bergslagen are available in the literature. Thus a large part of this project has been devoted to digitising published lithogeochemical analyses. The locations of the analysed samples were obtained from reported coordinates in publications, from figures in the publications showing sampling sites, or from maps in the archives of SGU's Mineral Resources Information Office in Malå. In each case the quality with respect to sample location and analytical quality was estimated. The latter includes method used, year of analysis and elements analysed. The quality classifications of the digitised data are shown in Table 1.

In all, 573 lithogeochemical data items, including the 35 analyses produced in this study, were digitised and stored in the SGU lithogeochemical database. Sample numbers and coordinates for the digitised data from the literature are found in Appendix 3. The locations of the different data sets are shown in Figure 2.

Table 1. Data sets analysed or digitised in this study with area of investigation, number of samples, analytical methods, quality estimation with respect to position of sample (Qpos) and estimated quality of analysis (Qchem), and references. Higher quality numbers (Q) represent a more precise location or a higher quality of analysis.

| Locality/area	No. sampl.	Methods	Qpos	Qchem	Reference	Comments
Sången Fm. & surroundings	35	XRF, ICP, NA	5	5	Hallberg, this paper	
Ekebergshöjden	1	-	5	5	Lundström et al 1998	
Western Bergslagen	36		4	4	SGU_db	
Persberg	13	XRF, NA	3	4	Outhius and van Berkel 1988	no LOI
Hjulsjö intrusions	22		2	4	Baker 1985a	no LOI
Hjulsjö	1	XRF, NA	2	4	Baker and de Groot 1983	no LOI
Old intrusion, Bastfallshöjden	6	XRF, NA	1	4	Baker 1985b	no LOI
Älgen Fm., Sjögruvan	23	ICP	1	4	Holtstam and Mansfeld 2001	no co-ordinates
Stollberg	28	-	1	4	Ripa 1996	no LOI
Mafics, Bergslagen	24	XRF, NA	1	4	Valbracht et al. 1991	no LOI, poor co-ordinates
Young granite, Gråshöjden, västra	3		-	4	Baker et al. 1987	no LOI
Mafics, Bergslagen	26	XRF, NA	-	4	Valbracht et al. 1991	no LOI, no co-ordinates
Sången Fm., Annehill	20	XRF, NA, ICP	3	3	Baker et al. 1988	no LOI, P_2O_5
Sången Fm., Hjulsjö	6	XRF, NA	3	3	deGroot and Baker 1992	no LOI, few traces
Sången Fm., Dunderbo	5	XRF, NA	3	3	deGroot 1993	no LOI, few traces
Sör Älgen area	80	XRF, NA	2	3	van Meerten 1982	no LOI, few traces
Riddarhyttan	7	-	1	3	Trägårdh 1988	no P_2O_5, few traces
Sången Fm., Ställbergstorp	10	XRF, NA	1	3	Valbracht and Helmers 1988	no LOI, few traces
Älvshyttan	83	ICP	4	2	Hellingwerf 1987	no SiO_2, LOI
Vassland Fm.	12	-	4	2	Lundström 1983	no traces
Sången, Älgen etc.	94	-	4	2	Lundström 1995	no traces
Älvshyttan	49	ICP	4	2	Sandahl 1988	no SiO_2, LOI
Stollberg, average elements	8	XRF	1	2	Ripa 1988	only XRF, no trace
Stollberg	9	-	1	2	Ripa 1994	no LOI, no traces
Young granite, Skålhöjden	7		-	2	Sundblad et al. 1993	no LOI, very few traces
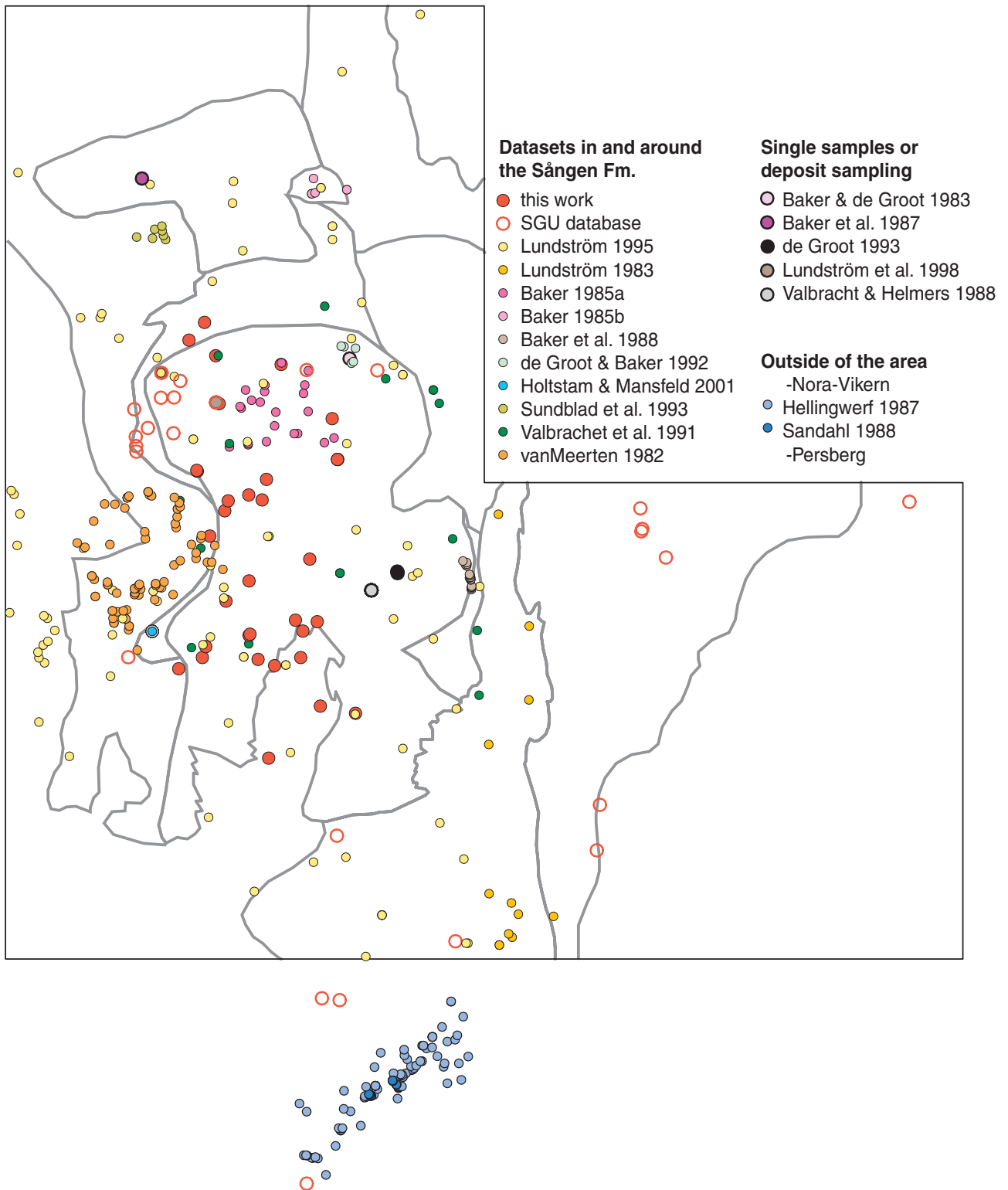
Fig. 2. Map showing sample locations for the chemical data produced in this study (red dots) and sample locations for other data from the literature. Not shown on the map are the sample locations for data from the Persberg area (Outhius & Berkel 1988). The map covers the same area as the geological map in Figure 1.

Results and discussion

The felsic group includes data from felsic metavolcanic rocks in the Sången fm., Vassland fm., and Älgen fm. and from the early orogenic granites. The mafic group is made up entirely of data from mafic intrusions.

Lithogeochemical rock classification

A very simple way of classifying rocks using less mobile elements is to plot the TiO_2 contents of the rocks against their Zr contents in a diagram. Figure 3a shows the distribution of the TiO_2 and Zr contents of felsic volcanic rocks of the Sången fm. and of mafic rocks and early orogenic granites intruding the Sången fm. The data set includes both less altered and strongly altered samples. The population is subdivided into two distinct groups, one scattered at high Zr/TiO_2 ratios and another at low Zr/TiO_2. The bimodal character of the data is further illustrated in Figure 5, where the numbers of samples plotting in the different rock-type fields of Figure 3a have been added together and plotted in a bar chart. This diagram is almost identical to the diagrams showing the relative abundance of rock types in Bergslagen, based on interpretation and point counting of 1:50 000 scale geological maps (Allen et al. 1996).

The data plotted in Figure 3a have been subdivided into different rock types using the Zr/TiO_2 ratios in accordance with Winchester and Floyd (1977) to characterise magmatic differentiation, and the methods suggested by Hallberg (1984). The majority of samples of metavolcanic rocks from the Sången formation and all samples of early orogenic granites plot within the rhyolite field. Most of the other samples, mainly intrusive mafic rocks, plot within the basalt or basaltic andesite fields.

The low TiO_2 part of the diagram in Figure 3a, i.e. the rhyolite field, is shown in Figure 3b. The Zr/TiO_2 ratios of the early orogenic granites from Hjulsjö (Baker 1985a) and from Bastfallshöjden (Baker 1985b) overlap and show a small spread of 0.078–0.109. The data set contains both less altered and completely Na-altered samples, but the alteration did not affect the Zr/TiO_2 ratio. Some, but not all, of the felsic volcanic rocks from the Sången formation have Zr/TiO_2 ratios within the range of the granites, indicating that they may be co-magmatic with them. The locations of these samples, together with the locations of other felsic rock samples from the Sången formation with Zr/TiO_2 ratios that fall outside those of the granites, are plotted on the map in Figure 4. Interestingly, the samples with a Zr/TiO_2 ratio similar to those of the early orogenic granites occur at some distance from the intrusions. Closest are two samples from Ekebergshöjden, about 1.5 km
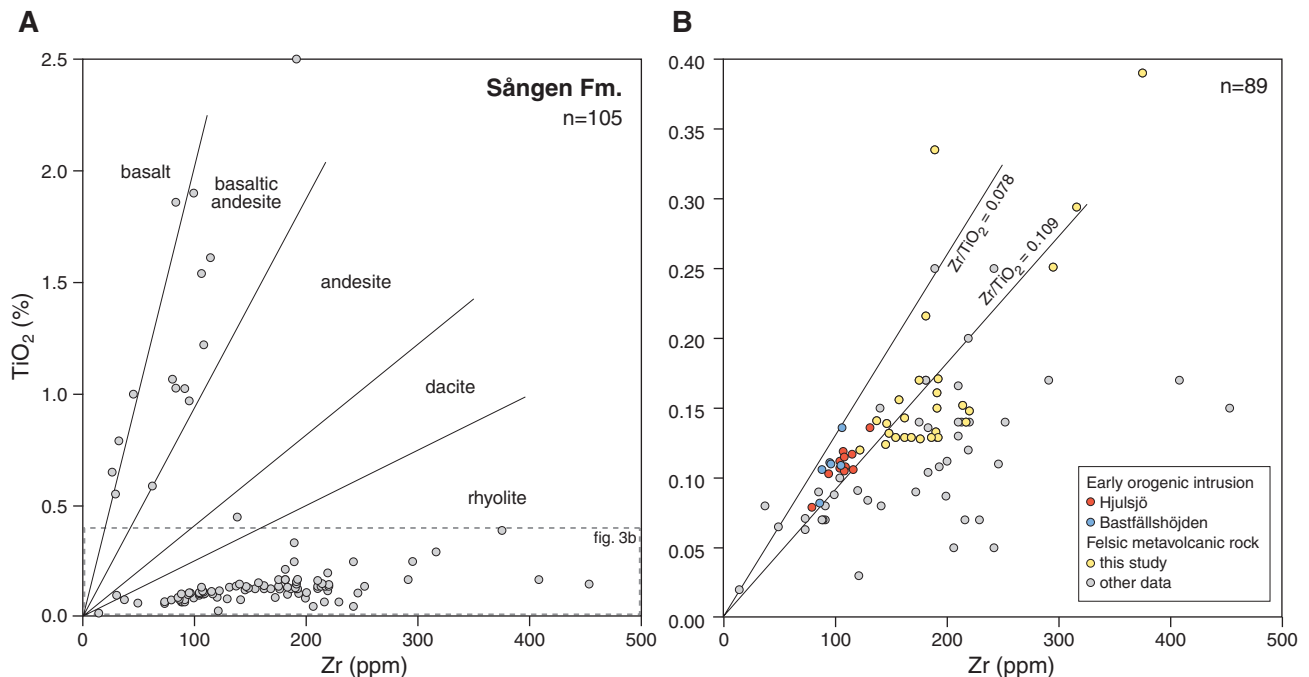
Fig. 3. A) TiO_2 vs. Zr diagram showing all samples from the Sången formation, early orogenic granites and mafic rocks intruding the Sången formation. Lines dividing different rock types are derived from Hallberg (1984) and Winchester & Floyd (1977). **B)** Section of the TiO_2 vs. Zr diagram in Figure 3A showing the samples that plot in the rhyolite field. The two lines (at $Zr/TiO_2 = 0.078$ and 0.109, respectively) show the range of Zr/TiO_2 ratios for the early orogenic granites of the area.
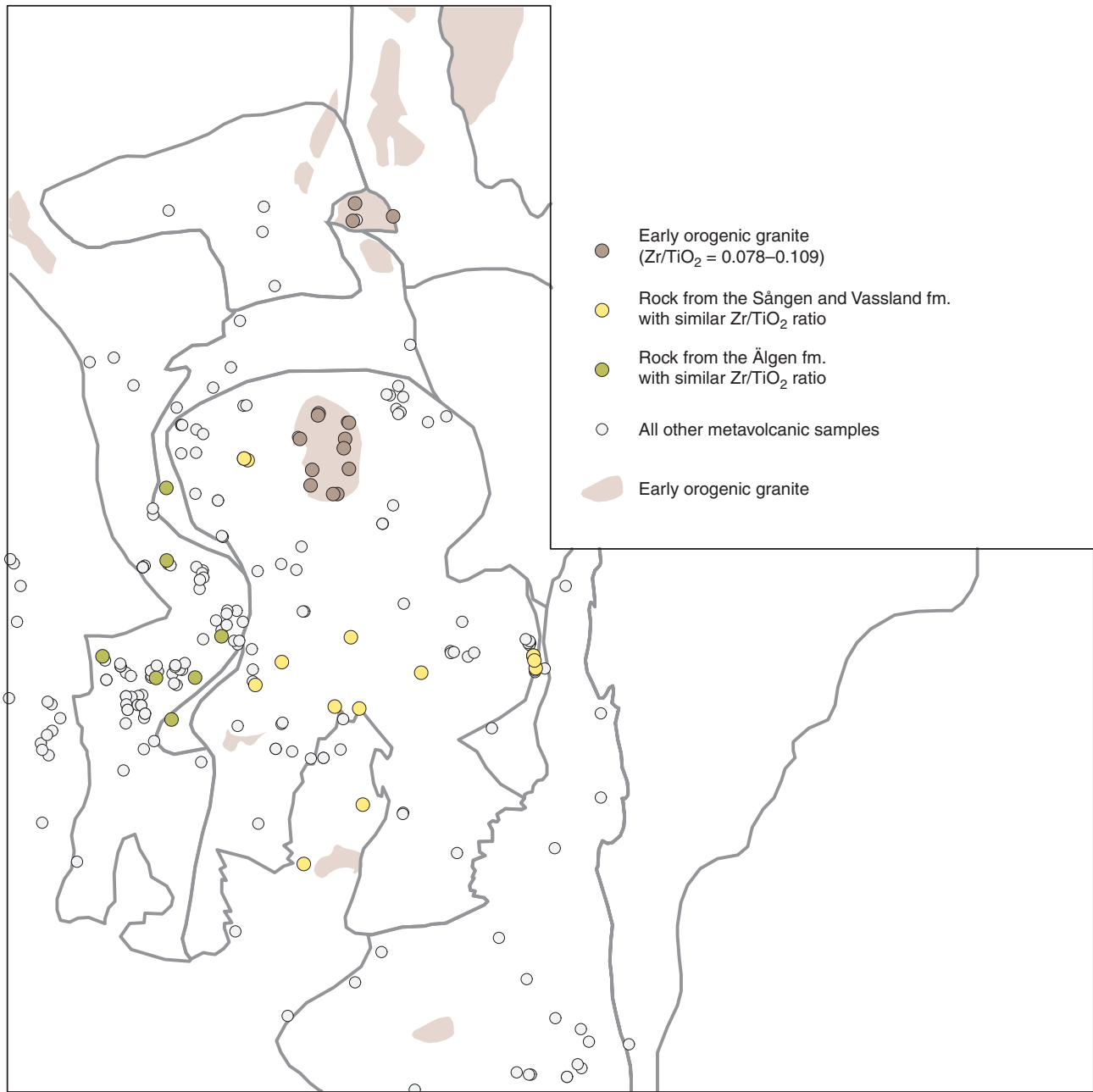
Fig. 4. Locations of the samples of felsic metavolcanic rock that have a Zr/TiO$_2$ ratio similar to those of the early orogenic granites. The map covers the same area as the geological map in Figure 1.

west of the Hjulsjö intrusion. Other samples were taken more than 5 km to the south of the Hjulsjö intrusion. Samples with a different Zr/TiO$_2$ ratio from the granites generally have higher ratios and should be considered more felsic than the granites. It must be stressed, though, that an investigation of co-magmatism of volcanic rocks requires high analytical quality and good control of sampling and sampling procedures. Naturally this cannot be achieved in this study, since a large proportion of the data comes from publications based on unknown sampling procedures and analytical methods. Nevertheless, it seems,

from the data produced in this study, that lithogeochemistry can be used to investigate co-magmatism.

The chemistry of alteration – the approach used

Any rock will alter its mineralogical and sometimes also its chemical composition if its environment is changed in such a way that the rock is no longer in equilibrium with its environment.

Changes in temperature or pressure cause metamorphic

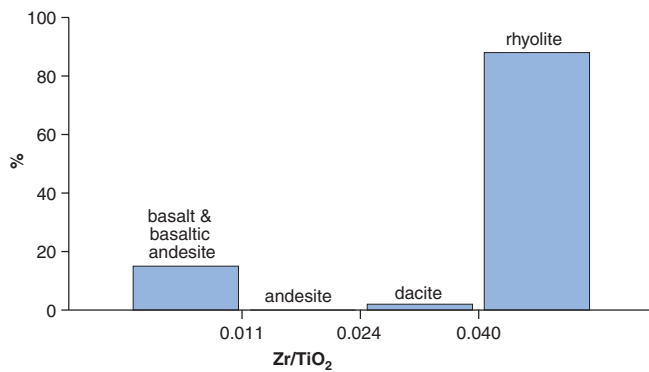**Fig. 5**. Bar chart showing the relative abundance of rock types in the area (Sången formation, early orogenic granites and mafic rocks intruding the Sången formation), based on the division shown in Figure 3.

alteration of the rock, with the formation of new minerals that are in equilibrium under the new conditions. Changes in the chemistry of the environment, commonly caused by the entry of an external fluid out of equilibrium with the rock, may cause large changes in both the chemistry and the mineralogy of the rock, especially if the environmental changes are combined with an increase in temperature. The ultimate result of the alteration process will be a rock that has adapted to the new situation and is in equilibrium with the new environment.

Water is the commonest and best solvent in nature. When water flows through a rock, through fractures and cracks and along mineral boundaries, it changes the environment of the rock and has the capacity to transport different elements in and out of the system. Hydrothermal alteration is therefore one of the most effective ways of changing a rock's chemical and mineralogical composition. Hydrothermal alteration, in the broad sense, takes place in many settings, from weathering of outcropping rocks in all climates to hydrothermal alteration at depth in volcanic terrains. Due to the sluggish nature of geological processes and the rapid changes in the physical and chemical properties of the hydrothermal fluids, the rocks will in many cases approach, but not reach, equilibrium with the new environment. In such cases different intermediate reaction products, resulting in a rock that is partly altered, will be the result. Since hydrothermal alteration causes changes in the chemical composition of a rock and the resulting chemistry is the product of the conditions prevailing during alteration, the chemistry of an altered rock can be used to identify, classify and characterise alteration. The following is an attempt to characterise some important styles of alteration in the Sången formation and in early orogenic granites intruding the Sången formation.

Large volumes of rocks in the Sången formation, and of the early orogenic granites that intrude the formation,

have been affected by hydrothermal alteration (Lundström 1995). Areas affected by the long recognised Na-K alteration (Frietsch 1982, Baker et al. 1988b) constitute large parts of the Sången fm. (Lundström 1995), but Mg-(chlorite) alteration, too, has been mapped over large areas (Lundström 1995) and must be considered to be regional in extent. These styles of alteration, considered here to represent regional styles of alteration, caused an increase in the K_2O, Na_2O or MgO content of the rocks, compared with the less altered precursor, and a decrease in other major elements. These alterations can thus be simplified as a three-component system and graphically illustrated in a ternary MgO-Na_2O-K_2O diagram. Although a few of the Mg-altered samples show an increase in the Fe_2O_3 content, this type of alteration should not be confused with the Fe-Mg alteration recorded near iron ores (e.g. Holtstam & Mansfeld 2001) or the skarn deposits discussed below. The igneous spectrum of Hughes (1973), although restricted to variations in the Na_2O-K_2O content of the rock, is useful to detect alkali alteration, but may also indicate breakdown of alkali feldspar. Altered rocks affected only by alkali replacement will plot along the same "equivalent alkali-feldspar content" line in the diagram as their less altered precursor, while deviation from the line indicates that other processes than simple alkali replacement have taken place. To complete the interpretation of the chemical data and to obtain qualitative and quantitative data on the element changes occurring during alteration, mass change calculations of sets of data were performed according to the method of MacLean (1990). The results of the mass change calculations are illustrated in mass change bar charts showing the percentage mass change caused by alteration of 100 g of unaltered rock. For each style of alteration identified, an attempts was made to look back at published documentation of the petrology and mineralogy of the alteration. In the calculations it is assumed that the rocks make up a single precursor system, that is, the precursor to all altered felsic volcanic rocks had an identical chemical composition. This is probably not entirely correct, but it is assumed that the chemical variation among the rhyolitic precursors was small and that it does not significantly affect the calculations.

More localised styles of alteration in the Sången fm. include alteration around intruding mafic rocks (Lundström 1995) and skarn-style alteration in and around skarn iron ores (Baker et al 1988a, Valbracht & Helmers 1988, De Groot 1993). At these localities the CaO and Fe_2O_3 contents were also drastically increased during alteration and mineralisation. Elsewhere in Bergslagen there are several well-documented alteration systems related to sulphide and iron ores, e.g. at Riddarhyttan (Trägårdh 1988, 1991) and at Stollberg (Ripa 1988, 1996), which show signifi-

cant changes in the CaO and Fe_2O_3 contents of the altered rocks. These styles of alteration cannot, for obvious reasons, be described as variation in the MgO-Na_2O-K_2O system and will therefore be discussed separately.

It seems that the regional MgO-K_2O-Na_2O alterations discussed below are not directly related to mineralisations, whereas those local alteration systems which also involve changes in Fe_2O_3 and CaO are contemporary with and directly related to mineralising events.

Alteration of the early orogenic granites

The early orogenic granites intruding into the Sången formation and surrounding rocks occur as subvolcanic high level intrusions and as deeper intrusions (Lundström 1995). Pervasive Na alteration of parts of the granites has produced a rock in which all K-feldspars and plagioclase, in phenocrysts as well as in matrix, have been altered to albite (Lundström 1995, Baker 1988a, b). The alteration has bleached the original pale red colour of the least altered granite into a more whitish colour, making the affected rocks easy to recognise in the field. The primary magmatic textures of the rocks are, however, preserved.

The eastern and western parts of the Hjulsjö intrusion (Fig. 2) are completely altered, while the northern, central, and southern parts are unaffected by alteration (Baker 1985a). In the Bastfallshöjden granite (Fig. 2), the alteration appears as up to 20 metre wide and north-west trending zones in the central part of the granite (Baker 1985b). The shallow Sundsjö intrusion is completely Na-altered (Lundström 1995). At some localities later Mg-chlorite (sheridanite) veins (Baker 1985a) cut the Na-altered rock. A more detailed description of the petrology and mineralogy of the Na alteration is given by Baker (1985a) for the Hjulsjö intrusion and by Baker (1985b) for the Bastfallshöjden granite.

Chemically, the Na alteration of the early orogenic granites has produced altered rocks with a similar composition. The K_2O content of early orogenic granite is reduced from 4–5% to less than 0.5%, while the Na_2O content increases from 3–4% to more than 6%. In the igneous spectrum of Hughes (1973), shown in Figure 6a, the least altered samples form a well-defined cluster within the igneous spectrum, while altered samples plot to the left of the igneous spectrum, in the field for Na-altered samples. A point to be noted is that most of the samples, least altered as well as Na-altered, plot along the same "equivalent alkali feldspar" line at around 50–60%, suggesting that the alkali feldspar content remained constant during alteration.

In the ternary MgO-Na_2O-K_2O diagram, Figure 6b, Na alteration forms a trend from the least altered samples, which plot on the base of the diagram roughly halfway between the Na_2O and K_2O corners, towards the Na_2O corner of the diagram. There is also a weak trend from the Na_2O corner towards the MgO corner of the diagram, indicating that a weak Mg alteration has affected the rocks. The Mg-chlorite veins developed in some samples of altered granite from the Hjulsjö granite (Baker (19885 a) are most likely the petrological expression of this weak Mg alteration.

The mass change diagram (Fig. 6c) illustrates the almost complete replacement of K_2O by Na_2O. The weak trend towards a higher MgO content due to the Mg alteration is seen as a slight net addition of MgO to the rock. The diagram also indicates a small increase in the SiO_2 content of altered rocks. This increase, however, is due to a residual enrichment of SiO_2 when the heavy K ion is replaced by the lighter Na ion. The locations of altered and least altered samples are shown in Figure 7.

Since all least altered granite samples from different localities have a very uniform composition and clearly plot within the igneous spectrum, it is suggested that these rocks have been affected by a minimum of alteration and that their composition approaches that of an unaltered granite in the area.

The Na alteration affected large volumes, as in the Hjulsjö granite case, and the chemistry of the alteration is within analytical errors and is found at several localities. This suggests that the alteration process forming Na-altered granites continued to completion and that the rocks reached equilibrium with the hydrothermal fluids. Thus Na alteration of the early orogenic granites can be regarded as one distinct type of alteration.

Alteration of the felsic metavolcanic rocks in the Sången formation

Compared with the early orogenic granite discussed above, the felsic metavolcanic rocks of the Sången fm. show a much more complex alteration history, an alteration that changed the chemistry of the rocks much more drastically than in the case of the granite. Most likely the felsic metavolcanic rocks, due to their higher porosity, more reactive components, and surface setting, were more exposed to hydrothermal fluids than the more or less contemporary granites.

Least altered felsic volcanic rocks

An initial task for any comparative lithogeochemical work is to identify the composition of the least altered rocks, in this case the least altered rocks in the Sången formation. To this end all data for felsic metavolcanic rocks from
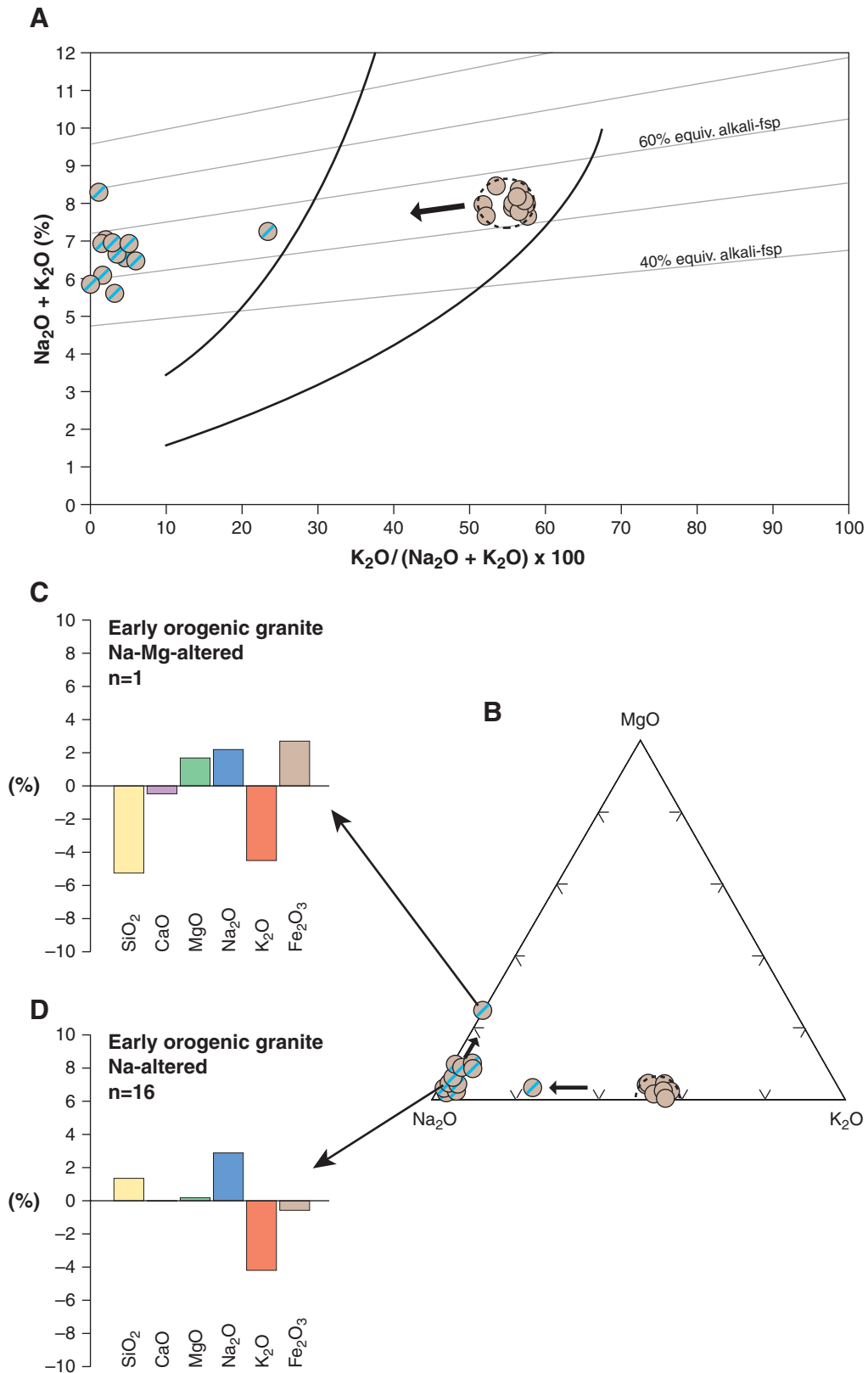
Fig. 6. A) Samples of least altered and Na-altered early orogenic granites plotted in the igneous spectrum of Hughes (1973). Black arrow shows trend of alteration. **B)** Same data as in Figure 6a plotted in the ternary MgO-Na$_2$O-K$_2$O diagram. **C)** Bar chart showing the result of mass change calculations for the most Mg-rich of the altered early orogenic granites, compared with the least altered granite. **D)** Bar chart showing the result of mass change calculations for Na-altered early orogenic granites, compared with the least altered granite The Al$_2$O$_3$ content of the samples has been used as monitor in both bar charts. Data from Lundström (1995), Baker (1985a, 1985b), and the present study
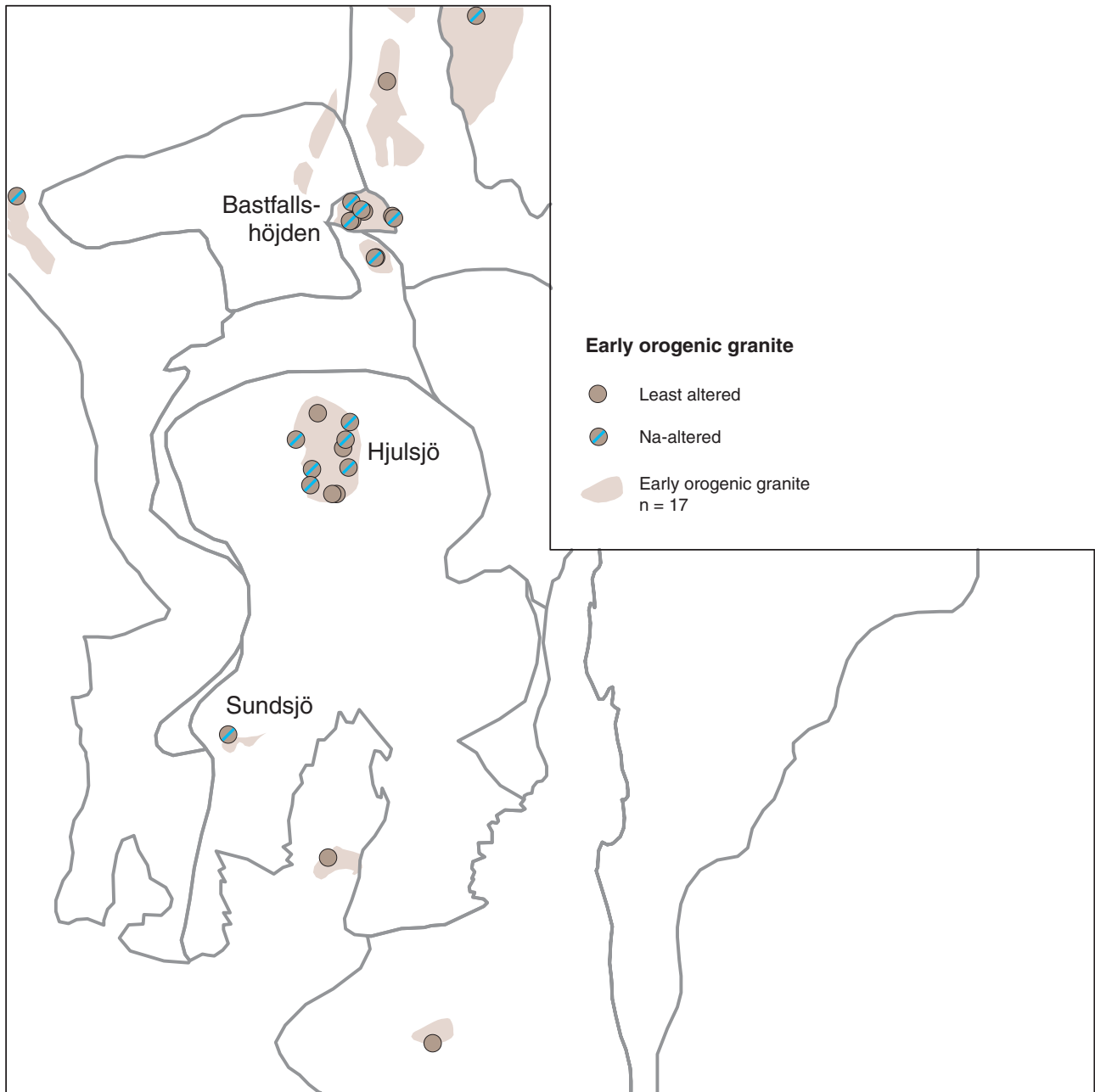
Fig. 7. Locations of least altered and Na-altered early orogenic granites. The map covers the same area as the geological map in Figure 1. Data sources as for Figure 6.

Fig. 8. **A)** Weakly altered felsic metavolcanic rocks from the Sången formation. Light blue, dark blue and green dots represents somewhat altered samples that plot within the igneous spectrum (Hughes 1973). The encircled areas show the positions of least altered granite (smaller circle) and least altered felsic metavolcanic rock from the Sången formation (larger circle). Black circles indicate composition of the least altered felsic metavolcanic rock from Bergslagen, according to Baker & de Groot (1983). Black arrows show trends of alteration. **B)** Same data as in Figure 8A plotted in the ternary $MgO-Na_2O-K_2O$ diagram. **C)** Bar chart showing the results of mass change calculations for weakly Na-altered samples of felsic metavolcanic rocks compared with the least altered metavolcanic rock in the Sången formation. See text for explanation. **D)** Bar chart showing the results of mass change calculations for weakly Mg-Fe-altered samples of felsic metavolcanic rocks compared with the least altered metavolcanic rock in the Sången formation. See text for explanation. The Al_2O_3 content of the samples has been used as monitor.

A

60% equiv. alkali-fsp

40% equiv. alkali-fsp

Na₂O + K₂O (%)

K₂O/(Na₂O + K₂O) x 100

C

Felsic metavolcanic rock weak Na alteration n=5

(%)

SiO₂ CaO MgO Na₂O K₂O Fe₂O₃

D

Felsic metavolcanic rock weak Mg-Fe alteration n=3

(%)

SiO₂ CaO MgO Na₂O K₂O Fe₂O₃

B

MgO

Na₂O

K₂O

least altered early orogenic granite

least altered felsic volcanic rock
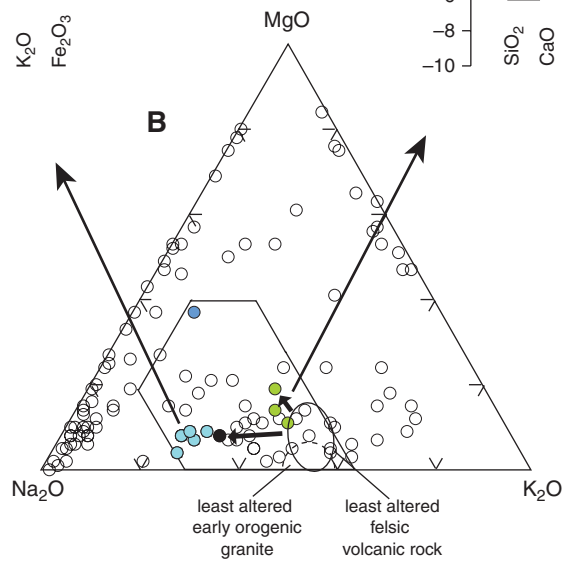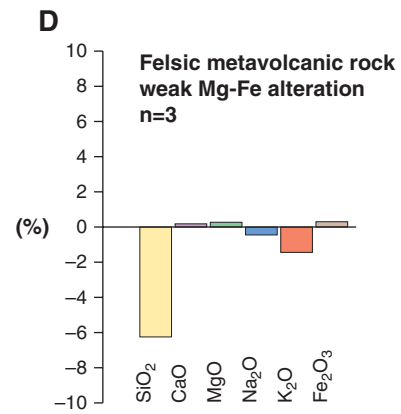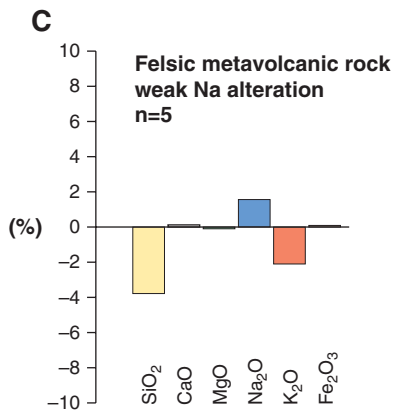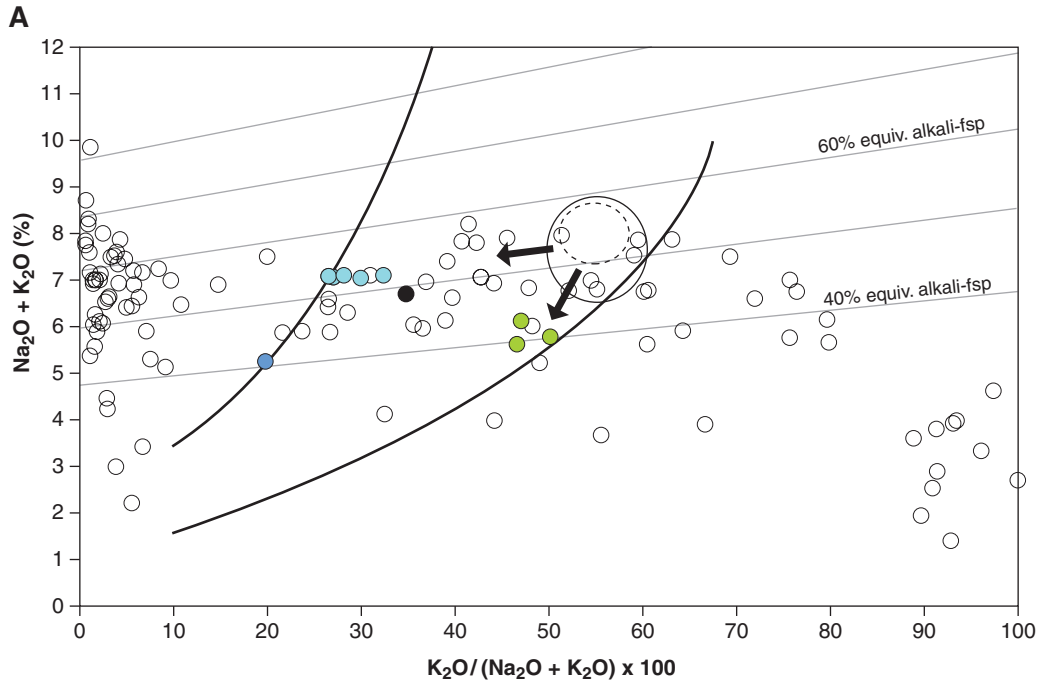
the Sången formation have been plotted in the igneous spectrum (Hughes 1973), as shown in Figure 8 a. About one third of the samples plot within the igneous spectrum and at a reasonable "equivalent alkali feldspar" of between 40 and 60%. However, the compositional variation in this group seems to be too large and probably does not represent the primary unaltered composition of the newly erupted felsic volcanic rocks in the Sången fm.

Some of the early orogenic granites that intrude the felsic volcanic rocks in the Sången formation are considered to be subvolcanic intrusions (Lundström 1995), and it was shown above, using the Zr/TiO_2 ratios of the rocks, that some felsic volcanic rocks may be co-magmatic with the granites. It was also stated that the composition of the least altered granites approaches that of unaltered granite in the area.

It is tentatively proposed that the least altered metavolcanic rock of the Sången formation should have a whole-rock geochemistry similar to the least altered early orogenic granite. Three samples in this study (SAN 20, SAN 21, and SAN 24, Appendix 1) fulfil these requirements. They show Zr/TiO_2 ratios similar to those of the early orogenic granites, they plot close to the least altered granites in both the igneous spectrum (Hughes 1973) shown in Figure 8 a and the ternary MgO-Na_2O-K_2O diagram (Fig. 8 b), and they are similar in major, minor, and trace element chemistry. The similarities with the least altered early orogenic granites suggest that these felsic metavolcanic samples may represent the least altered felsic volcanic rocks in the Sången formation. Samples B 87:17, T 87:12, and L 89:40 from Lundström (1995) also plot close to the least altered samples, but since Zr analyses are not available co-magmatism with the granites cannot be investigated. The average composition of the six samples is consequently used as the composition of the least altered felsic metavolcanic rock of the Sången formation.

The other samples that plot within the igneous spectrum in Figure 8 a (Hughes 1973), but away from the least altered felsic metavolcanic samples, are considered to be weakly altered. Among these weakly altered samples there is a trend towards lower total alkali, with "equivalent alkali feldspar" down to 40%. The ternary MgO-Na_2O-K_2O diagram in Figure 5 shows that, in comparison with the least altered granite samples and the least altered felsic volcanic samples, these samples are somewhat enriched in

MgO. The mass change diagram in Figure 8 c shows that the weak enrichment in MgO is coupled to a small addition of Fe_2O_3 and CaO and a net removal of K_2O and some Na_2O. Most likely this is the chemical manifestation of the weak chloritization reported for some of the felsic volcanic rocks (Lundström 1995).
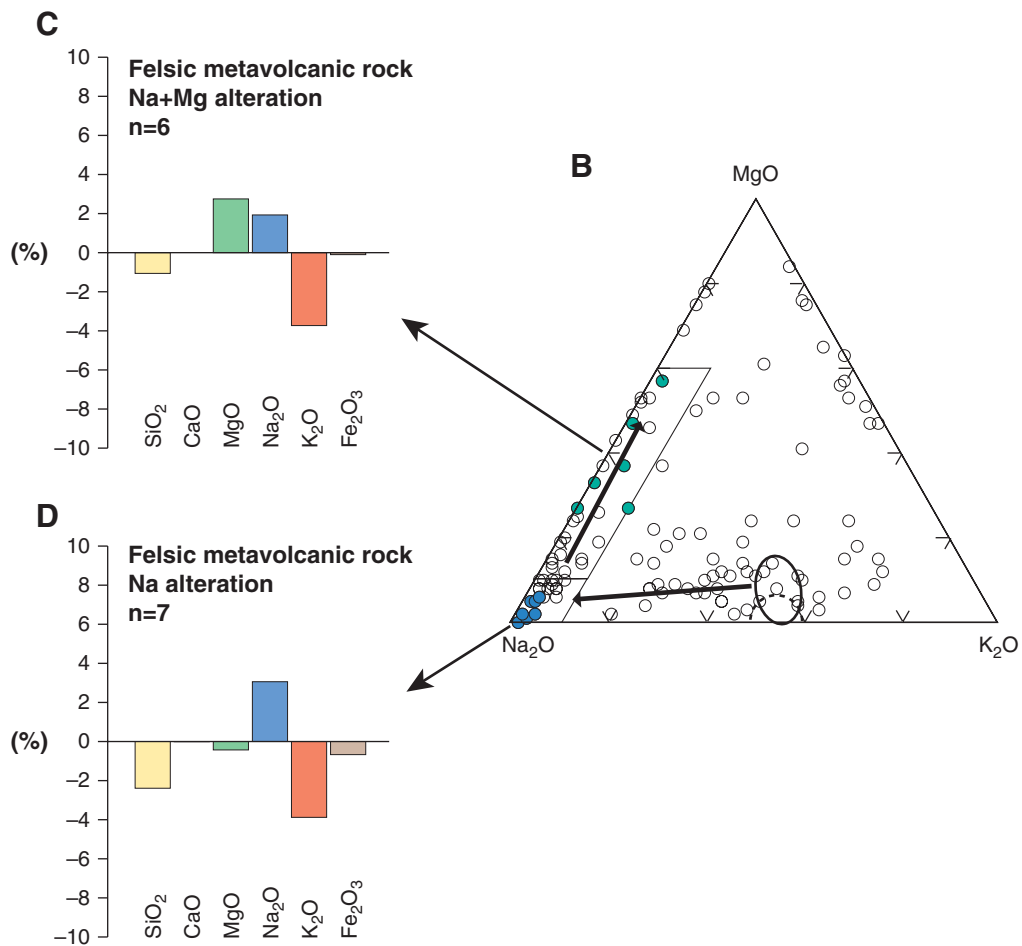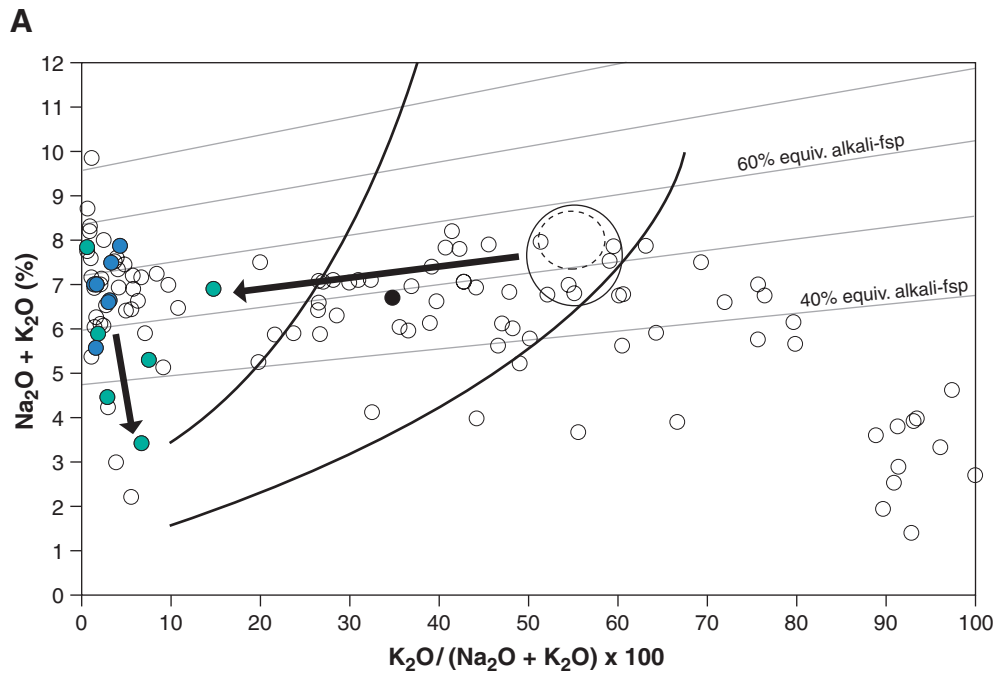
There is also a weak trend towards slight Na enrichment among the samples that plot within the igneous spectrum but away from the least altered samples. The mass change diagram (Fig. 8 c) shows that this alteration resembles the Na alteration of the early orogenic granites, but at a smaller magnitude. The least altered samples of felsic volcanic rocks selected by Baker and de Groot (1983) are close to the slightly Na-enriched samples in this study. Bearing in mind that fully developed Na-altered volcanic rocks can be difficult to identify in the field (Lundström 1995, 1993), the weak Na alteration probably cannot be identified without the use of chemical analyses or detailed microscope work.

The chemistry of the weakly altered felsic metavolcanic rocks discussed above forms a very heterogeneous cluster in the diagrams in Figure 8. This indicates that the metavolcanic rocks have been somewhat affected by alteration, but did not reach equilibrium with the new conditions. The weak alteration of felsic metavolcanic rocks of the Sången fm. is not a distinct type of alteration.

Na alteration

Some of the felsic metavolcanic rocks of the Sången formation have been affected by a Na alteration that is broadly similar to the Na alteration affecting the early orogenic granites, with respect to both chemistry (Fig. 9 a, b) and mineralogy (e.g. Lundström 1995). In common with the granites, some of the samples also show a trend towards Mg enrichment. In the mass change diagrams (Fig. 9 c) these alterations are illustrated in two diagrams, one showing intense Na alteration, the other showing the trend towards Mg alteration of Na-altered rocks. The latter group include samples from the country rocks of the skarn deposits at Annehill (Baker et al. 1988), Dunderbo (de Groot 1993) and Ställbergstorp (Valbracht & Helmers 1988). Samples from Annehill are briefly described as pervasively altered (Baker et al. 1988), those from Ställbergtorp are characterised as albitised and actinolitised

Fig. 9. A) Na- and Na+Mg-altered felsic metavolcanic rocks from the Sången formation plotted in the igneous spectrum of Hughes (1973). Blue dots indicate Na-altered samples, green dots Na+Mg-altered samples. Black arrows show trends of alteration. B) Same data as in Figure 9 A plotted in the ternary MgO-Na_2O-K_2O diagram. C) Bar chart showing the results of mass change calculations for Na+Mg-altered samples compared with the least altered metavolcanic rock in the Sången formation. D) Bar chart showing the results of mass change calculations for Na-altered samples compared with the least altered metavolcanic rock in the Sången formation. See text for explanation. Fe_2O_3 + CaO content is less than 4%. The Al_2O_3 content of the samples has been used as monitor in both bar charts.

A

B

MgO

Na₂O

K₂O

60% equiv. alkali-fsp

40% equiv. alkali-fsp

$K_2O/(Na_2O + K_2O) \times 100$

$Na_2O + K_2O$ (%)

C

**Felsic metavolcanic rock
Na+Mg alteration
n=6**

(%)

SiO_2 CaO MgO Na_2O K_2O Fe_2O_3

D

**Felsic metavolcanic rock
Na alteration
n=7**

(%)

SiO_2 CaO MgO Na_2O K_2O Fe_2O_3

metavolcanic rocks (Valbracht & Helmers 1988), while the Dunderbo samples are characterised as highly altered metavolcanic rocks (de Groot 1993). Noteworthy is the fact that they are very low in both CaO and Fe_2O_3, despite their proximity to an iron-, magnesium-, and calcium-rich actinolite skarn.

Based on the same arguments as for the Na-altered granites, the Na-altered felsic metavolcanic rocks are considered to represent the end products of alteration. It is thus suggested that the same processes that resulted in Na-altered early orogenic granites caused Na alteration of these felsic metavolcanic rocks of the Sången formation.

The compositional variation of the Na+Mg-altered samples, on the other hand, indicates that the rocks have been affected by an overprinting alteration that has not reached completion.

The locations of Na-altered and Na+Mg-altered samples are shown in Figure 15.

K alteration

Classical K alteration with replacement of Na_2O by K_2O, which is found elsewhere in Bergslagen, for example in the Älgen formation (see below), is not very frequent in the Sången formation (Lundström 1995). There are, however, a few samples that plot in the field for K-altered rocks in the Hughes (1973) igneous spectrum (Fig. 10 a), although not all the samples plot at the same "equivalent alkali feldspar" as the least altered samples. In the ternary diagram (Fig. 10 b) they occupy the K_2O sector. The mass change diagram (Fig. 10 c) shows a weak addition of K_2O to the rocks, combined with a weak net removal of Na_2O. The small addition of MgO and Fe_2O_3 to the rocks suggests that they have been affected by a weak chloritization although no study confirms this. The net mass changes during alteration are of the same magnitudes or smaller than in the case of the weakly altered felsic metavolcanic samples discussed above. Like the weak alteration noted there, the weak K alteration observed cannot be regarded as a distinct type of alteration.

Many of the weakly K-altered samples are found close to skarn mineralisations at Annehill (Baker et al. 1988) and Dunderbo (de Groot 1993). Others constitute the outer alteration zone at Hjulsjö (de Groot and Baker 1992).

The locations of the weakly K-altered samples are plotted in Figure 15.

Mg alteration

Several of the K-altered samples, as defined in the igneous spectrum of Hughes (1973), plot well below the "equiva-lent alkali feldspar" line of 40%, indicating an alteration that breaks down the feldspars or dilutes the alkali content in some way (Fig. 11 a). This process is fully developed among a group of rocks that are described as Mg-meta-somatised rocks (Lundström 1995). These constitute the rocks of the inner hydrothermal alteration zone at Hjulsjö (de Groot and Baker 1992) and they occur close to the skarn mineralisations at Annehill (Baker et al. 1988) and at Dunderbo (de Groot 1993). They are found in the Kottbo area and at a few other localities within the Sången formation (Fig. 2). The mineralogy and petrology of the transition from least altered felsic rocks to this type of strongly altered rocks were described by de Groot and Baker (1992) for the Hjulsjö alteration zone.

The Mg-altered samples are characterised by a significant increase in the MgO content of the rocks and a large, but somewhat variable, depletion in alkali. Almost all of the Na is leached from the rock and K is strongly depleted. In the ternary diagram, Figure 11b, these rocks constitute a less well defined group and have been subdivided into a K-Mg group and a K-Na-Mg group. However, the chemical similarities among this group of strongly altered rocks are indicated by the mass change diagrams (Fig. 11c), in which they differ mainly in the amount of alkali that has been removed.

When data from different localities of Mg-altered rocks (Annehill, Hjulsjö, and Kottbo) are plotted separately on the ternary $MgO-Na_2O-K_2O$ diagram, they display trends from least altered or Na-altered rocks towards a common end point, completely Mg-altered rocks (Fig. 11 b). The fact that several samples from different localities show a trend towards a common style of alteration chemistry, as displayed in the diagrams in Figure 11, indicate that the alteration has reached some sort of completion and that the Mg alteration is a distinct type of alteration.

The major difference among the most completely Mg-altered rocks is in their alkali content and alkali ratio. Possibly the alteration has not reached completion and the rocks bear some remnants of previous alterations.

Skarn alteration and mineralisation

Skarn alterations and mineralisations have been excluded in the discussion above since they not only include changes in the MgO, Na_2O, and K_2O contents, but also show marked enrichments in Fe_2O_3 and CaO. They thus cannot be properly described as variations in the $MgO-Na_2O-K_2O$ diagrams. The igneous spectrum of Hughes (1973), however, indicates a trend from intensely Na-altered samples towards intensely skarn-altered ones (Fig. 12, see also Valbracht & Helmers 1988, Fig. 5) and clearly shows that alkali feldspars are destroyed by the al-

Fig. 10. A) Weakly K-altered felsic metavolcanic rocks (red dots) from the Sången formation plotted in the igneous spectrum of Hughes (1973). Black arrows show trends of alteration. **B)** Same data as in Figure 10 A plotted in the ternary MgO-Na$_2$O-K$_2$O diagram. **C)** Bar chart showing the results of mass change calculations for weakly K-altered samples compared with the least altered metavolcanic rock in the Sången formation. See text for explanation. Fe$_2$O$_3$ + CaO content is less than 4%. The Al$_2$O$_3$ content of the samples has been used as monitor.

teration. Detailed investigations of skarn mineralisations in the Sången formation show that the skarn (actinolite) alteration is local and overprints a regional, pre-existing Na alteration. At Ställbergtorp, Valbracht & Helmers (1988) divided the alteration into two stages: an early stage with complete albitization of the felsic rocks followed by massive replacement of albite by amphibole (actinolite). The early stage caused almost total depletion of K and strong enrichment of Na. The second stage added Mg, Ca, and

Fe to the rock. The end product of the alteration was a magnetite-bearing actinolite skarn. Similar models of alteration are suggested for the skarn mineralisations at Annehill (Baker et al. 1988) and Dunderbo (de Groot 1993). However, the authors disagree on the emplacements of the skarn. De Groot (1993) noted that skarn mineralisation at Dunderbo occurred in carbonate-bearing strata, indicating a skarn mineralisation by replacement of carbonates. At Annehill, Baker et al. (1988) suggested that skarn
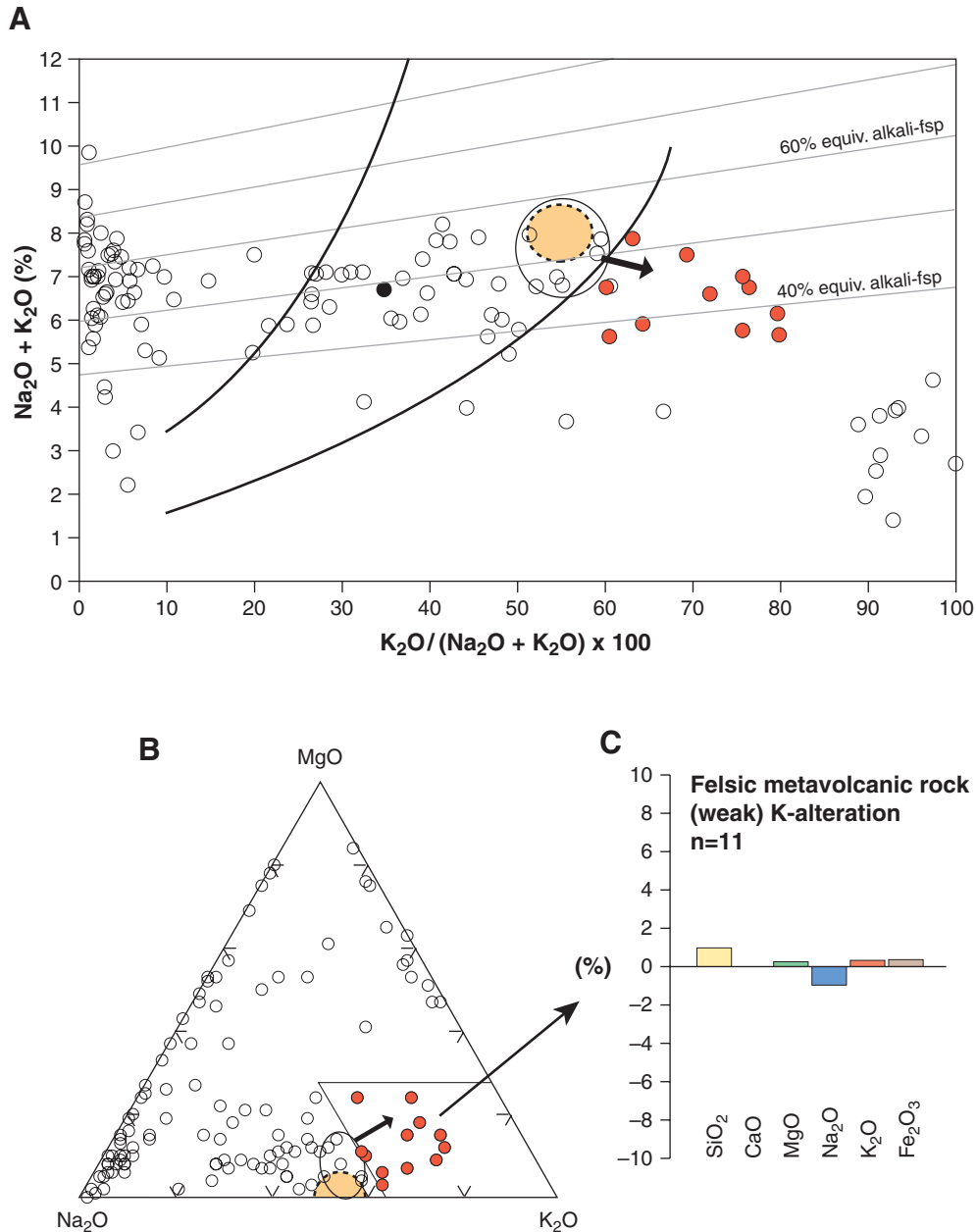
Fig. 11. A) Mg-altered felsic metavolcanic rocks from the Sången formation plotted in the igneous spectrum of Hughes (1973).
B) Same data as in Figure 9a plotted in the ternary MgO-Na$_2$O-K$_2$O diagram. Alteration trends for the Kottbo area, the Hjulsjö area, and the Annehill area indicated by hatched lines. See text for explanation. **C, D)** Bar charts showing the results of mass change calculations for Mg-altered samples with somewhat different alkali ratios. Mass changes compared with the least altered metavolcanic rock in the Sången formation. Fe$_2$O$_3$ + CaO content is less than 4%. The Al$_2$O$_3$ content of the samples has been used as monitor.

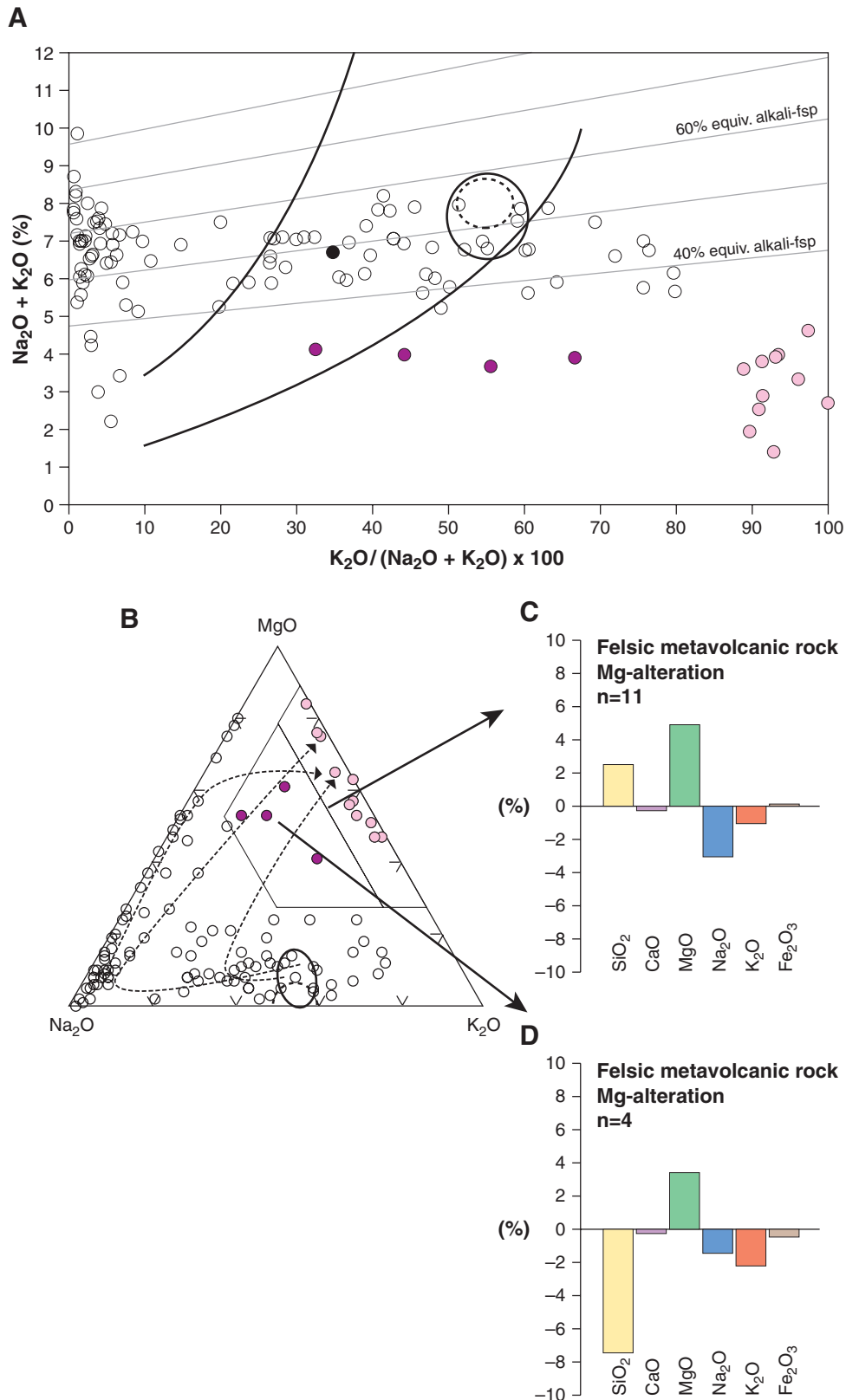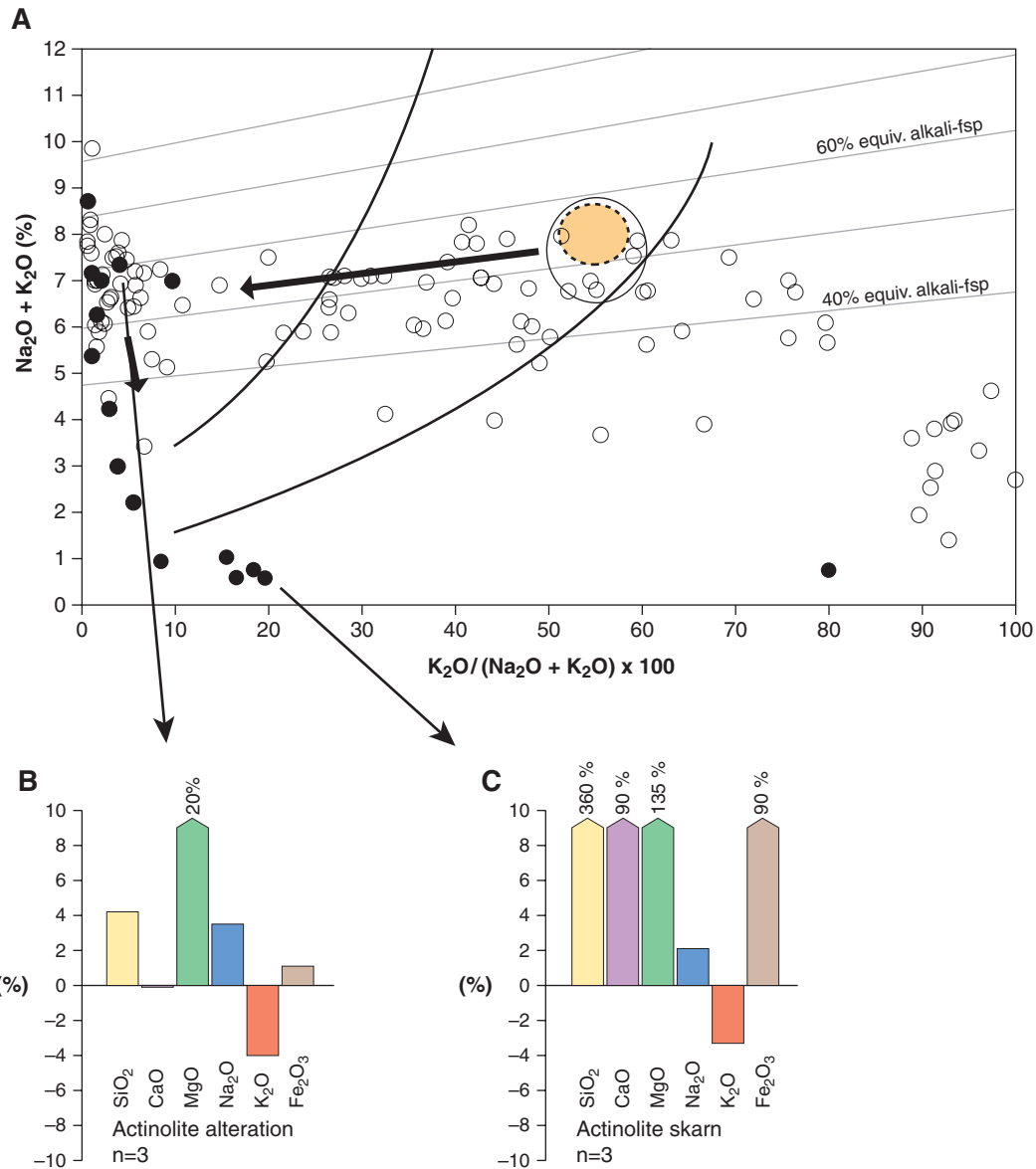**Fig. 12. A)** Skarns and skarn-altered felsic metavolcanic rocks from the Sången formation plotted in the igneous spectrum of Hughes (1973). Black arrows show trends towards complete skarn alteration/mineralisation. **B)** Bar chart showing the results of mass change calculations for skarn-altered samples compared with the least altered metavolcanic rock in the Sången formation. **C)** Bar chart showing the result of mass change calculations for skarn samples compared with the least altered metavolcanic rock in the Sången formation. See text for explanation. The Al_2O_3 content of the samples has been used as monitor.

mineralisation was preceded by brecciation, followed by a hydrothermal phase that emplaced the skarn minerals. Valbracht & Helmers (1988) gave a third explanation for skarn mineralisation in the case of the Ställbergstorp skarn, suggesting replacement of albite by actinolite.

The mass change diagram for actinolite-altered rocks from Ställbergtorp is shown in Figure 13. The mass changes have been calculated with respect to the Na-altered country rocks and the Zr content was used as a monitor. The diagram shows that skarn alteration causes a loss of Al_2O_3 coupled with a loss of Na_2O, supporting

the replacement model suggested by Valbracht & Helmers (1988). It seems, however, that not all the actinolite mineralisation can be explained by albite replacement, and that other processes must be considered. The quality of the analyses from Annehill (Baker et al. 1988) does not permit similar calculations for that deposit.
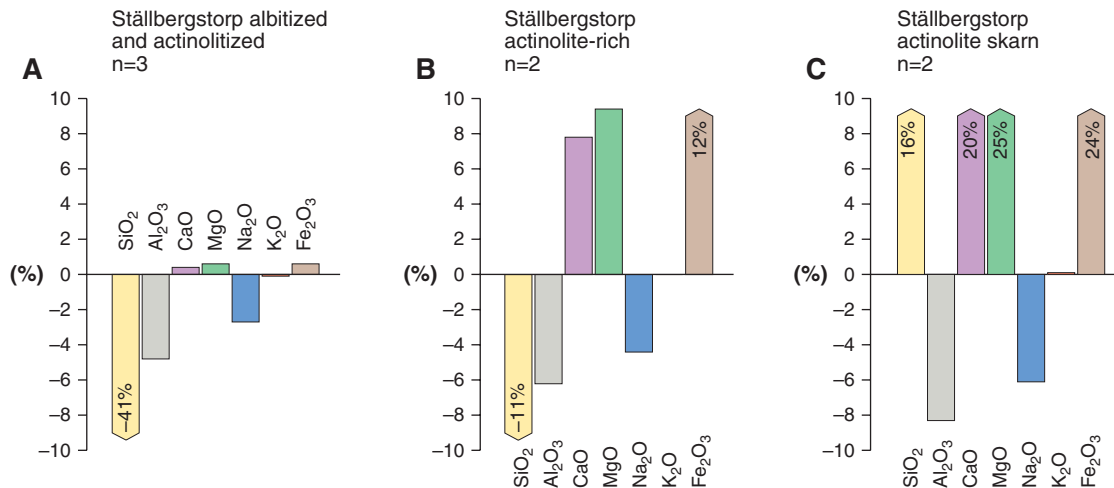
Fig. 13. Bar charts showing the results of mass change calculations for progressively skarn-altered or mineralised samples from the Ställbergstorp deposit (Valbracht & Helmers 1988) compared with the Na-altered country rock to the deposit. In order to show mass changes in the Al_2O_3 content, the Zr content of the samples has been used as monitor.

Alteration diagrams applied to data from the Älgen formation

To investigate the usefulness of this simple alteration classification, the same methods and diagrams were applied to chemical data on rocks from the Älgen formation. Around 120 analyses of rocks from the Älgen formation are available from the literature and from the present study. Roughly half of them come from the work of van Meerten (1982), while other sources are Lundström (1995) with 32 analyses and Holtstam & Mansfeld (2001) with 17 analyses from the Sjögruvan deposit (no coordinates available for individual samples). Additional chemical data come from the database of the Geological Survey of Sweden and from the present work. For about half of the data set TiO_2 and Zr analyses are given, although the quality of the data is uncertain.

A large share of the samples from the Älgen formtion come from the vicinity of skarn iron ores and are rich in Fe_2O_3, CaO and also MnO. Other samples are carbonate-bearing, with high contents of CaO and MgO. Since the classification described above is restricted to changes in the $MgO-Na_2O-K_2O$ content, these samples cannot be used. Among the most iron-rich samples are those from iron ore, generally with more than 30% Fe_2O_3. These data, together with data for samples with a $CaO+Fe_2O_3+MnO$ content of more than 4%, must be removed from the database. The remaining data, some 90 analyses, are plotted in the igneous spectrum of Hughes (1973), shown in Figure 14a, and the ternary $MgO-Na_2O-K_2O$ diagram, Figure 14b. In comparison with the Sången formation, there are several samples that plot as intensely K-altered,

but no examples of Mg alteration. There seems to be only one sample from the Älgen formation that overlaps with the field of least altered rocks as defined above. Otherwise, the intense Na-alteration, with a trend towards Mg alteration, is also displayed in the Älgen data.

In Figure 15 the locations of samples from both the Älgen formation and the Sången formation, classified according to the ternary $MgO-Na_2O-K_2O$ diagram, are shown. From the map it can be concluded that the area with intense Na and Mg alteration around Kottbo continues into the Älgen formation. The area with less altered volcanic rocks in the north-western part of the Sången formation also continues into the Älgen formation. It can thus be concluded that different alterations are continuous across formation boundaries although there is a tendency for more K-altered rock in the younger Älgen formation.

Remote sensing

Airborne geophysical measurements were performed by SGU in the area in 1973 at 200 m line spacing and an altitude of 30 m. As well as VLF and magnetic measurements, radiometric measurements, including channels for U, Th, and K, were produced. Figure 16 shows an interpolated image with the K_2O/U ratio. Samples with a very low total K+U+Th signal, generally recorded over lakes and bogs, were removed before interpolation of the data. On the map in Figure 16, blue areas are very low in K and red areas are rich in K. The K_2O and U contents of differently altered rocks in the area are given in
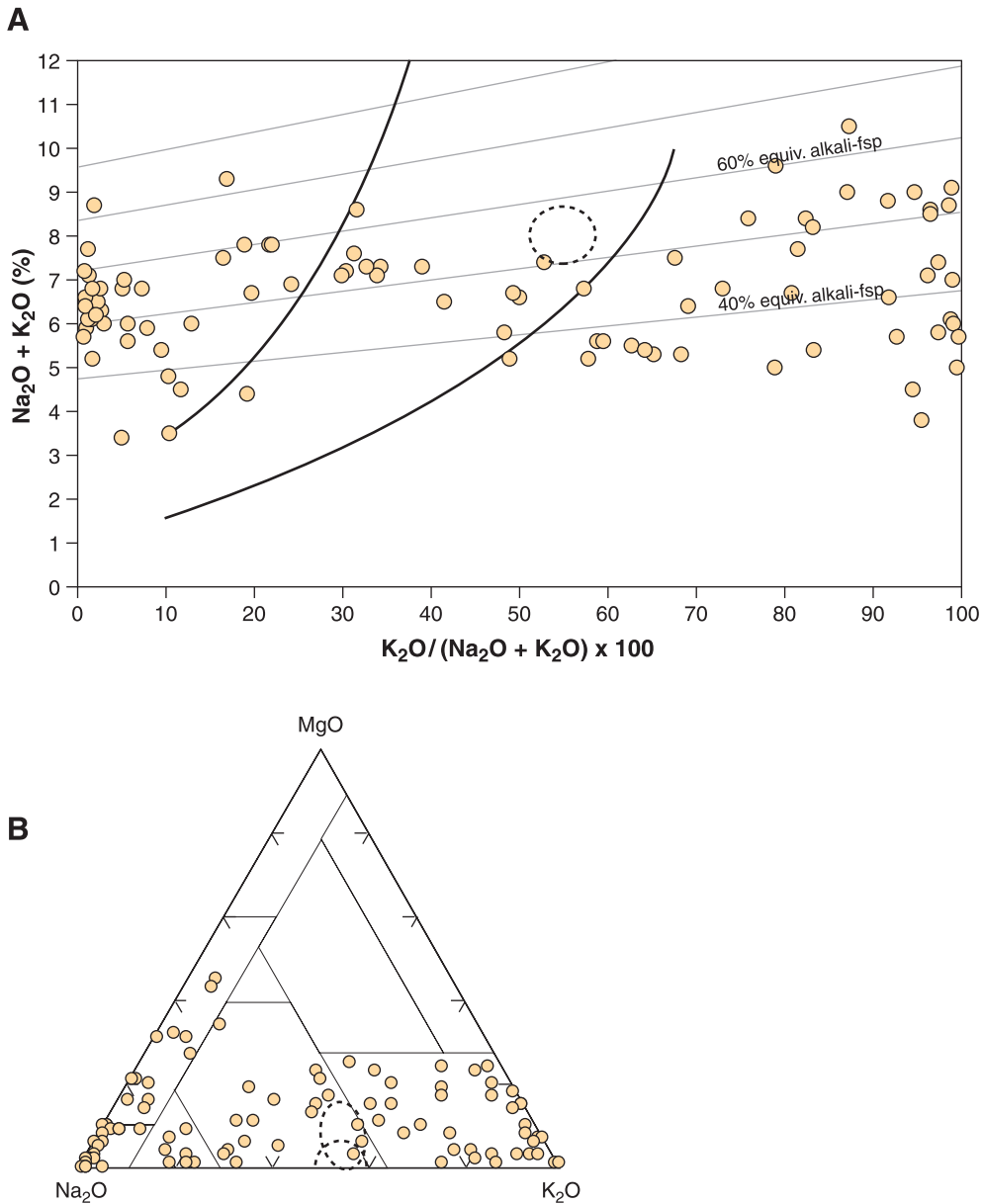
Fig. 14. A) Data from rocks in the Älgen formation plotted in the igneous spectrum of Hughes (1973). B) The same data as in Figure 14 a plotted in the ternary MgO-Na$_2$O-K$_2$O diagram. Fields for differently altered rocks are derived from the work on data from the Sången formation.

Table 2. The K$_2$O and U contents and K$_2$O/U ratios of variously altered rocks from the Sången and the Älgen formations.

Alteration	K$_2$O (%)	U (ppm)	K$_2$O/U-ratio
Sången Fm.			
Na	0.3	3.7	0.07
Na+Mg	0.3	3.4	0.09
least alt.	4.0	3.8	1.06
Mg	4.3	3.7	1.17
K	2.7	2.3	1.14
Älgen Fm.			
Na	0.1	3.6	0.04
Na+Mg	0.3	4.0	0.08
weak Na	1.5	4.3	0.36
least alt.	2.7	4.1	0.66
Mg	3.6	4.4	0.81
K	5.9	3.8	1.53

Table 2. There is a general agreement between the radiometric map (Fig. 16) and the map showing differently altered rocks as deduced from their chemistry (Fig. 15). Airborne radiometry correlated to whole-rock geochemistry provides a powerful tool for mapping some types of regional alteration.
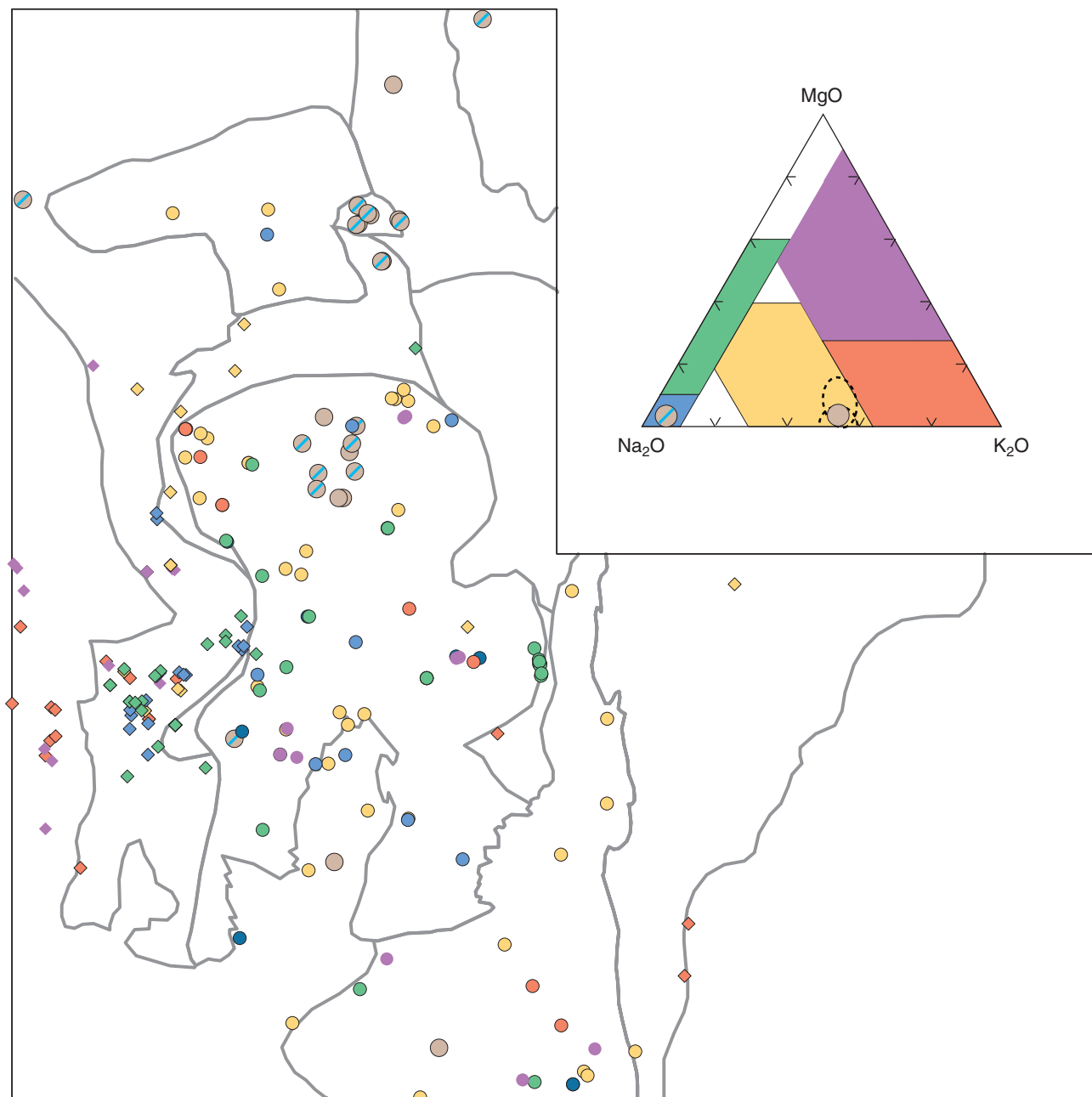
Fig. 15. Map showing positions and degrees of alteration of all samples of felsic metavolcanic rocks from the area. Inset coloured ternary diagram serves as a legend for the dot colours used.

Origin of alteration in the Sången formation

Jazinsky et al. (1988), de Groot (1990), and Baker & de Groot (1983) argued, using a thermodynamic approach, that variations in the style and mineralogy of alteration in Bergslagen (i.e. Na-K-Mg alteration) were caused by variations in the temperature of the circulating seawater. Deeper and hotter conditions, under which albite is stable, produced Na alteration, while the cooler settings

higher up in the stratigraphy produced K alteration. However, if temperature alone governed the alteration, strongly albitised rocks would be much more common in the alteration zones around most volcanic-hosted sulphide deposits.

In the Skellefte district, northern Sweden, a region whose mineralisations are broadly similar in age to alterations found in Bergslagen (Weihed and Billström 1996), various types of K-altered rocks dominate the alterations
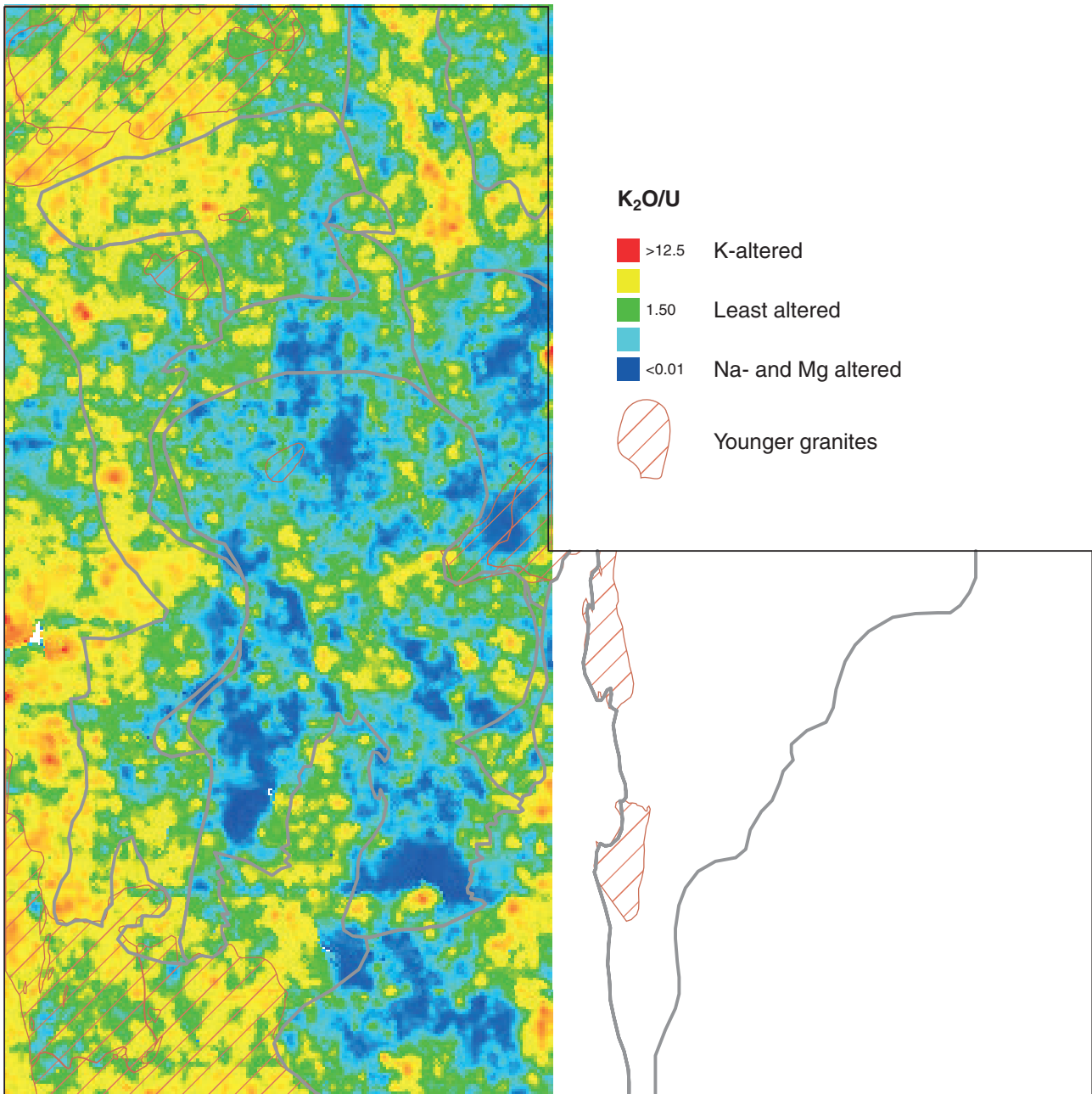
Fig. 16. Radiometric map showing the K_2O/U ratio.

found, despite the fact that they are considered to be formed at high temperatures (Weihed et al. 1993). This questions a model which ascribes the observed variation in alteration in Bergslagen to temperature alone, and suggests that other factors also have to be considered.

One possible way of explaining the large abundance of Na-altered rocks in Bergslagen would be to assume that the hydrothermal fluids were highly saline. It is obvious from the diagrams presented by Jazinsky (1988) that a strong increase in Na^+ activity will expand the stability field for albite.

Barton and Johnson (1996) suggested the involvement of evaporites as an important ligand source and as an explanation for the large areas of Na-altered rocks associated with Fe-oxide Cu-Au deposits. Hypersaline fluids, possibly of evaporitic origin, have been suggested for regional metasomatic alteration in the Willyama Supergroup, South Australia (Kent et al. 2000) and for the host rock to the Starra Fe-oxide Cu-Au deposit in Queensland, Australia (Davidson 1994). Thus, at several places around the world, where large volumes of Na-altered rocks have been formed during hydrothermal alteration, it is suggested that

the hydrothermal cell incorporated pre-existing evaporites or contemporary salars forming highly saline fluids.

However, there is no evidence for evaporites within the Sången formation. The basement to the Sången formation is unknown, but at Utö in eastern Bergslagen the rocks underlying the felsic metavolcanic rocks consist of quartz-rich greywackes with no evidence of evaporites. Indications of evaporitic environments have, however, been reported from the Dannemora mine in north-eastern Bergslagen (Lager 2001). In a similar setting at the south-eastern edge of the Sången/Vassland formation gypsum pseudomorphs, indicative of evaporitic conditions, have been observed (R. Allen and S. Bull, pers. comm.). In the same area Hellingwerf et al. (1994) located and described several tourmalinites and argued that they could be related to sulphide mineralisation in the area. Tourmalinites, however, can also be interpreted as remnants of evaporites. Using boron isotopes and sedimentological studies, Byerly and Palmer (1991) showed that some of the tourmalinites in the Archean Barberton greenstone belt were derived from evaporites. No such study has yet been applied to the Bergslagen tourmalinites. Other indications of evaporite-derived fluids include a brief discussion by de Groot (1993) explaining an anomalously high $d^{18}O$-value of a phlogopite sample from the Hjulsjö alteration zone.

If evaporites occurred at the boundary between the Sången and Vassland formations and in overlying rocks, evaporitic conditions could also have existed above the intensely Na-altered rocks in the Sången and Älgen formations. In the subsurface to these possible evaporitic environments, the fluids should be highly saline (see for example Warren 2000).

It is thus suggested that high-salinity fluids occurring as groundwater under evaporite-forming sequences, combined with heat from the waning volcanism and channelled by fractures formed by the ongoing extension, provided the fundamental conditions for a long-lived environment in which rocks could be completely Na-altered.

If this assumption is correct, it also implies that different processes cause Na alteration and K alteration. At the few localities where the relative timing of Na vs. K alterations can be observed, it seems that the rocks were first K-altered, followed by pervasive Na alteration and with Mg alteration occurring as veinlets in the rock (Lundström 1995).

Lundström (1995) suggested that the K alteration in Bergslagen could have occurred already during diagenesis of the rocks. Such an early diagenetic K alteration has also been suggested for much younger rocks in the western US (Rougvie & Sorensen 2002, Brooks 1986). This would also explain why none of the early orogenic granites in the

area have been affected by K alteration, since they were never exposed to a surface environment.

In conclusion, although a simple temperature-dependent alteration cannot be excluded, it is suggested that evaporite-derived fluids played an important role in the formation of completely Na-altered rocks in western Bergslagen.

Acknowledgements

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Appendix 1. Brief description of the samples analysed in this study.

sample #	N (RT90)	E (RT90)	porfyric?	grain size	colour	structure/texture	comments
SAN 01	6615673	1438103		fine	greenish white		mica-rich
SAN 02	6618731	1436409	fsp-dark min.	medium	white		
SAN 03	6632420	1434477		very fine	dark grey-black	foliated	
SAN 04	6633356	1435283	qz-fsp	medium	grey		
SAN 05	6631595	1435872	fsp?	medium	red-grey		epidot
SAN 06	6630699	1433009	qz	medium-corse	grey		
SAN 07	6629080	1436063	qz-fsp	fine	light grey		red minerals
SAN 08	6628298	1441982	fsp	fine	dark grey-black		
SAN 09	6622144	1435559		very fine	dark grey		
SAN 10	6625543	1434919		very fine	dark grey-red		waste rock from mine
SAN 11	6625593	1434874		very fine	greenish white		
SAN 12	6623466	1436355		fine	dark grey		
SAN 13	6623983	1436522		medium	white-red		granitic
SAN 14	6625111	1438533	qz-(fsp)	fine	light grey		
SAN 15	6626164	1442260	qz-fsp	medium-fine	dark grey		
SAN 16	6626162	1442264	qz-fsp	very fine	pale red		
SAN 17	6626157	1442277	qz-fsp	medium	dark grey-red		hematite stains on fractures
SAN 18	6620940	1440808	fsp-dark min.	medium-fine	dark grey-red	foliated	granitic
SAN 19	6617653	1441198	qz-fsp	fine	grey-red	foliated	white weathering
SAN 20	6617165	1440449		very fine	light grey		
SAN 21	6617736	1440062	fsp	fine	pale red		
SAN 22	6615773	1440328	qz	fine	white		
SAN 23	6615357	1438963	fsp	fine	light grey-red	foliated	
SAN 24	6616940	1437617	qz-fsp	medium	light grey-green		white weathering, qz-blasts
SAN 25	6616997	1437665	qz	fine	dark grey	foliated	calcite-Kfsp veinlets
SAN 26	6619793	1437630		medium	white-light grey		granitic
SAN 27	6624041	1438307		very fine	dark grey-red		red+epidot veinlets
SAN 28	6615193	1433928		fine	dark grey		
SAN 29	6616352	1435358		fine	dark grey-green		sulphides, alteration veins
SAN 30	6615780	1435173	fsp?	fine	dark grey-green		
SAN 31	6613229	1441361	qz	fine	pale red	foliated-lineation	
SAN 32	6612858	1443214	qz	fine	grey-green		
SAN 33	6631150	1439300	fsp-qz	medium	red-grey		
SAN 34	6624300	1437600	fsp	fine	light grey-red		
SAN 35	6610500	1438650		medium	grey	foliated	granitic

Appendix 2. Whole rock geochemical analyses. For location and description see Appendix 1.

sample #	SAN 01	SAN 02	SAN 03	SAN 04	SAN 05	SAN 06	SAN 07	SAN 08	SAN 09	SAN 10	SAN 11	SAN 12
SiO_2	76,4	75,8	71	77,1	63,3	75,2	77	51,5	73,5	77,8	79,6	46,4
Al_2O_3	11,9	12,2	10,8	10,9	18,1	13,1	12	13	11,2	11,2	8,84	15,3
CaO	0,02	0,13	0,22	0,14	1,55	0,45	0,42	7,29	0,26	0,58	0,14	6,74
MgO	4,56	2,84	4,52	1,76	0,61	1,3	0,87	4,16	3,62	0,68	4,53	9,84
Na_2O	2,22	5,78	4,32	3,32	6,45	1,4	6,08	2,89	4,27	6,09	3,19	2,84
K_2O	1,76	0,11	2,14	3,32	4,81	4,36	0,36	1,65	0,49	0,32	0,23	0,88
Fe_2O_3	0,67	1,52	5,42	2,32	2,29	2,83	1,57	16,1	3,99	1,78	1,67	14,4
MnO	<0,01	<0,01	0,01	0,01	0,02	0,01	<0,01	0,17	0,02	<0,01	<0,01	0,16
TiO_2	0,14	0,294	0,186	0,145	0,251	0,161	0,17	1,859	0,131	0,129	0,171	0,553
P_2O_5	<0,01	0,03	<0,01	<0,01	0,01	<0,01	<0,01	0,26	<0,01	<0,01	<0,01	0,07
LOI	2,1	1,05	0,75	0,85	0,75	1,45	0,45	0,85	1,55	0,85	1,7	2,85
SUM	99,8	99,8	99,5	100	98,4	100,4	99,1	99,8	99,1	99,5	100,2	100,1
Cu	2,1	4,3	4,3	6,9	56,8	57,6	6,3	35,6	8,9	6,4	2,4	11
Zn	6,5	5,8	15,8	12,9	21,2	14,1	11,7	72,5	22,4	6,6	6	63
Pb	<2	<2	2	<2	<2	3	<2	2	2	<2	<2	<2
Cd	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Au	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Ag	0,6	0,2	0,3	0,4	0,3	<0,2	<0,2	<0,2	0,4	0,4	0,2	<0,2
As	3	4	<3	<3	6	4	4	<3	3	<3	<3	<3
Sb	<0,2	0,5	0,6	<0,2	<0,2	0,8	<0,2	1,8	0,5	<0,2	0,3	0,5
Bi	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Br	<1	<1	<1	1	<1	1	<1	<1	<1	<1	<1	<1
Co	<1	2	5	4	4	1	1	40	4	4	<1	36
Ni	7	12	12	21	9	16	14	14	11	22	7	150
Cr	75	143	192	236	87	177	134	78	156	203	74	368
Mo	4	7	8	16	6	11	11	3	10	19	5	2
V	3,04	6,84	10,8	20	21	11,3	10,9	524	14,5	20	5,2	240
Ba	87	12	50	564	1060	589	89	276	59	29	23	158
Cs	<3	<3	<3	<3	<3	<3	<3	<3	3	<3	<3	<3
Rb	38	8	139	64	80	192	14	61	17	19	13	30
Sc	4,5	6,5	8,7	3,8	10,8	5	5,8	42,8	2,8	2,1	4,3	44
Sr	5,8	14,6	12,6	16,2	200	15,7	63,4	145	14,3	13,7	8,8	65,6
Be	0,6	0,9	2,6	1,9	1,3	2,9	2,1	2,3	1,2	1,4	<0,5	1
Hf	7	9	8	10	8	9	8	3	7	9	5	1
W	6	5	<4	11	<4	9	9	4	8	11	<4	<4
Ta	1	4	2	2	1	2	<1	1	2	1	<1	<1
Nb	13	14	17	14	16	19	14	11	17	11	11	<2
Th	14,4	5,3	10,7	9,7	9,5	17,4	10,3	3,3	13,3	8,4	7	1,3
U	3,2	3,4	0,7	3,6	<0,5	5,3	4,1	2,1	3,9	7,7	2,1	0,8
Y	13,7	21,8	24,9	34	41	59,6	28,7	30,4	41,6	22,9	10,3	13,4
Zr	217	316	273	203	295	191	175	83	213	154	192	29
La	14	47	53	14	71	71	58	18	8	14	30	4
Ce	29	79	84	26	106	119	86	40	23	39	66	17
Nd	12	11	14	22	46	51	20	14	20	11	17	18
Sm	1,9	6,6	5,7	2,9	9,1	11,4	7,5	4	3,4	2	4,5	1,5
Eu	<0,2	2,1	0,7	<0,2	2	0,9	1	1,3	0,8	1,1	0,6	1,1
Tb	1	1,8	0,6	1,2	0,8	0,9	0,6	0,6	1,6	1,5	1,2	0,7
Yb	2,8	2,7	3,7	4,3	5,3	6,2	5,3	3,5	5,8	2,5	2,8	1,8
Lu	0,48	0,4	0,47	0,62	0,68	0,84	0,78	0,38	0,7	<0,05	0,43	0,13

sample #	SAN 13	SAN 14	SAN 15	SAN 16	SAN 17	SAN 18	SAN 19	SAN 20	SAN 21	SAN 22	SAN 23	SAN 24
SiO_2	74,7	77,9	77,3	76,9	75,4	75,4	77,1	76,5	78,1	80,2	79,7	77,5
Al_2O_3	11,9	11,1	11,3	13,6	10,5	12,1	11,9	11,8	11,1	11,1	11,1	11,5
CaO	1,87	0,58	0,19	0,19	0,23	0,76	0,58	0,58	0,73	0,6	0,25	0,1
MgO	0,94	1,68	1,56	0,18	3,11	0,46	0,53	0,89	0,59	0,67	0,52	1,17
Na_2O	6,35	2,66	5,77	7,53	4,9	6,21	4,93	3,24	3,05	5,48	5,98	3,18
K_2O	0,18	2,56	0,7	0,34	0,4	0,42	2,11	3,53	3,75	0,42	0,13	3,81
Fe_2O_3	1,42	2,05	1,85	0,48	3,37	2,32	1,73	2,26	1,83	0,38	1,61	1,55
MnO	0,02	0,01	<0,01	<0,01	0,01	0,01	0,02	0,02	<0,01	<0,01	<0,01	<0,01
TiO_2	0,335	0,129	0,129	0,129	0,152	0,216	0,141	0,128	0,156	0,129	0,143	0,124
P_2O_5	0,04	<0,01	<0,01	<0,01	<0,01	0,02	<0,01	<0,01	<0,01	<0,01	<0,01	<0,01
LOI	1,5	1,1	0,4	0,05	1,25	0,55	0,2	1,05	0,45	<0,01	0,45	0,85
SUM	99,3	99,9	99,3	99,4	99,5	98,6	99,4	100,3	100	99	100	100,1
Cu	7,3	6,3	8,6	6,9	7,7	4,5	5,6	5,1	5	4,5	11,6	5,4
Zn	15,5	12,5	21	5,5	14,4	9,1	17,5	12,5	7,4	5,5	6,7	5,8
Pb	<2	4	4	<2	5	<2	3	4	3	<2	<2	<2
Cd	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Au	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Ag	0,3	<0,2	0,2	0,4	<0,2	<0,2	0,2	<0,2	<0,2	0,6	<0,2	<0,2
As	<3	11	3	<3	9	<3	<3	4	<3	<3	4	5
Sb	0,6	<0,2	0,9	0,5	<0,2	0,8	0,3	<0,2	<0,2	0,4	<0,2	0,6
Bi	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Br	1	<1	<1	<1	1	<1	<1	<1	<1	<1	<1	<1
Co	3	<1	3	9	33	1	2	<1	<1	1	3	2
Ni	15	9	13	12	14	10	13	12	11	8	11	13
Cr	141	124	142	100	235	141	108	129	104	46	120	179
Mo	10	8	11	12	11	8	10	13	8	6	9	11
V	18,7	8,32	10,2	11,1	16,2	10,1	14,2	11,9	7,55	4,94	9,11	14,4
Ba	22	481	53	23	44	65	754	1100	1410	55	18	1040
Cs	4	<3	<3	3	<3	<3	<3	<3	<3	<3	4	<3
Rb	9	80	45	12	21	26	49	97	86	22	11	54
Sc	9,1	3,4	3,7	0,5	7,2	7,3	4,4	5,1	3,8	3,4	5,5	4,6
Sr	27,1	32,2	26,3	15,2	19,2	66,8	61,4	81,4	102	78,4	16,5	30,5
Be	1,1	12,6	3,7	1,2	1,7	2,3	1,8	3,2	1,8	2,5	1,6	2
Hf	6	10	8	9	10	5	7	9	6	7	6	6
W	6	8	<4	8	9	7	5	8	5	4	<4	6
Ta	<1	3	<1	4	1	1	<1	2	<1	2	<1	3
Nb	9	15	18	19	19	14	15	18	12	16	16	15
Th	4	14,4	10,6	9	10,8	7,9	10,5	17,2	12,4	12,4	12,7	13,3
U	<0,5	3,8	3,8	2,3	4	3,4	4,1	2,5	3	4,4	1,3	5,9
Y	25,5	156	39,1	37	33,3	37,3	27	52,8	32,7	9,9	40,5	27,8
Zr	189	186	192	168	214	181	137	176	157	162	162	145
La	6	245	36	1	192	37	23	71	39	9	56	77
Ce	11	401	64	10	309	62	28	111	70	25	79	149
Nd	27	232	20	18	160	24	22	12	36	20	38	43
Sm	1,7	40,9	6	1,1	23	5,3	3,2	10,3	6,1	1,6	7,2	8
Eu	1,2	4,6	0,3	1,2	2,3	2	0,5	1,2	1,2	1,3	0,7	1,1
Tb	1	7,1	1,9	1	0,6	0,7	<0,5	1,1	1,3	1	0,6	1,5
Yb	3,3	11,5	4,9	3,6	5	4,7	4,3	7,7	4,5	4,3	4,3	4,5
Lu	0,45	1,39	0,7	0,44	0,63	0,49	0,42	1,04	0,63	0,5	0,55	0,7

sample #	SAN 25	SAN 26	SAN 27	SAN 28	SAN 29	SAN 30	SAN 31	SAN 32	SAN 33	SAN 34	SAN 35
SiO_2	73,2	76,7	76,7	75,6	49	48,3	77,1	76,8	76,9	77,4	76,1
Al_2O_3	12,5	13	11,3	12,3	13,4	13,1	11,9	12,1	11,9	11,3	11,4
CaO	<0,01	0,15	0,67	0,2	10,1	9,73	0,39	0,28	0,39	0,51	0,75
MgO	4,12	1,16	1,57	1,14	7,87	6,84	0,28	1,19	0,3	0,93	0,83
Na_2O	0,12	6,97	3,78	6,31	2,71	2,38	5,15	3,99	3,18	3,56	2,69
K_2O	4,5	0,16	2,18	0,5	0,48	1,14	1,91	2,63	5,08	3,27	4,06
Fe_2O_3	3,09	1,11	2,73	2,41	13,1	14,4	1,8	1,59	1,2	2,08	3,1
MnO	<0,01	<0,01	0,02	<0,01	0,18	0,2	<0,01	<0,01	<0,01	<0,01	0,02
TiO_2	0,15	0,12	0,148	0,133	0,791	1	0,139	0,132	0,136	0,133	0,39
P_2O_5	<0,01	<0,01	<0,01	<0,01	0,13	0,19	<0,01	<0,01	<0,01	<0,01	0,02
LOI	2,15	0,5	1	0,65	2	1,15	0,1	0,65	0,45	0,45	0,4
SUM	100	100	100,4	99,3	99,9	98,5	99	99,5	99,8	99,9	100
Cu	5	5,6	6,7	4	133	116	4,2	6,5	5,1	5,5	7,8
Zn	11,7	6,5	11,4	7,4	46,6	92	5,9	10,1	10,8	5,5	16,8
Pb	2	4	3	<2	<2	<2	3	<2	4	<2	4
Cd	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Au	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Ag	<0,2	0,2	<0,2	0,3	<0,2	<0,2	<0,2	0,3	<0,2	<0,2	0,2
As	3	<3	4	<3	<3	<3	3	<3	5	5	<3
Sb	<0,2	0,7	0,3	<0,2	0,8	1,2	<0,2	0,4	0,4	<0,2	0,3
Bi	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Br	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1
Co	2	2	5	4	47	47	<1	1	1	1	2
Ni	13	12	20	9	94	68	9	8	12	15	18
Cr	202	119	246	117	265	143	62	102	120	192	254
Mo	12	11	32	9	2	3	4	7	9	16	16
V	12,1	10,2	32	7,54	283	339	4,69	7,17	9,24	16,7	18,9
Ba	653	28	419	38	45	88	1190	846	865	475	1130
Cs	<3	5	<3	<3	<3	4	<3	3	<3	<3	<3
Rb	106	12	62	27	16	40	41	64	106	65	109
Sc	5,3	3,1	3,8	5,9	48,8	47,5	4,1	3,6	2	3,8	7,3
Sr	4,5	14,3	82,7	9	93,9	102	58,9	43,1	54,7	34,1	62,3
Be	1,9	1,9	2,2	2,3	0,7	0,9	2,1	1,9	1,6	3,1	1,7
Hf	7	7	10	7	<1	3	5	5	5	7	10
W	12	11	14	4	<4	4	<4	5	8	9	12
Ta	<1	4	1	1	<1	2	<1	<1	<1	1	1
Nb	13	13	18	19	<2	3	15	13	14	15	16
Th	14,8	13,8	16,2	11,3	2,3	1,2	11,2	11,4	15,8	12	6,1
U	1,5	3,2	3,8	3,2	0,6	0,8	3,6	4,2	3,9	2,9	1
Y	18,4	25,2	71,5	42,4	18,4	24,1	34,6	24,2	32,3	70,5	30,6
Zr	191	122	220	171	32	45	146	148	131	190	375
La	37	10	57	12	4	6	35	18	44	88	44
Ce	69	24	94	30	8	13	57	34	67	149	75
Nd	21	<10	65	36	19	24	24	18	26	64	33
Sm	5,7	3,5	11,6	2,9	1,8	2,4	5,1	3,6	4,6	13,3	7,2
Eu	0,9	1,1	0,9	0,4	0,9	0,3	0,8	0,2	0,4	1,4	1,5
Tb	1,3	1,2	<0,5	1,1	0,8	0,9	0,7	1,4	0,7	1,6	2
Yb	6,3	4,5	8	5,4	2,2	3,6	4,6	4,9	4,2	6,3	4,4
Lu	0,91	0,58	0,83	0,79	0,33	0,47	0,61	0,8	0,46	0,83	0,51

Appendix 3. References, sample number and co-ordinates for whole rock chemical analyses obtained from the literature.

sample #	N (RT90)	E (RT90)
Baker 1985a		
51	6629270	1437760
66	6627520	1439990
86	6627290	1442090
88	6627050	1441570
120	6630060	1438460
220	6626930	1437580
234	6630810	1440720
242	6629160	1438220
246	6631230	1439320
250	6629810	1437440
258	6628850	1437220
265	6626990	1437570
270	6627920	1438960
392	6628940	1437150
451	6629730	1438440
463	6630070	1440540
466	6629630	1440490
468	6628680	1440720
518	6627090	1438540
824	6627520	1440180
423a	6626810	1436590
528a	6628640	1439030
Baker 1985b		
1067	6640150	1441080
1066a	6640100	1440900
1066b	6640100	1440900
1068b	6640900	1441000
1069a	6640300	1442750
1069b	6640300	1442750
Baker et al. 1988		
910	6619990	1449240
911	6619970	1449240
912	6619955	1449195
913	6620140	1449190
914	6620090	1449220
916	6620660	1448980
917	6620660	1448990
918	6619470	1449310
919	6619470	1449310
920	6620580	1449035
921	6619510	1449310
922	6620050	1449210
923	6620760	1449040
924	6620840	1448850
925	6620670	1449060
926	6619410	1449280
927	6619335	1449285
928	6619870	1449250
929	6619840	1449260
930	6620090	1449220
Baker & Hellingwerf, IAGOD 1988 327-338		
DU	−	−
de Groot 1993		
1L1	−	−
1L2	6620290	1445400
1L3	6620200	1445410
1L4	−	−
1L5	−	−
de Groot & Baker 1992		
2J11	6632110	1442460
2J13	6632070	1442610
2J18	6631990	1443210
2J21		
3J3	6631290	1443100
BJ550	6631210	1443000
Baker & de Groot 1983		
	6631450	1442900
Baker et al. 1987		
	6640900	1432000
	6640900	1432000
	6640900	1432000
Hellingwerf 1987		
86028	6591100	1442530
86049	6594500	1447880
86050	6594500	1448640
86056	6593440	1448030
86059	6593630	1448760
86071	6594850	1449130
86100	6594300	1444200
86101	6593970	1445210
86102	6589670	1440500
86103	6589670	1440620
86104	6589660	1440660
86106	6589540	1440900
86108	6589520	1440950
86113	6589580	1441110
86117	6589510	1441230
86143	6591230	1443480
86150	6588650	1441650
86152	6590170	1442170
86158	6591970	1442950
86159	6592110	1442590
86225	6594870	1447510
86226	6594320	1447830
86508	6596950	1448860
86510	6596400	1447750
86514	6595740	1448440
86515	6595970	1448550
86522	6595630	1448030
86523	6595330	1447220
86524	6595280	1446940
86525	6595420	1446770
86526	6595420	1446700
86532	6593780	1445700
86533	6593920	1445585
86536	6594130	1446130
86537	6594170	1446220
86538	6594250	1446280
86540	6594600	1446600
86541	6594610	1446690
86542	6594370	1446400
86544	6594350	1446110
86549	6593970	1445860
86557	6593290	1445650
86560	6595050	1444540
86568	6593130	1444350
86572	6593260	1443770
86574	6592780	1443700
86576	6592990	1443990
86577	6592810	1443960
86578	6592700	1443680
86582	6593050	1442610
86596	6591090	1442330
86597	6591010	1442480
86598	6590970	1442420
86606	6592380	1440270
86609	6591960	1440640
86615	6595210	1445750
86621	6594710	1445920
86622	6594910	1445780
86623	6593880	1445660
86624	6593860	1445610
86631	6592850	1444180
86632	6593200	1445470
86634	6592640	1445420
86658	6592750	1443820
86503A	6597740	1448220
86503B	6597720	1448220
86513A	6595880	1447250
86513B	6595880	1447250
86513C	6595880	1447250
86513D	6595880	1447250
86513E	6595880	1447250
86525B	6595420	1446770
86532B	6593780	1445700
86538B	6594250	1446280
86541B	6594610	1446690
86566C1	6593320	1444260
86566C2	6593320	1444260
86566C3	6593320	1444260
86566D1	6593320	1444260
86566D2	6593320	1444260
86566D3	6593320	1444260
86576B	6592990	1443990
86632B	6593200	1445470
Holtstam & Mansfeld 2001		
99113	6617150	1432550
65:116	6617150	1432550
87:206	6617150	1432550
93:201	6617150	1432550
94:094	6617150	1432550
94:102	6617150	1432550
94:141	6617150	1432550
94:142	6617150	1432550
A02	6617150	1432550
B	6617150	1432550
F	6617150	1432550
G02	6617150	1432550
g33076	6617150	1432550
g33078	6617150	1432550
H	6617150	1432550
I	6617150	1432550
R01	6617150	1432550
R02	6617150	1432550
R03	6617150	1432550
R04	6617150	1432550
R05	6617150	1432550
RI2	6617150	1432550
RI7	6617150	1432550
Lundström 1983		
L73:7	6602200	1453600
L74:18	6611220	1450200
L74:2	6602900	1451390
L74:26	6602320	1451760
L74:29	6603400	1450220
L74:30	6601100	1451420
L74:31	6601280	1451250
L74:32	6600700	1450750
L74:33	6600700	1450750
L81:16	6623290	1450700
L81:19	6617430	1452320
L81:20	6613550	1452310
Valbracht et al. 1991		
Bj122	6631600	1436000
Bj490A	6627000	1436600
Bj705A	6634200	1441600
Cad15	6616500	1437600
Cad45	6616300	1434600
Hel8445	6621500	1435100
Hel8446	6624000	1434000
Hw369	6626900	1418300

sample #	N (RT90)	E (RT90)	sample #	N (RT90)	E (RT90)	sample #	N (RT90)	E (RT90)
Hw531/1	6630200	1419500	LB 80:12	6619300	1430470	BBAA87214	6592852	1443948
Hw734	6626600	1419400	LB 80:138	6618730	1432800	BBAA87215	6592804	1444005
Hw89/2	6626700	1421100	LB 80:143	6616970	1430450	BBAA87216	6592803	1444006
Rr208	6653000	1452600	LB 80:25	6619350	1431650	BBAA87217	6592803	1444006
Vb350	6630400	1444800	LB 80:41	6617820	1431000	BBAA87218	6592803	1444006
Vb480A	6629800	1447300	R 83:10	6621640	1445930	BBAA87219	6592792	1444019
Vb480B	6629800	1447300	R 83:12	6620040	1446200	BBAA87220	6592791	1444020
Vb64	6629100	1447600	r 83:13	6620220	1446480	BBAA87221	6592791	1444020
Vd1535	6623570	1433870	R 83:14	6620250	1445550	BBAA87222	6592791	1444021
Vp132	6613800	1449700	R 83:19	6619500	1449730	BBAA87223	6592790	1444022
Vp33A	6622000	1448300	R 83:20	6619950	1449260	BBAA87224	6592783	1444030
Vp346K	6620200	1442400	R 84:10	6602270	1444600	BBAA87225	6593386	1445354
Vp346R1	6620200	1442400	R 84:10	6602270	1444600	BBAA87226	6593385	1445354
Vp346R2	6620200	1442400	R 84:17	6605050	1441000	BBAA87227	6593385	1445355
Vp503	6617200	1449600	R 84:5	6617800	1445200	BBAA87228	6593384	1445356
Za54-85F	6633500	1452400	R 84:7B	6600100	1443750	BBAA87229	6593383	1445356
Lundström 1995			R 84:9	6602270	1444600	BBAA87230	6593383	1445357
B 84:10B	6622120	1438670	R 84:9	6602270	1444600	BBAA87231	6593382	1445358
B 84:9B	6622120	1438600	R 85:13	6610600	1428200	BBAA87232	6593275	1445473
B 87:17	6640580	1432430	R 87:13	6640400	1441400	BBAA87233	6593274	1445474
B 89:19	6641200	1425500	R 87:14	6640400	1441400	BBAA87234	6593274	1445475
GL 87:3	6630700	1433000	R 87:3	6634400	1443540	BBAA87235	6593273	1445475
GL 87:5	6630500	1433700	R 87:7	6638400	1442000	BBAA87236	6593273	1445476
H 83:12	6615380	1439550	R 87:8	6638400	1442000	BBAA87237	6593271	1445478
H 83:13	6615380	1439550	R 87:9	6637700	1442000	BBAA87238	6593270	1445479
H 84:11B	6612350	1436550	R 89:14A	6630600	1445700	BBAA87239	6593258	1445492
L 82:11	6615750	1426600	R 89:15B	6630600	1445700	BBAA87240	6593257	1445494
L 83:12	6612800	1443200	R 89:15B	6631100	1445200	BBAA87242	6593596	1445147
L 83:32	6613080	1448500	T 85:10	6615800	1437350	BBAA87243	6593596	1445147
L 83:9	6611000	1445700	T 85:11	6616450	1435200	BBAA87244	6593596	1445148
L 84:13A	6605200	1448900	T 85:13	6616850	1435600	BBAA87245	6593595	1445148
L 84:17B	6622470	1443250	T 85:4A	6618900	1436300	BBAA87246	6593569	1445171
L 84:17B	6651600	1449650	T 85:7B	6619450	1436300	BBAA87247	6593569	1445172
L 84:23	6616750	1447300	T 85:9	6615800	1437350	BBAA87248	6593261	1445489
L 84:24	6600800	1449100	T 87:12	6640750	1436800	BBAA87249	6593260	1445490
L 84:2A	6600800	1449000	T 87:5	6635500	1435700	van Meerten 1982		
L 84:31	6610800	1439800	T 87:8B	6637100	1437300	Mv 1	6621790	1428610
L 84:33	6603500	1437900	T 87:9	6639600	1436750	Mv 100	6617420	1431340
L 85:28	6630150	1438380	T 88:10	6649500	1446600	Mv 101	6617420	1431340
L 86:15	6615500	1426900	T 88:5	6646500	1442500	Mv 102	6617220	1431300
L 86:25	6624330	1425300	Lundström et al. 1998			Mv 105	6618280	1431210
L 86:26B	6621650	1425450		6629150	1435900	Mv 106	6618230	1431020
L 86:28	6614800	1430350	Outhius & van Berkel 1988			Mv 128	6619450	1432930
L 86:3	6612400	1426600	79	6628750	1416500	Mv 129	6619560	1432720
L 87:35B	6619260	1432600	285	6628000	1416300	Mv 130	6619640	1432730
L 87:36A	6619440	1433040	281/1	6628710	1416400	Mv 131	6619640	1432730
L 87:41	6620600	1435600	301L	6628950	1415140	Mv 132	6618810	1432670
L 87:52	6624300	1432400	80/1A	6628650	1416850	Mv 148	6622580	1433810
L 88:16	6607100	1447630	80/1B	6628650	1416850	Mv 169	6624470	1432330
L 88:20A	6605300	1442700	80/2	6628650	1416850	Mv 172	6624470	1432330
L 89:10	6632500	1443000	80/5	6628650	1416850	Mv 173	6624470	1432330
L 89:11B	6627000	1442750	23B	6630180	1415400	Mv 174	6624250	1432510
L 89:40	6627220	1434700	80/5A1	6628650	1416850	Mv 246	6621550	1429020
L 89:41	6627220	1434700	80/5A2	6628650	1416850	Mv 253	6621700	1430320
L 89:45	6627100	1437550	80/5A3	6628650	1416850	Mv 257	6622930	1429480
L 90:27	6632520	1430800	82A	6631100	1415980	Mv 264	6623820	1430040
L 90:31	6631500	1432800	Sandahl 1988			Mv 270	6623810	1430590
L 90:35	6633800	1429900	BBAA87200	6592880	1443920	Mv 285	6620620	1433680
L 90:41	6633600	1428780	BBAA87201	6592880	1443920	Mv 295	6619740	1433170
L 90:47	6633600	1429820	BBAA87202	6592879	1443921	Mv 319	6623160	1433850
L84:40	6607400	1435500	BBAA87203	6592879	1443921	Mv 334	6624160	1431240
LB 79:1	6624530	1425140	BBAA87204	6592879	1443921	Mv 338	6624230	1431320
LB 79:3	6623300	1425610	BBAA87205	6592879	1443921	Mv 340	6624160	1431240
LB 79:383	6617840	1427040	BBAA87206	6592879	1443921	Mv 341	6624160	1431240
LB 79:384	6617200	1427430	BBAA87207	6592879	1443921	Mv 342	6624160	1431240
LB 79:387	6621500	1428940	BBAA87208	6592878	1443922	Mv 343	6624160	1431240
LB 79:388	6616050	1426550	BBAA87209	6592878	1443922	Mv 397	6619070	1433640
LB 79:43	6618130	1425070	BBAA87210	6592878	1443922	Mv 44	6618980	1429560
LB 79:76	6617960	1426860	BBAA87211	6592853	1443947	Mv 44a	6618980	1429560
LB 79:81	6616630	1427070	BBAA87212	6592853	1443947	Mv 45	6619870	1429500
LB 79:98	6616430	1426820	BBAA87213	6592852	1443948	Mv 50	6618220	1430460
						Mv 51	6618220	1430460
						Mv 55	6617840	1430480

sample #	N (RT90)	E (RT90)
Mv 58	6617590	1430530
Mv 59	6617590	1430530
Mv 61	6618180	1430710
Mv 62	6619600	1430210
Mv 63	6619600	1430210
Mv 64	6619600	1430210
Mv 65	6619080	1431620
Mv 70	6619170	1431640
Mv 71	6619170	1431640
Mv 73	6619390	1431610
Mv 74	6619390	1431610
Mv 77	6619390	1431680
Mv 87	6619360	1431940
Mv 88	6619540	1431830
Mv 98	6617800	1431160
Mv 99	6617800	1431160
Ra 193	6616160	1431760
Vd 1136	6622380	1432150
Vd 1492	6624170	1433700
Vd 1507	6622800	1433760
Vd 1530	6623890	1433970
Vd 1531	6623680	1434020
Vd 1535	6623570	1433870
Vd 1671a	6622170	1435120
Vd 1674	6622020	1435090
Vd 1689	6621710	1434600
Vd 199	6620390	1436250
Vd 31	6620770	1435430
Vd 315	6621260	1434850
Vd 405	6621650	1435830
Vd 597	6623610	1431100
Vd 70c	6620970	1434850
Vd 804	6620770	1435670
Vv 29	6620060	1429380
Vv 30	6620060	1429380
Vv 31a	6619720	1430200
Vv 32	6619150	1430690
Vv 36	6619060	1431840
Vv 37	6619620	1431870
Vv 6	6620850	1434010
Vv 80	6622000	1432180
Valbracht & Helmers 1988		
2961	6619300	1444050
102B	6619300	1444050
102CD	6619300	1444050
102CL	6619300	1444050
102ED	6619300	1444050
102EL	6619300	1444050
102F	6619300	1444050
1O2A	6619300	1444050
296B	6619300	1444050
296III	6619300	1444050
Sundblad et al. 1993		
S-1	6637700	1433240
S-2	6637900	1433130
S-3	6638150	1433070
S-4	6638400	1433050
S-5	6638240	1432670
S-6	6637760	1432560
S-7	6637830	1431720

The Morön silver deposit

Anders Hallberg

Abstract

Two distinct types of mineral deposits have in the past been mined at Morön, in the north-eastern outskirts of Skellefteå, northern Sweden. The geologically oldest of the mineral deposits is a Palaeoproterozoic marble occurrence with documented quarrying since the 16th century. The geologically younger is a galena-bearing vein mineralisation that was mined intermittently during several periods in the 19th century. In unpublished documents, written during the time the mines were active, it was reported that the galena-bearing veins cut all rocks in the area and consist of calcite with accessory fluorite and galena.

The lead isotopic composition of vein galena is highly radiogenic indicating that the vein is substantially younger than the country rocks and that the lead was derived from selective leaching of radiogenic lead in source rocks. Galena-bearing calcite-fluorite veins with similar lead isotopic compositions are also found close to and within the Caledonides where they have been interpreted to be of Caledonian age. However, similar veins, with radiogenic lead isotopic compositions, are also found elsewhere in the Fennoscandian Shield suggesting that this vein type is not necessarily related to the Caledonian orogeny, although Phanerozoic ages are suggested for most of them.

It is suggested that the galena-bearing vein mineralisation at Morön is another example of this type of widespread galena-bearing vein deposits that has no direct relation to any of the Precambrian ore-forming events, thus excluding any relation to the Palaeoproterozoic mineralisations of the Skellefte district.

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Introduction

The Morön silver deposit, located in the north-eastern outskirts of the town of Skellefte in northern Sweden, is often mentioned in overviews of mineralisations in the Västerbotten County (Tegengren 1924, Högbom 1937, Gavelin & Kulling 1955). Although this deposit was mined for silver in the past it has no present economic significance.

Several authors have pointed out the resemblance of the Morön silver deposit to other galena-bearing vein type deposits elsewhere in the Västerbotten County (Högbom 1937, Gavelin & Kulling 1955), deposits that are interpreted to be related to the Caledonian orogeny (Johansson 1983, Grip 1973). However, galena-bearing veins with similar mineralogy and isotopic signature have also been recognised at several locations in the Fennoscandian Shield at large distances from the Caledonides (Sundblad et al. 1999) and a Caledonian age and genesis for these can be questioned.

This paper presents a summary of older descriptions of the Morön deposit, together with new lead isotopic data on galena, with the purpose to shed light on the timing and genesis of the deposit.

History of the Morön deposit

André (1996) has documented the mining history of the Morön deposit. The following is a brief summary, translated to English, of that publication.

Limestone for mortar production was mined at Morön already in the beginning of the 16th century. Fine veins of galena in the limestone quarry were first mentioned in the beginning of the 19th century, but nothing was said of the silver content of the veins. A couple of years later, in 1807, a mining company was established by local entrepreneurs and farmers with the purpose to mine silver at Morön. According to documents at the Mining Inspectorate mining was initiated in 1806 and continued the next summer during which an ore zone a few inches wide had been followed to a few meters depth and some ten meters along strike.

Mining activity was interrupted by the war 1808–1809 and was stopped in 1814 due to the very poor results.

A new initiative to mine silver at Morön started in 1834–35. After excavations, one of them 18 meters deep, it was concluded that the ore zone did not become wider with depth, the silver-bearing galena was still only a few inches wide, and mining at Morön was finally terminated in 1841. An attempt to restart mining in the beginning of the 20th century was never successful. Limestone quarrying at Morön continued on at least until the mid-19th century.

In 1958 it was decided that a cemetery should be built immediately to the north of the Morön deposit. The small excavation from the silver mining was filled and a few years later also the limestone quarry was filled.

Regional geology

The bedrock of the Morön area has recently been published on map sheet 22K Skellefte NO (Nilsson & Kero 1998 a) and a part of this map by is shown in Figure 1.

From this figure and the description in Nilsson & Kero (1998 a), it can be seen that the Morön area is dominated by an east–west trending belt of medium-grade metamorphosed supracrustal rocks. The supracrustal sequence consists of metagreywackes with subordinate felsic and mafic metavolcanic rocks with calcite marble as smaller and larger lenses. The supracrustal rocks are considered to belong to the Palaeoproterozoic Bothnian Supergroup (Kathol et al. in prep.). The area has been intruded by Early Svecokarelian intrusive rocks, mainly granites to granodiorites with an assumed age of 1.90–1.86 Ga, and younger, syn- to post-svecokarelian intrusive rocks, mainly granites (Nilsson & Kero 1998a). The mining activities in Morön took place in one of the marble lenses belonging to the metamorphosed supracrustal sequence. Several other marble quarries are found further to the east within the same supracrustal belt (Nilsson & Kero 1998b).

The Morön deposit

Galena-vein mineralisation was first noted in the marble quarry at Morön in 1804 by S.G. Hermelin (André 1996). No geological documentation is available from the mining activity during the early 19th century, but the deposit has been briefly described by several authors that visited the deposit after it was closed, but before the restoration of the area. Tegengren (1924) describes the Morön silver deposit as a nearly one hundred meter long galena-bearing calcite vein with accessory quartz, fluorite, and pyrite cutting pyritic felsic volcanic rocks with limestone layers and pegmatite dikes. Högbom (1937) distinguished the Morön limestone quarry from the Morön silver mine and mention that other deposits in the Västerbotten County (Grundfors, Djupselberget, and Norra Sjöliden) are similar to the Morön silver mine. Characteristic minerals for this type of deposits are, according to Högbom (1937), quartz, calcite, fluorite, and unevenly distributed galena with variable silver contents. Gavelin & Kulling (1955) briefly discuss the Morön Silver mine as one of several subeconomic galena-bearing calcite-fluorite veins in Västerbotten County.
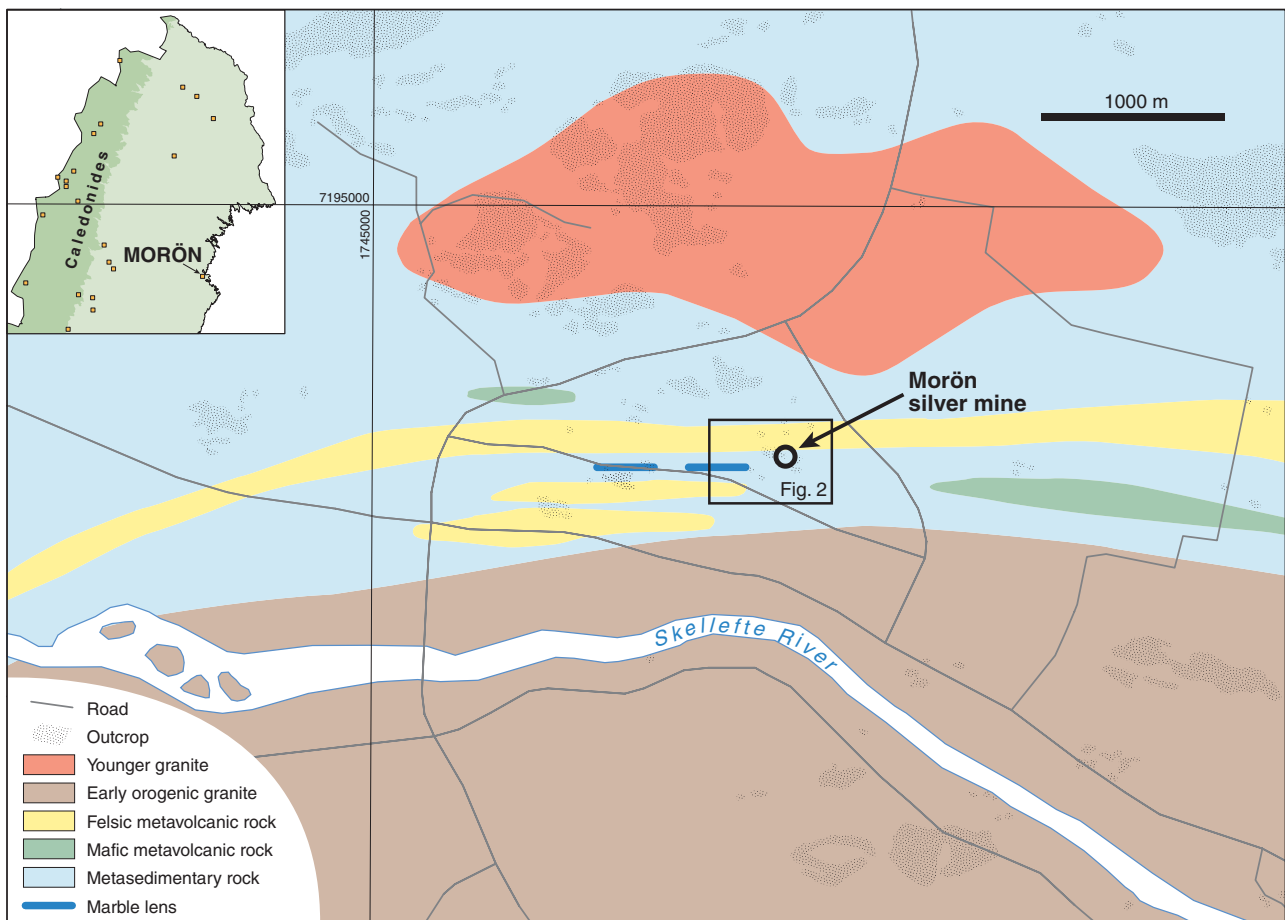
Fig. 1. Part of the geological map sheet 22K Skellefteå NO simplified from Nilsson and Kero (1998a). The location of the "Morön Silver Mine" and the outline of Figure 2 are shown. Inset map shows the location of the "Morön Silver Mine" in relation to other galena-bearing veins in northern Sweden.

Today very little can be seen of the remnants of the mining activity at Morön. Most of the mine area, including the limestone quarry and the Morön Silver mine, has been restored. Only the northern entrance to the limestone quarry and some of the NE-trending trenches from the silver mine can be seen. Some waste is found close to the entrance to the limestone quarry, but there is no trace of galena in the rocks.

Sampling and analytical procedures for the lead isotopic study

Two galena samples, M55 and M57, from the Morön silver mine, provided from the collections of the Geological Survey of Sweden (SGU) by Pär Weihed, were selected for a lead isotopic study. Small galena crystals were hand-picked and dissolved in HCl. The solution was further purified by electrolysis and finally mounted on Re-filaments. The analytical work was done on a Finnegan Mat mass spectrometer. The first run of sample M55 was of poor quality and a new batch was produced and the sample was rerun. Both results from sample M55 are reported together with the results from sample M57 in Table 1.

Table 1.

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
M-55*	25.27	16.532	41.496
M-55	25.285	16.553	41.563
M-57	25.086	16.51	41.292

Results and discussion

From the descriptions by Högbom (1937) it can be concluded that two types of economic mineralisation exist at Morön: a limestone deposit mined since the early 16th century and a sulphide mineralisation, the Morön silver mine, that was recognised and mined in the beginning of the 19th century. The locations for the deposits are given in Table 2.

Table 2.

Deposit	N	E
"Morön limestone quarry"	7293660	1747250
"Morön Silver Mine"	7293660	1747300
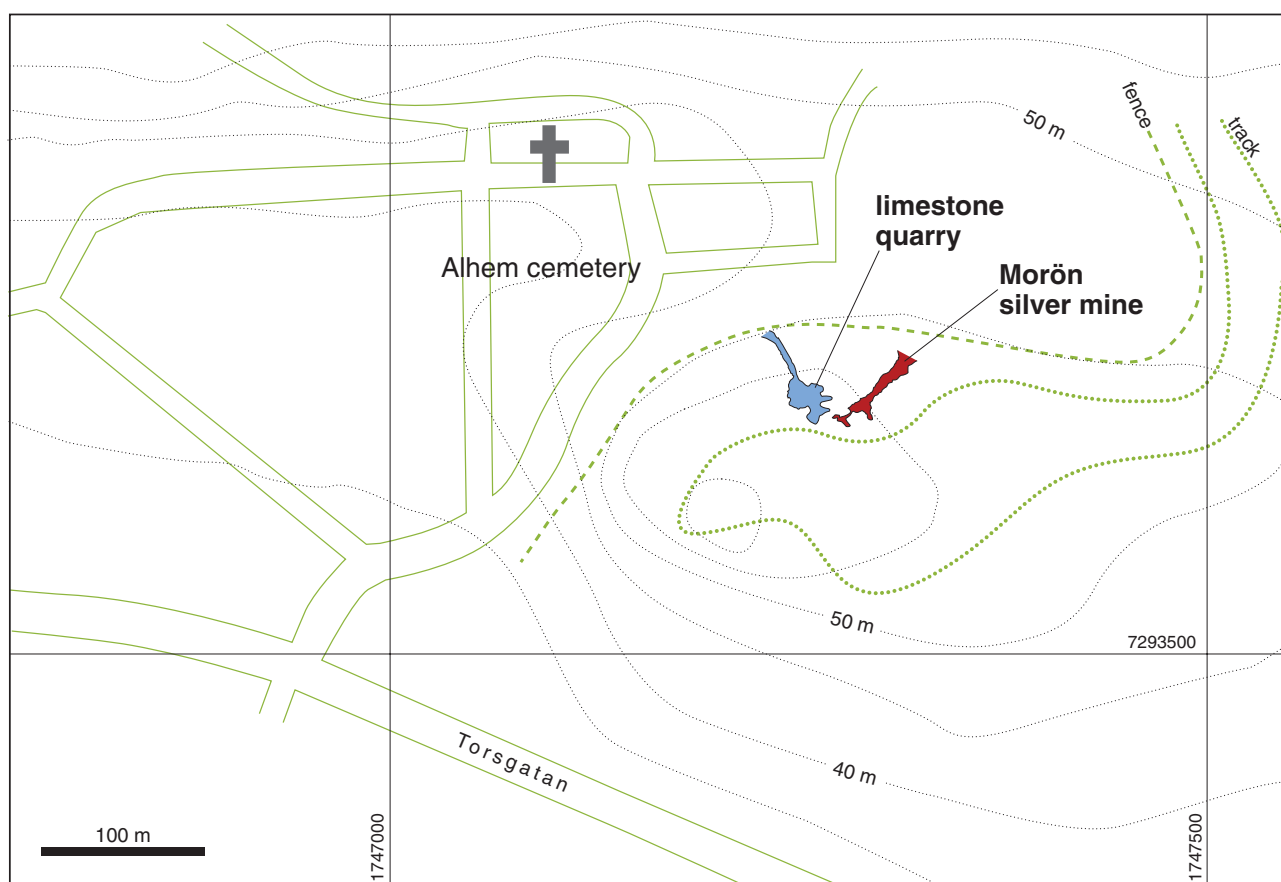
Fig. 2. Sketch map of the Morön area with location of the limestone quarry and the "Morön silver mine". Redrawn from old mine maps reproduced in André (1996). Co-ordinates for the deposits in the Swedish grid RT 90 are given in Table 2. The location of the map is shown in Figure 1.

The geological position of the Morön limestone quarry, within an east–west trending belt of carbonate-bearing metasupracrustal rocks, suggests that the limestone deposit at Morön consists of Palaeoproterozoic marble. Larger marble deposits occur further to the east where several have been mined (Nilsson & Kero 1998 b).

Old documents of the Morön silver deposit describe it as a galena mineralisation hosted by calcite veins with subordinate fluorite and pyrite (Tegengren 1924, Högbom 1937). The sulphide mineralisation cuts all other rocks in the area (Tegengren 1924) and the mine-map from 1810 (in André 1996) indicates that the sulphide mineralisation trends towards north-east (Fig. 2).

The lead isotopic composition of the galena is shown in Table 1 and graphically illustrated in Figure 3. Both sets of data show a highly radiogenic composition. Such a highly radiogenic nature of ore lead requires a source-rock with a significant crustal residence time to generate the radiogenic lead.
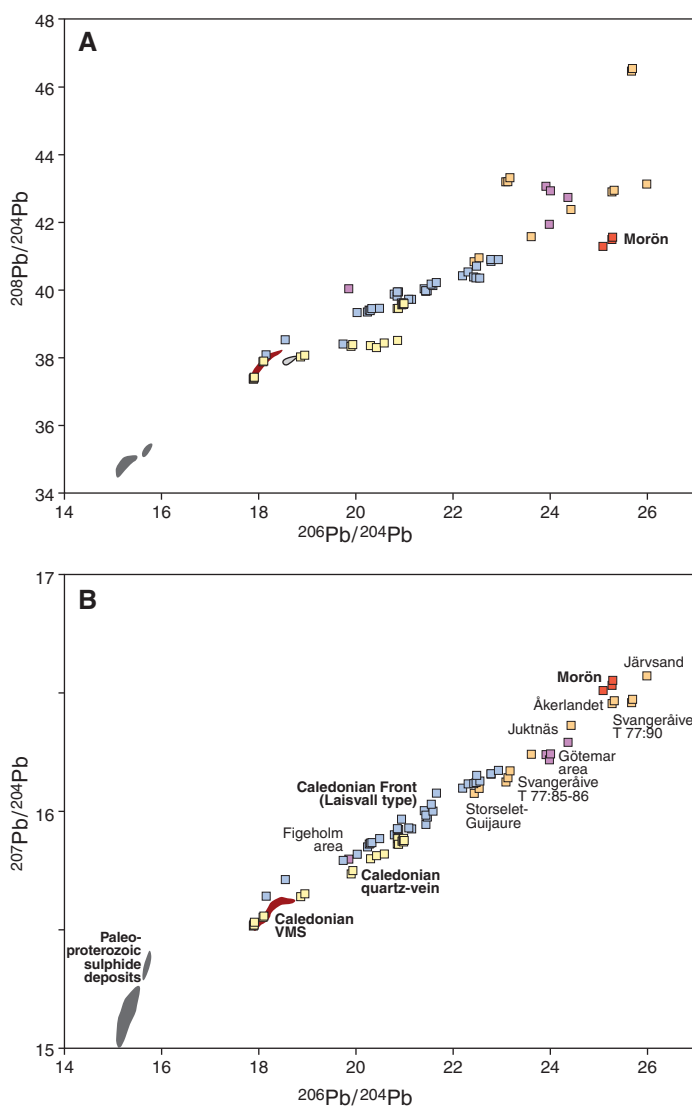
It also requires the radiogenic lead to be selectively leached from the source rock. The radioactive decay in uranium- and thorium-rich minerals not only produces radiogenic lead but also destroys the mineral making the lead more easily leachable. Thus, the strongly radiogenic ore lead composition suggests that the mineralisation was formed from selective leaching of radiogenic lead from much older source rocks than the galena.

In comparison with other sulphide deposits in Sweden, the isotopic ratio of galena from the Morön deposit shows strong resemblance to the compositions recorded for galena-bearing carbonate vein deposits in and close to the Caledonides, more than 250 km to the west of the Morön deposit (Johansson 1983). These galena-bearing calcite veins typically occur in the Palaeoproterozoic basement close to the Caledonides or in windows within the Caledonides (Johansson 1983). They occur as fractures and breccia fillings and are made of calcite with fluorite, galena, sphalerite, and locally pyrite (Johansson 1983). The radiogenic character of the Caledonian vein deposits has been interpreted to be due to selective leaching of easily accessible radiogenic lead from the host rocks, possibly also involving some magmatic lead (Johansson 1983). Grip (1973) considered the galena-bearing veins to be of Caledonian age based on their geographical location close to the Caledonian front and on their mineralogical similarities with the sandstone-hosted lead deposits along the Caledonian front (Laisvall-type). Based on the lead isotope composition of the veins Johansson (1983) agreed with Grip (1973) on a Caledonian or younger age.

However, galena-bearing veins with calcite or fluorite as dominant gangue minerals and with radiogenic lead isotopic composition have been recognised at several locations in the Fennoscandian Shield at large distances from the Caledonides

(Sundblad et al. 1999, Alm & Sundblad 2002). It can thus be questioned if the so-called Caledonian veins close to and within the Caledonides have any relation to the Caledonian orogeny or if they, together with other galena-bearing veins in the Fennoscandian Shield, make up a distinct ore forming event. Differences in lead isotopic compositions between the galena-bearing vein deposits can easily be explained by differences in age, provenance, chemical composition and initial lead isotopic composition of the source rocks.

Conclusions

Two mineral deposits exist at Morön, a Palaeoproterozoic marble and a later galena-bearing vein-type mineralisation. The galena-bearing vein mineralisation crosscuts all other rocks in the area and the strongly radiogenic isotopic composition of lead in the vein galena shows that the deposit is significantly younger than the country-rocks. This eliminates the possibility that sulfide mineralisation at Morön should be related to the major ore-forming event in the nearby Palaeoproterozoic Skellefte district where the main mineralisation event is dated at 1875–1885 Ma (Billström & Weihed 1996).

Mineralogical and ore lead isotopic similarities with galena-bearing veins found at other localities in the Fennoscandian Shield (Alm & Sundblad 2002, Sundblad et al. 1999) suggest that the galena-bearing vein mineralisation at Morön belongs to this group of vein-type deposits. Ore lead isotope data do not allow any precise age determination, but a Phanerozoic age, as argued for this type of deposits elsewhere (Alm & Sundblad 2002), is fully compatible with the data for the deposit at Morön.

Acknowledgements

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The Nyborg Zn-Ag-mineralisation, Skellefte District, Sweden

Jan-Anders Perdahl

Abstract

The Nyborg Zn-Ag-mineralisation, situated within the Kristineberg mining area, has been known since 1943 through drillings, although exploration in the area started already around 1930. The mineralisation occurs stratigraphically high in the Skellefte volcanic sequence. The rock types immediately above the mineralisation comprise metatuffites, schists, metabasalts, calc-silicate rocks, and ultramafic metavolcanic rocks. The mineralisation occurs as a stratiform thin layer following the stratigraphy but is atypical for ores of the Skellefte mining district as it is disseminated, whereas typical deposits are massive pyrite bodies. Ore minerals are sphalerite and pyrite with varying amounts of chalcopyrite and galena. A characteristic feature for some sections with high contents of Zn (5–12%) is creamy coloured sphalerite, which has caused some problems recognising the ore. Some massive pyrite bodies also occur within the sequence but without ore grades. Strong alteration occurs within the volcanic sequence as shown by the occurrence of mainly white mica and chlorite, but also andalusite. In the most extremely altered sections, the mineralogy consists of quartz and pyrite and, for example, the Al_2O_3 content is as low as 0.5%.

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Introduction

The Nyborg Zn-Ag-mineralisation is situated in the western part of the Palaeoproterozoic Skellefte mining district (Allen et al. 1997), 8 kilometres NE of the Kristineberg mine (Fig. 1). A large anticlinorium comprising metavolcanic and metasedimentary rocks with a central synmagmatic metagranitoid part (Claesson 1979) domi-
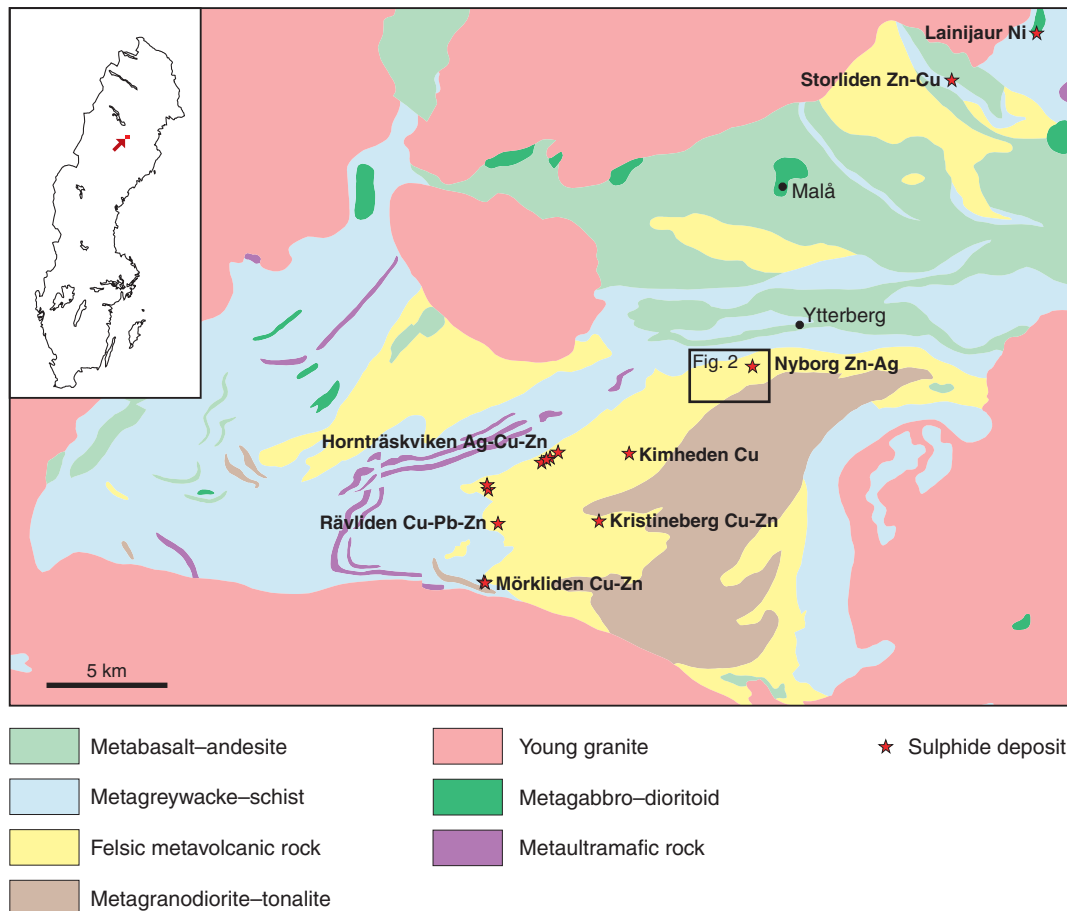
Fig. 1. Geological map of the Kristineberg mining area. Modified from Bergström & Sträng 1999.

nates the geology of the area. The metavolcanic rocks are felsic volcanoclastic rocks and subordinate mafic rocks. A stratigraphically overlying metasedimentary sequence comprises thick sequences of pelitic and arenitic rocks, locally turbiditic, with graphitic units in the lowermost parts. Mafic and ultramafic metavolcanic rocks and sills are frequent within the sedimentary units. Higher up in the sequence, a thick mafic metvolcanic unit with volcanoclastic rocks and subordinate lava flows occur, the Tjamstan Formation (Bergström & Sträng 1999). The mineralisation is situated, as most of the ores of the Skellefte mining district, close to the contact between the felsic metavolcanic rocks and overlying metasediment.

The eastern part of the mineralisation is located in a simple stratigraphic sequence of mineralised felsic metavolcanic rocks overlain by tuffites with intercalation of mafic metavolcanic rocks and intrusions overly the mineralised felsic metavolcanic rock. The westernmost part is characterised by a rapid increase in thickness of the felsic metavolcanic rocks and alteration zone (Fig. 2). There are indications of presence of isoclinal folds, shears and brittle fracture zones, but the lack of outcrops restricts mapping

to drillcores. The absence of marker horizons makes it difficult to reconstruct the geology.

Prior to 1983, chemical analyses of samples from the area were mainly of the elements Cu, Pb, Zn, and Ag. After that, in 1983–84, 165 XRF whole-rock analyses of major and trace elements were made from drillcores, but were not fully evaluated. In this study, apart from compilation of the old material, new core logging and chemical analyses were made on cores from some of the 1977 drillings west of the mineralisation, that did not locate a Zn-mineralisation. The aim of this study was to compare an area with strong alteration without Zn-mineralisation with the immediate surroundings to the known Nyborg Zn-Ag-mineralisation.

Exploration history

The Nyborg area gained attention when magnetic and electromagnetic surveying were performed in 1929–30 in order to examine the ore-critical boundary between overlying metasedimentary rocks and felsic metavolcanic rocks south of the village of Ytterberg. Metasedimentary rocks
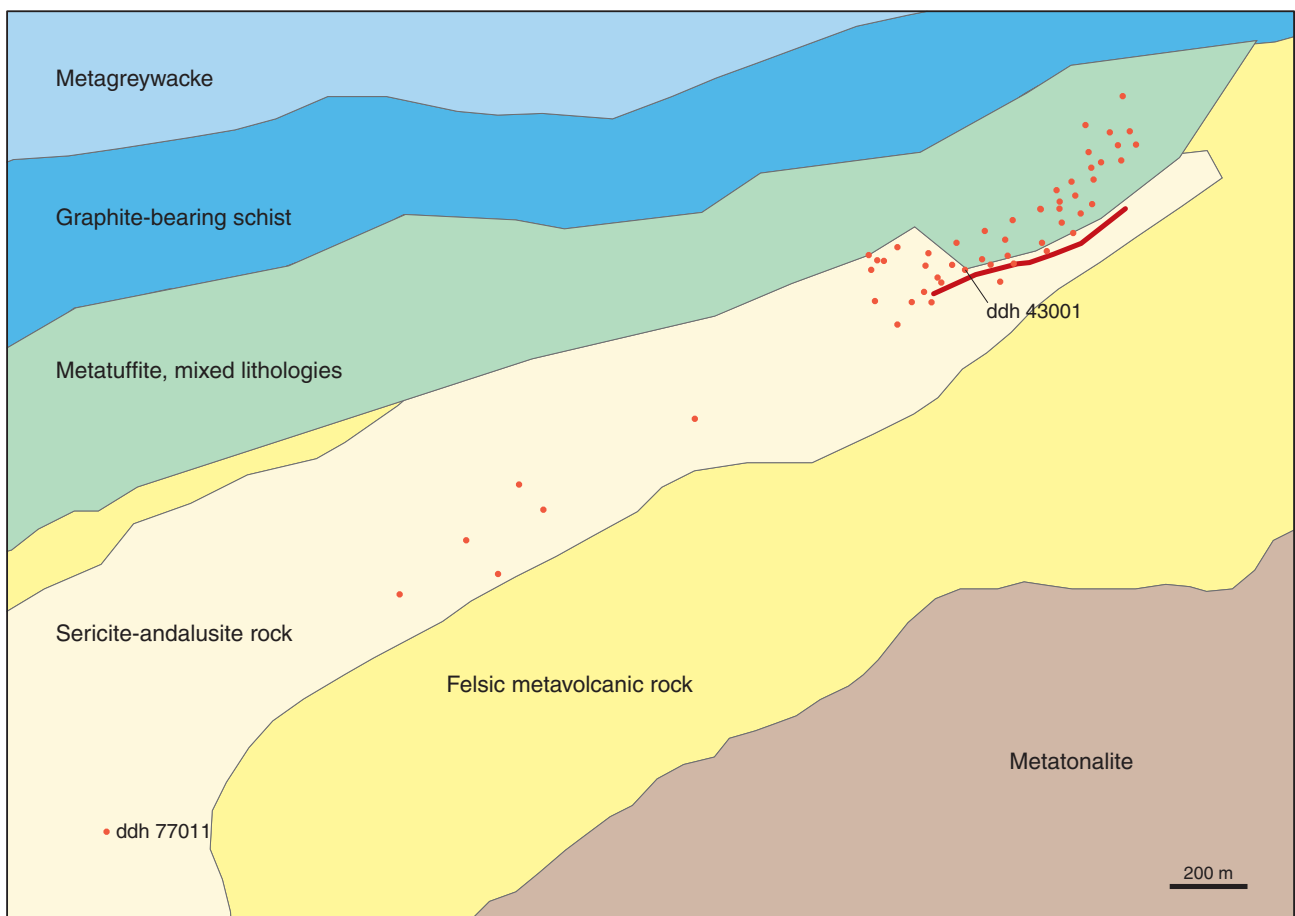
Fig. 2. Detailed geological map of the Nyborg area. Modified from Bergström & Sträng 1999.

Fig. 3. Detail from map of electrical measurements in the Nådagubbliden area. Hatched line denotes good conductor, thick dotted line weak conductor.
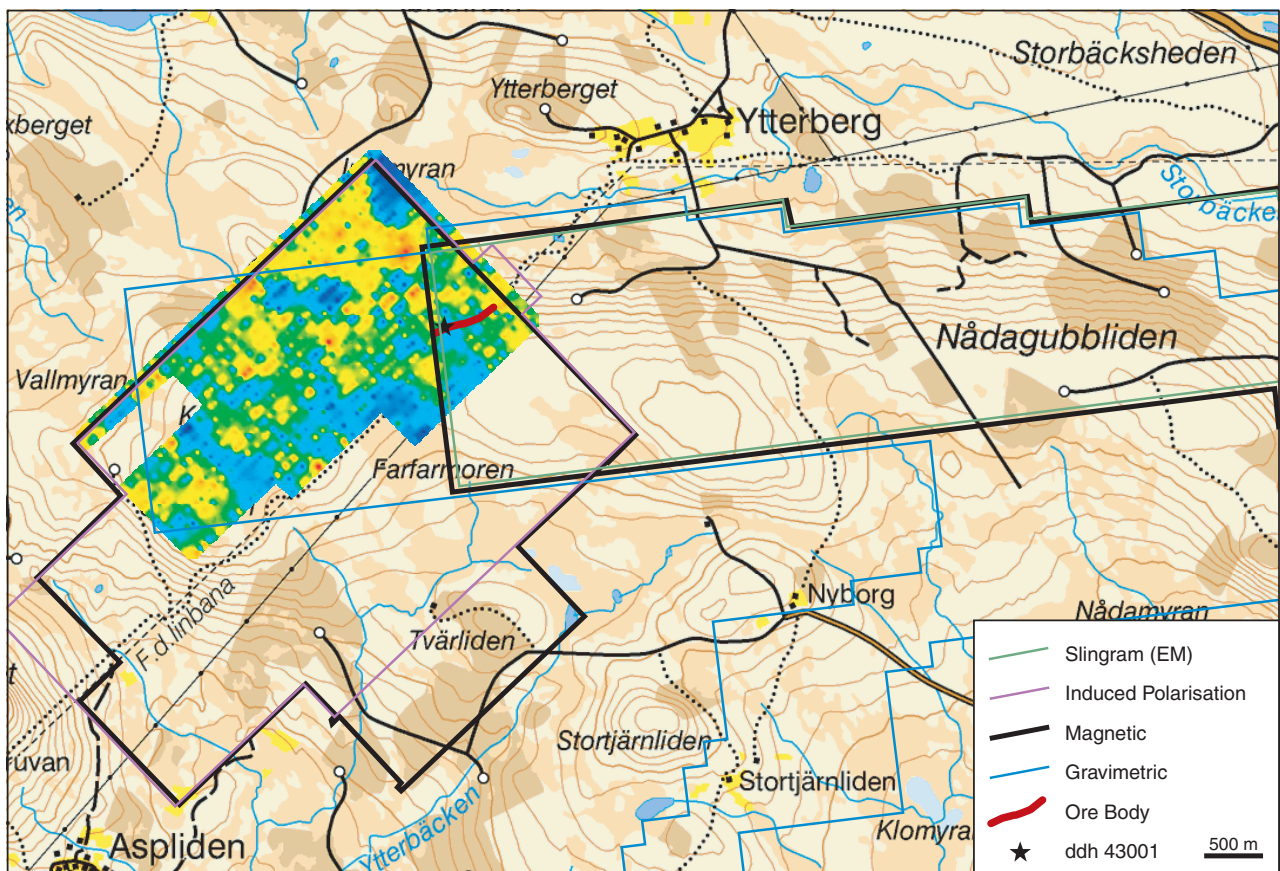
Fig. 4. Map of ground-geophysical measurements and geochemical soil Zn-anomaly map of the Nyborg area. Red colour denotes high Zn-content, blue colour low content.

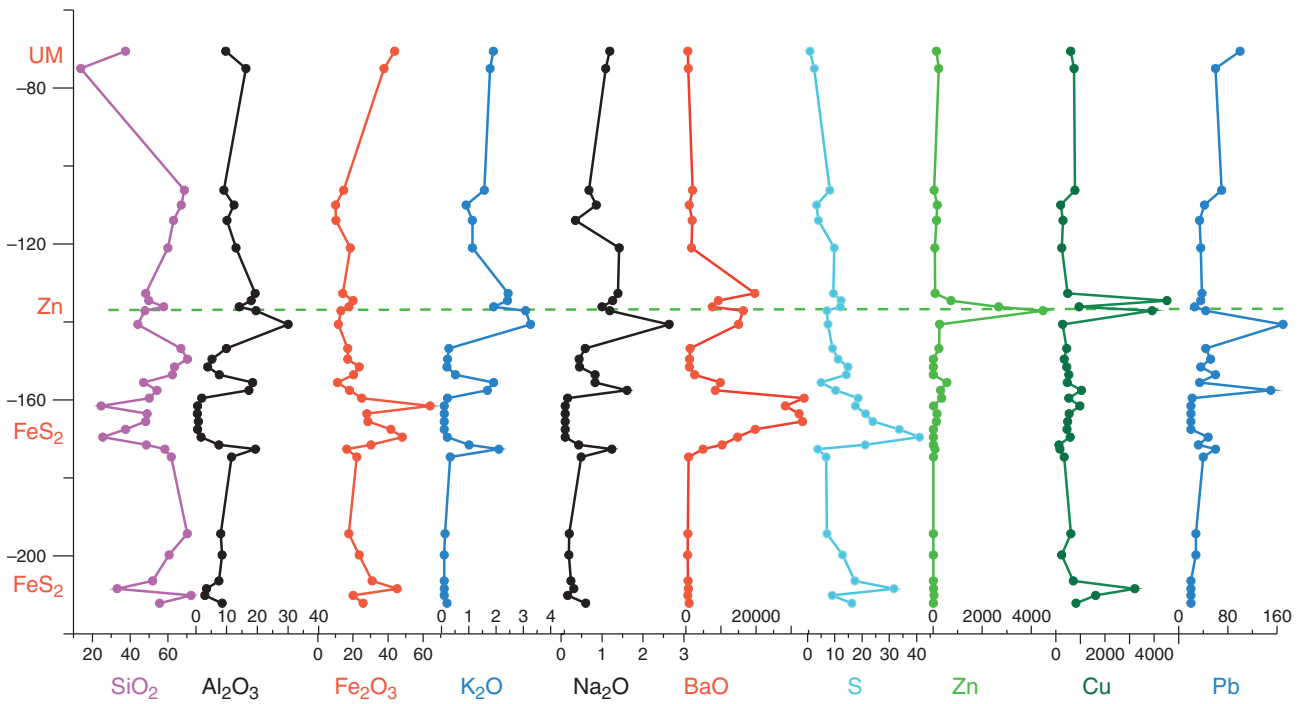**Fig. 5.** Chemical cross section of drillcore 83004. Western part of the Nyborg deposit. UM = metaultramafic rock, FeS_2 = massive pyrite body, Zn = Zn-mineralisation.
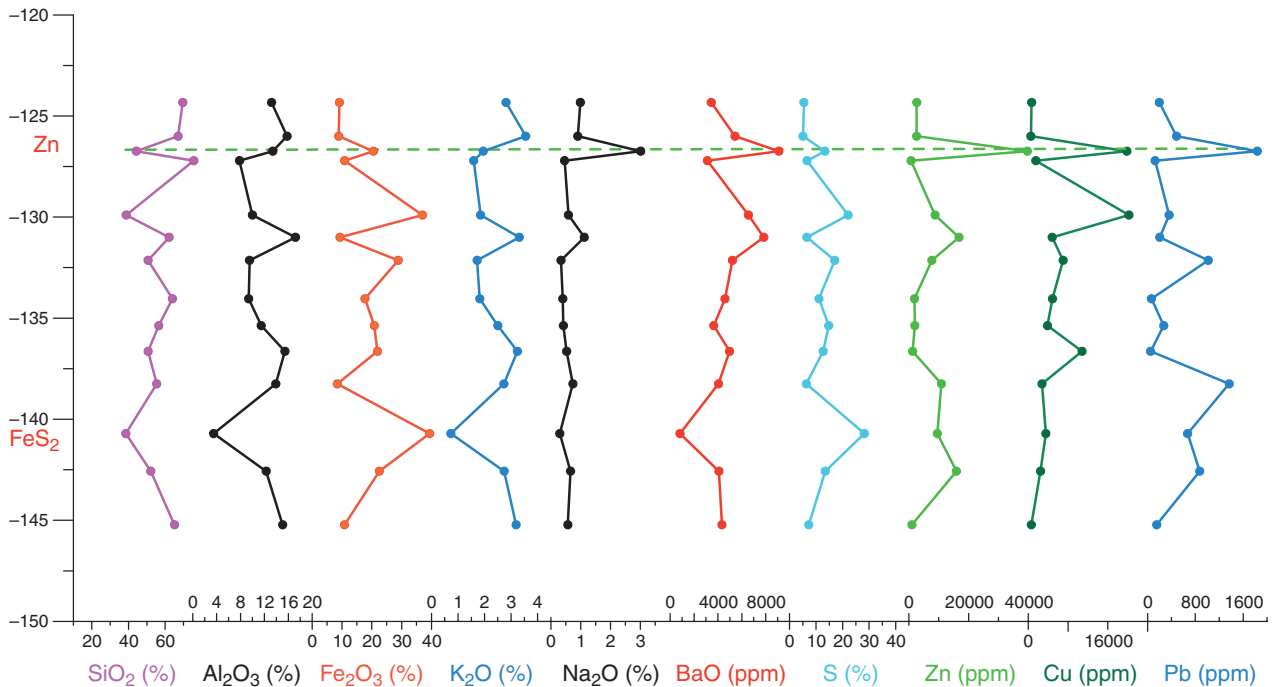
Fig. 6. Chemical cross section of drillhole 84001. Eastern part of the Nyborg deposit. FeS_2 = massive pyrite body, Zn = Zn-mineralisation.
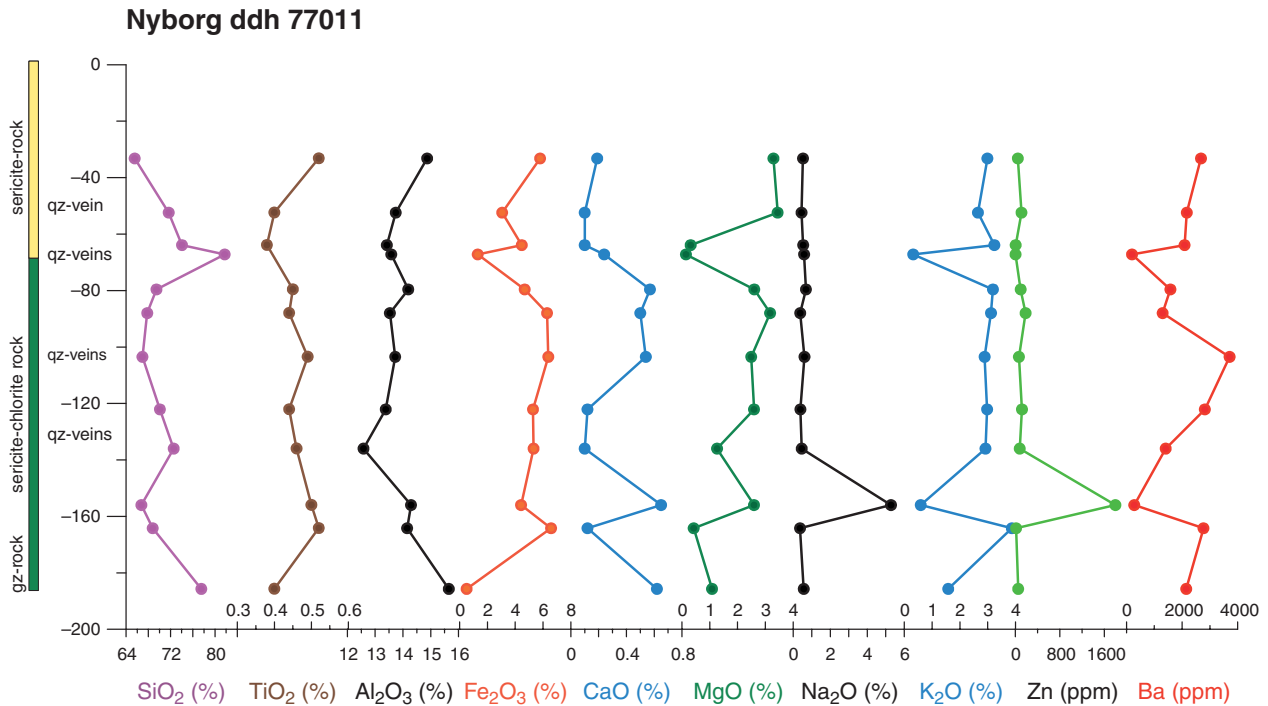
Fig. 7. Chemical cross section of drillhole 77011 and mapping of core. Unmineralised, west of the Nyborg deposit. FeS_2 = massive pyrite body, qz-veins = cross-cutting qz-veins, qz-rock = silicified rock.
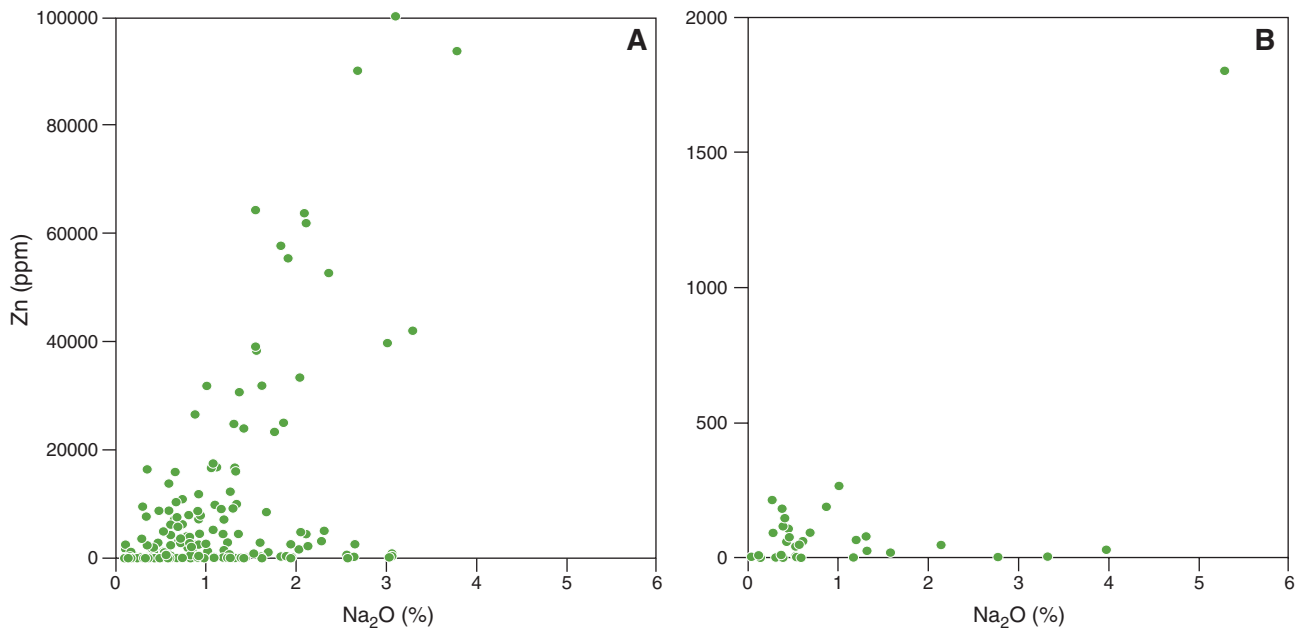
Fig. 8. Na_2O-Zn covariation diagram. a) within mineralised area, b) outside mineralised area (W of deposit). Observe the differences in scales on the Y-axes.

were known from a location at the northern base of the hill Nådagubbliden and to the south of the hill metavolcanic units outcrop (ABEM 1930). Several electric conductors were found in the Nyborg area (Fig. 3) and trenches were dug across some of them. The results, however, were not encouraging enough and the area was abandoned.

In 1943, a core (ddh 43001) was drilled through one of the conductors and a 1.3 metre thick section with 4.4% Zn, 1.58% Pb and 35 ppm Ag was intersected. The mineralisation was considered to be too thin and uneconomical.

Gravimetric measurements were performed in 1966–
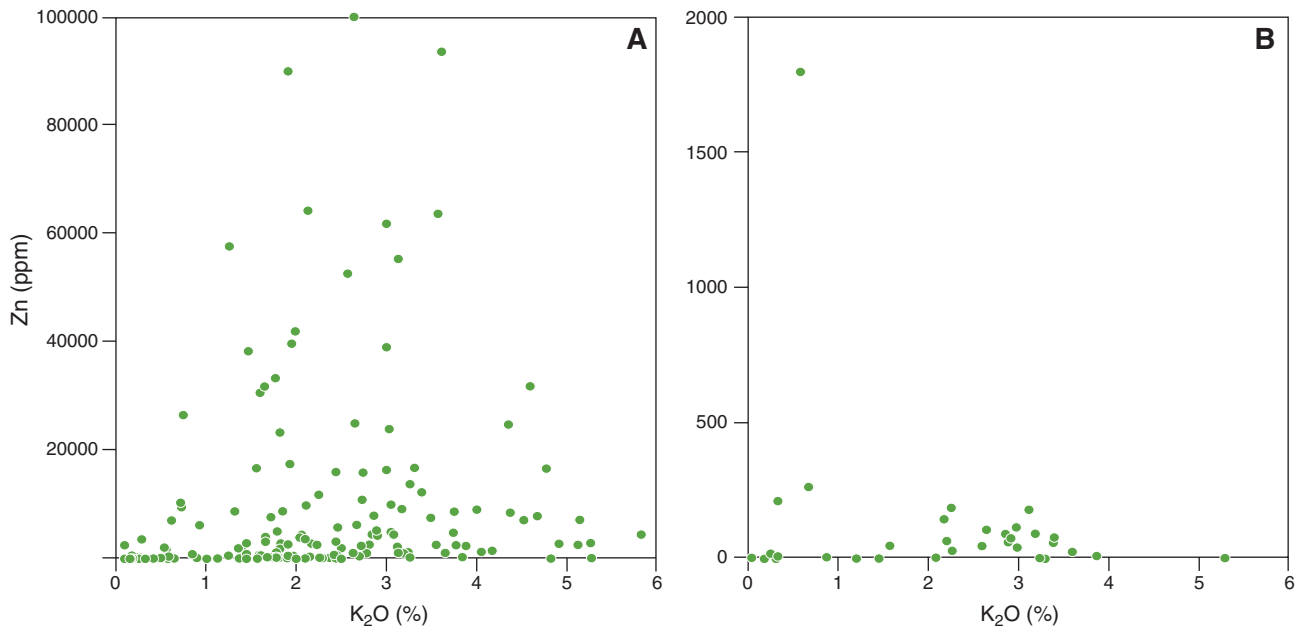
Fig. 9. K₂O-Zn covariation diagram. a) within mineralised area, b) outside mineralised area (W of deposit). Observe the differences in scales on the Y-axes.

67 in the Nåda area and they also covered the Nyborg area (Fig. 4). Aeromagnetic measurements in 1973 showed magnetic anomalies in the Nyborg area and they were followed up by detailed magnetic and electric measurements between 1974 and 1977. Dense geochemical bog and soil sampling at Nyborg done in 1975 showed Cu, Zn and Pb anomalies. Some of the geochemical anomalies coincide with the ore ropeway from the Kristineberg mine and most likely pollution from the ore concentrate (Claesson 1979).

Drilling programmes in 1976–77 (23 cores) and 1982–84 (33 cores) revealed an approximately 600 m long Zn-mineralisation and ore estimation resulted in 621 000 tonnes at 2.8% Zn, 0.47% Cu and 28 ppm Ag (Lindberg 1982, Lindberg & Theolin 1984). An alternative ore estimation increased the Zn content to 4.02% Zn, but decreased tonnage to 380 000 tonnes (Theolin 1985). Most of the drillcores from 1983–84 were analysed for major and trace elements by XRF technique shortly after they were drilled, but the analyses focussed mainly on sections close to the mineralised horizon.

Boliden Mineral AB claimed the mineralisation in 1996 and has since then been active in the area.

Mineralisation and alterations

The Zn-Ag-mineralisation occurs as a thin disseminated layer following the general strike of the stratigraphy (Fig. 2). It is a disc-shaped body, which measures c. 300 x 150 x 2–5 metres. The body strikes N70E and the plunges

gently to the east. The dip is 70–80 degrees towards NW in the eastern and central parts, but flattens out to 60 degrees towards NW in the western part (Theolin 1985). The rocks, just above the mineralisation (Fig. 2), comprise biotite schists, graphite schists, mafic metavolcanic rocks and intrusions, calc-silicate rocks, and metaultramafic rocks. The rocks are biotite-rich and increasingly chloritised and silicified towards the contact to the underlying mineralised horizon (Lindberg & Theolin 1984, Theolin 1985).

The ore mineralogy comprises pyrite, sphalerite, chalcopyrite, and galena in varying amounts. Characteristic for the mineralisation is the occurrence of cream-coloured sphalerite in some Zn-rich sections. This type of light-coloured sphalerite has also been reported from the Kristineberg mine (Du Rietz 1953). Scheelite has been found above the mineralised horizon within Ca-Mg-silicate rocks and mafic dykes.

Sericite alteration to varying degrees is typical for the volcanic sequence. In intensely altered parts the rock consists almost entirely of muscovite and quartz and in some sections the Al₂O₃-content reaches 30%. Biotite and other dark minerals have been altered to chlorite, sericite and pyrite. Zinnwaldite and lepidolite have been found in the muscovite-rich rock. Pyrite occurs as dissemination throughout the altered volcanic sequence. Small massive pyrite bodies occur locally and coarse-grained idioblastic pyrite is found in some altered mafic rocks. Ba-anomalous sections are associated with massive pyrite ore and also with Zn-mineralisation (Fig. 5). Sections with several

percent BaO are common even in the most intensely altered rocks. The most altered rocks occur in the western part of the mineralisation where all other elements but Si, Fe, S and Al have been strongly depleted (Fig. 5). Even the Al_2O_3-content decreases below 1% in some sections. The eastern part of the mineralisation does not show that strong alteration, having almost normal K-, Na- and Al-contents (Fig. 6).

Secondary andalusite occurs in the western part of the Nyborg mineralisation, stratigraphically below the Zn-mineralised horizon, and also to the west of it (Lindberg 1982). It occurs both as fine-grained impregnation and as up to cm-size, pinkish porphyryblasts. It has been considered to be useable as an industrial mineral (Hammergren 1991). The andalusite content varies between 5 and 40% and seems to increase with depth.

In some drillcores west of the Nyborg mineralisation massive pyritic bodies occur, however without ore grades of Cu, Zn or Pb. A relatively unaltered rock with rather primary mineralogy was encountered in drillcore 77011 at 156 m depth (Fig. 7). The sample is feldspar rich with pyrite impregnation, without macroscopic sericite and similar in character to the sericite-altered surrounding rocks. It is Na-enriched (5.28% Na_2O), but has very low K-content (0.59% K_2O) and the highest Zn-content (1800 ppm) of the analysed sections in the area west of the Zn-mineralisation. All other sections have less than 300 ppm Zn. This may indicate that fluids causing sericite alteration leached Na and Zn from rocks that already had undergone Na alteration. High contents of Zn often coincide with elevated Na contents (Fig. 8), indicating that Na-rich fluids probably also transported Zn. Potassium shows poor correlation with Zn (Fig. 9), and high K_2O content (>5%) seems to exclude high Zn-content.

Conclusions

The Nyborg Zn-Ag-mineralisation has several similarities to other mineralisations of the Skellefte mining district, in particular concerning stratigraphic level and wall rock and alteration mineralogy. However, the mineralisation is atypical for the district in that it is of disseminated type. Sericite and chlorite alteration is common within the foot-wall rocks, whereas andalusite is common below the ore in the western part of the mineralisation and further to the west. The barren 1977 drillings west of the Nyborg mineralisation was probably drilled too deep in the stratigraphy where K-altered unfavourable stratigraphic horizons occur. The Nyborg Zn-Ag-mineralised horizon occurs close to the contact zone between tuffites and felsic metavolcanic rocks and, if followed to the west, Hornträskviken and Rävliden deposits are found (Fig. 1). A continuation of the Nyborg mineralisation could be found along that contact zone rather than towards the Kimheden and Kristineberg mineralisations that occur deep down in the stratigraphy.

At least three alteration events can be discerned: a) an early stage with Na-alteration, b) a later overprinting stage with K-alteration, and c) a final stage with locally strong silicification. The latter stage formed andalusite, dissolved and diluted most elements except Si, Fe, Ba and S, and probably represents a proximal high thermal intense alteration. The low contents of Zn in massive pyrite ore bodies below the Zn-mineralisation implies that the K-alteration (that also caused andalusite formation) may have leached Zn and Na in the deeper parts and precipitated Zn (and Na) higher up in the sequence.

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Apatite-bearing iron ores in the Bergslagen region
of south-central Sweden

Magnus Ripa & Lutz Kübler

Abstract

The present paper reviews the genesis of apatite-rich iron ores of the Bergslagen region in south-central Sweden. Bergslagen is one of four major ore districts in the country. It is mostly known for sulphide deposits, but must, from a metallogenetic point of view, be regarded as an iron ore district. Economic iron deposits in Bergslagen comprise three different styles of mineralisation: banded iron formation, skarn iron ore, and apatite-rich iron ore. Traditionally, the apatite-rich iron ores are considered to be largely synvolcanic, but their restricted geographical distribution, as opposed to the other types of iron ores, which occur throughout the district, and their alignment along a roughly linear zone must be accounted for. These linear zones are roughly parallel to gravimetrical lineaments. It is concluded that most of the geological data suggest that the traditional genetic interpretation of the apatite-rich iron ores is correct, i.e. they formed epigenetically through processes related to the intrusion of synvolcanic dykes and cryptodomes. However, definite evidence of a premetamorphic origin is lacking.

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Introduction

The Bergslagen region of south-central Sweden is one of four major ore districts in the country. The other three are the northern Norrbotten county, the Skellefte district, and the Caledonides. Bergslagen is, from a historical point of view, the most important district, but today only three mines, mainly zinc deposits: Zinkgruvan, Garpenberg Odalfält and Garpenberg Norra (Fig. 1), are in production.

The region is mostly known for sulphide deposits like the Falun copper mine, the Sala silver mine, and the mines still in operation. From a metallogenetic point of view, however, the region must be regarded as an iron ore district – both in number of deposits and in total tonnage of Fe. Of the 42 largest deposits in the region (production ≥1 Mt), 32 are iron and 9 sulphide ores, producing (un-til 1993) 421 and 74 Mt, respectively (Åkerman 1994). In total, 5 955 iron and 1 000 sulphide occurrences in Bergslagen are found in the official database for mineral deposits (MDEP) of the Geological Survey of Sweden (SGU).

Economic iron deposits in Bergslagen comprise three different styles of mineralisation: banded iron formation, skarn iron ore, and apatite-rich iron ore (Geijer & Magnusson 1944). The latter type accounts for almost half of the production stated above. However, it was mined at only 54 sites in 5 ore fields (the Grängesberg, Blötberg, Fredmundsberg, Lekomberg, and Idkerberg fields, from south to north), which are all situated in a rather restricted area of western Bergslagen along a roughly north–north-easterly trending zone (Fig. 1).

The present project aims at reviewing the genesis of the apatite-rich iron ores of Bergslagen. Traditionally, they are considered to be largely synvolcanic (Geijer & Magnusson 1944; Allen et al. 1996), but their restricted geographical distribution, as opposed to the other types of iron ores which occur throughout the district, must be accounted for. Their alignment along a roughly linear zone parallels that of gold-bearing iron ores in Bergslagen (Fig. 1). The gold in the latter type is presumably synmetamorphic (Ripa 2001) and, as can be seen in Figure 1, geographically restricted to the western and southern parts of the area. These linear zones are also parallel to gravimetrical lineaments (figs. 1 and 2). Recent field work by SGU in other parts of Bergslagen has shown that some magnetite mineralisations may be related to synmetamorphic igneous activity, although apatite has not been identified in those cases (Bergman et al. 2001).

Initially, the project was planned to involve some field work, including geophysical investigations, but hitherto only a literature study has been performed. It is presently unclear if and when more investigations will be done within the project.

Activities

The literature study started with a review of the GeoRegister (a SGU-based metadatabase of geological literature in Sweden; cf. www.sgu.se). Some data, including geographical position, name, name of ore field (in some cases also name of sub-ore field), commodity, host rock, alteration minerals, country rock, tonnage (production and reserve),
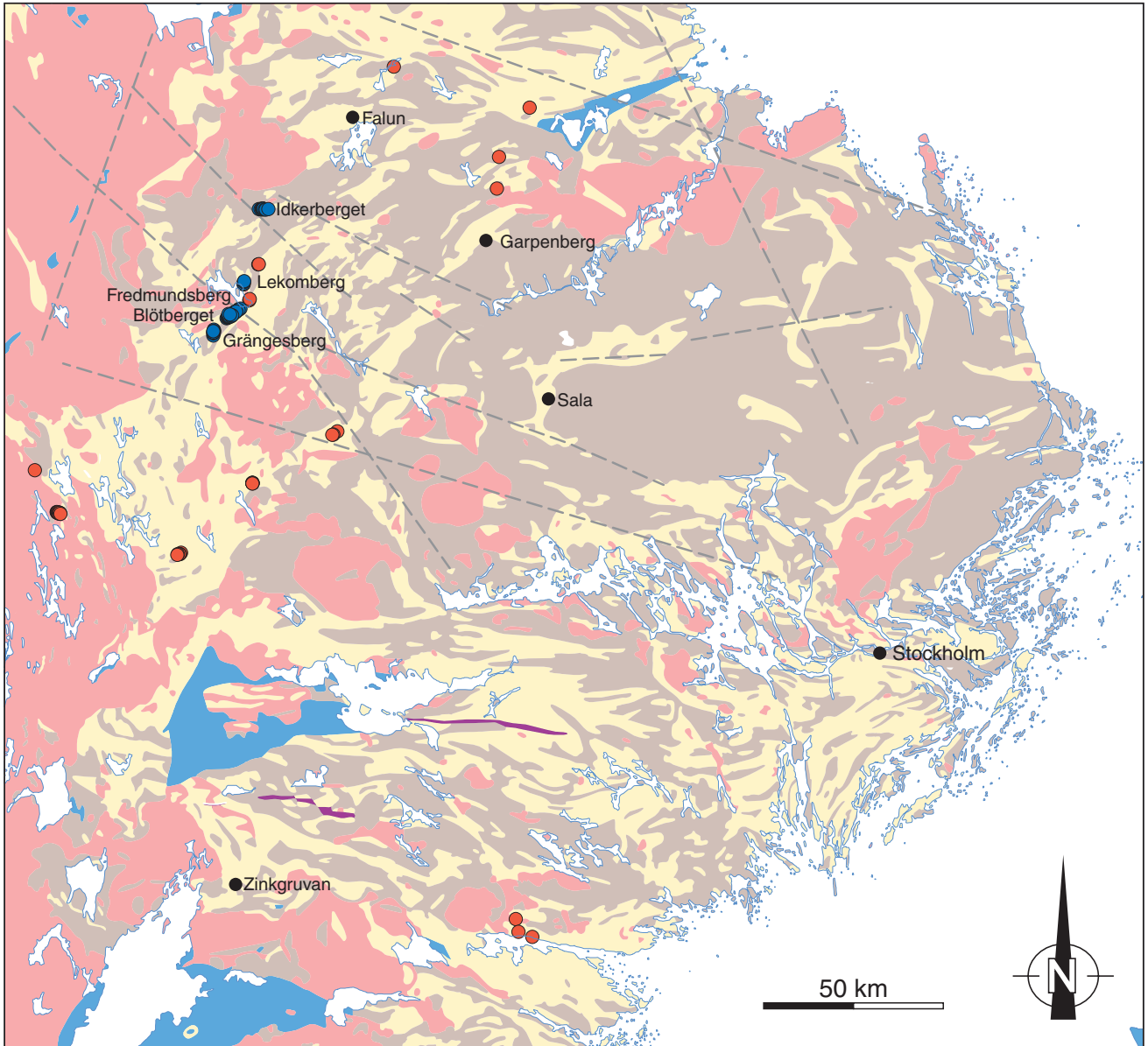
Fig. 1. Simplified geological map of the Bergslagen area (modified from Ripa 2001). The position of apatite-rich (blue dots) and gold-bearing (red dots) iron ores are indicated. Grey broken lines denote interpreted lineaments from the Bouguer anomaly map (Fig. 2). Sulphide deposits mentioned in the text are shown.

and production years and grade, for the 54 apatite-rich iron ores were compiled and MDEP was updated. Most of the data stem from Geijer & Magnusson (1944), Magnusson (1973) and Åkerman (1994). Some production figures are from an unofficial database at SGU (C. Åkerman pers. com.).

Regional geology

The oldest recognised rocks in the Bergslagen region belong to a Palaeoproterozoic, c. 1 900 Ma old (Lundström et al. 1998), metamorphosed volcano-sedimentary succession (Svecofennian), informally known as the "leptite formation" (e.g. Magnusson 1936). The metasupracrustal rocks consist dominantly of rhyolitic volcanic, subvolcanic and volcaniclastic rocks deposited in a submarine environment (Oen et al. 1982, Van der Welden et al. 1982, Lundström 1987, Allen et al. 1996). Subordinate intermediate and mafic volcanic rocks together with chemical, epiclastic and organogenic sediments occur at different stratigraphic levels of the volcanic pile.

Most mineral occurrences are hosted by skarn-altered carbonate rocks interlayered with volcanogenic ash-siltstone strata interpreted to represent distal volcanic facies (Allen et al. 1996). There is, however, a spatial and probably genetic relationship between more or less coeval subvolcanic intrusions emplaced into the distal facies and mineralisation. Thus, the ores are hosted by distal facies, but are genetically related to this somewhat later phase of igneous activity (Allen et al. 1996). Overlying (and locally also underlying) the volcanic rocks are argillites, greywackes, quartzites and conglomerates (Lundström 1995).

The supracrustal rocks were intruded by largely synvolcanic ("older") ultramafic to granitic rocks, mafic dykes, younger plutonic rocks, and late dolerites (Lundqvist 1979). The younger plutonic rocks consist of anatectic I- and S-type granites formed during peak metamorphism and of more or less coeval plutonic rocks of TIB-type, which formed a differentiated, syenitoid suite with alkali-calcic affinity (e.g. Ripa 1998).

The supracrustal rocks, the older plutonic rocks, and the mafic dykes were deformed and metamorphosed at varying grades during the Svecokarelian orogeny (Lundqvist 1979). Minor Mesoproterozoic and Phanerozoic sedimentary rocks are present in some areas.

Geology of the apatite-rich iron ores

The following description of the geology of the apatite-rich iron ores is mainly compiled from Geijer & Magnusson (1944). Some data is from Allen et al. (1996) and from field work by the authors during the regular SGU mapping programme.

The host rocks of the massive, economic parts of the ores are mostly dacitic to andesitic, feldspar porphyritic metavolcanic rocks. According to Geijer & Magnusson (1944) the host rocks are in part "agglomerates" and they suggest that the agglomeratic character may be due in part to primary and in part to secondary (alteration) factors. We suggest that the term volcanic breccia (or possibly volcanic conglomerate) is preferable to "agglomerate" since the primary pyroclastic origin of the rocks is uncertain. Conformable amphibolites of unclear origin (volcanic or intrusive?) are rather abundant, especially in the northern ore fields, and the northernmost deposit is hosted by an amphibolite. The amphibolite is surrounded by syenitic gneiss. Disseminated ore is locally hosted by bedded, felsic volcanic siltstone. The host rocks and mineralisations were cut by largely coeval dacitic, andesitic and basaltic dykes and subvolcanic intrusions, and by synvolcanic, granitic to intermediate plutonic rocks. Pegmatites, granites and aplites intruded during subsequent metamorphism. The youngest rocks in the area are dolerite dykes.

In general, the premetamorphic rocks were severely deformed and metamorphosed and show a strong cleavage and a pronounced lineation. The main deformational events that are recognized in the area were largely synmetamorphic. Possible older tectonic structures were overprinted or obliterated. The metamorphic grade varies from medium to upper amphibolite facies. The country rocks in the northernmost ore field, Idkerberget, are described as gneisses in the older literature, whereas in Grängesberg primary volcanic textures may still be identified (although with uncertainty).

The host and country rocks of the deposits were, like most volcanic and subvolcanic rocks in Bergslagen (cf. Frietsch 1982, Lagerblad & Gorbatschev 1985), variably hydrothermally altered during or shortly after deposition. Geijer & Magnusson (1944) state that the host rocks at Grängesberg initially were K-altered, but then partly Na-altered during the mineralising event. Ore-related alkali alteration was accompanied by skarn formation. Iron mineralisation and skarn formation was stronger in the matrix of the volcanic breccias than in the clasts. Allen et al. (1996) documented magnetite dissemination and brecciation in subvolcanic metadacitic rocks.

Both magnetite and hematite constitute the ores. The former mineral dominates, but it is evident that much magnetite formed from original hematite. Hematite ores are commonly less massive, less apatite-bearing, less skarn-altered and have a slightly different skarn mineralogy compared to the magnetite ores. The hematite-dominated parts of the ores contain more quartz and feldspar.

In general, the skarns are composed of variable modal contents of apatite, quartz, actinolite, hornblende, biotite, muscovite, feldspar, epidote, garnet, pyroxene, orthite, fluorite, scheelite, molybdenite, and sphene. Locally, more Mg-rich minerals like tremolite, anthophyllite, and cummingtonite are found. Calcite occurs in some deposits.

Geijer & Magnusson (1944, p. 340) claim that in the larger ores "pegmatitic material mixes with the ore itself … and with the alteration zones (*gränskölarna* in Swedish)" and conclude that a genetic link is apparent between (these) skarns and pegmatite intrusions. On p. 490 they note that pegmatitic to aplitic rocks are impregnated by iron ore and a biotite-hornblende skarn. In parts of the Grängesberg field (at the Risberget subfield), skarn brecciation cross-cuts the main ore horizon. In the contacts between late pegmatites and iron ore, hematite was altered to magnetite, locally via a zone of martite.

Ore grades vary between the different ore fields. The richest ores at Idkerberget locally had 62% Fe, but generally ranges were from 49 to 53% in the Lekomberg field and from 58 to 60% in the Blötberget, Grängesberg and Idkerberget fields. Phosphorus ranged from 0.6 to 1%, but was locally high enough for mining as apatite ore.

Geophysical data

Geophysical data for the Bergslagen district was compiled and evaluated by Stephens et al. (2000). In this study only a preliminary geophysical interpretation based on that information has been performed.

No regional scale geophysical feature has any obvious bearing on the distribution of the apatite-rich iron ores. The roughly parallel trends of the apatite-rich and gold-bearing iron ores are more or less parallel to the western limit of an area of slightly denser rocks in northern Bergslagen (Fig. 2). The low-density areas shown in Figure 2 may be correlated with the intrusion of syn- to post-metamorphic, mainly felsic rocks (Öhlander & Zuber 1988). A geographical correlation with rocks with higher densities may possibly be interpreted from Figure 2. The positive Bouguer anomaly roughly corresponds to the distribution of the older intermediate metaintrusive rocks mentioned above. At depths, they may grade into more mafic and denser rocks.

Discussion

The apatite-rich iron ores of Bergslagen constitute an oddity among the iron ores of the region: They occur only in a relatively small number (54 of 5 955) in a geographically restricted part and their tonnage is relatively large compared to the other types of iron ore. It is thus possible that their style of formation is different from that of the others.

The host and country rocks of the apatite-rich iron ores are different from the other two iron ore types. The latter are both hosted by skarn-altered carbonate rock or by skarn-altered volcanic ash-siltstone (Allen et al. 1996, Ripa 2001). Most volcanic country rocks in Bergslagen are rhyolitic in composition and intermediate and mafic volcanic rocks are subordinate. They form, together with the synmagmatic, older intrusive suite of rocks, a calc-alkaline differentiation trend (e.g. Ripa 1998). In the restricted part of Bergslagen where the apatite-rich iron ores occur, intermediate volcanic rocks (subvolcanic intrusions and dykes) are dominant and amphibolites are rather frequent. At Idkerberget, the surrounding country rock is a syenitic gneiss, which may suggest alkaline affinity. Thus, the volcanic host stratigraphy of the apatite-rich iron ores is different from that of the other types.

The observations by Geijer & Magnusson (1944), that apatite-rich iron mineralisation is hosted by volcanic breccias ("agglomerates") and that both host rocks and ores were cut by synvolcanic dykes favour an interpretation of an epigenetic, but synvolcanic genesis for the apatite-rich iron ores. This interpretation is to some extent contradicted by the observation by Allen et al. (1996) that subvolcanic intrusions also were mineralised, since the dykes and the subvolcanic intrusions most likely were synmagmatic (probably also comagmatic). However, in a synvolcanic scenario, the subvolcanic intrusions, including the dykes, would be the most likely energy source for metal-transporting systems and parts of the subvolcanic rocks could therefore also be mineralised.

The fact that skarn-altered rocks associated with the apatite-rich iron ores locally grade, in an unclear fashion, into pegmatites and that hematite was altered to magnetite at pegmatite contacts (Geijer & Magnusson 1944) is direct evidence that late, synmetamorphic processes, other than solely providing heat, were important for the genesis of the present parageneses. Some skarn minerals, like feldspar, fluorite, scheelite, and molybdenite, have distinct granophil affinities. Thus several of the present minerals may have formed due to inflow of metamorphic fluids. From the description by Geijer & Magnusson (1944) it is evident that skarn formation occurred during at least two stages. These were either a) one synvolcanic phase and then a metamorphic phase or b) two metamorphic phases.

The linear trend (Fig. 1) of the apatite-rich iron ore occurrences (and the gold-bearing iron ores) is roughly parallel to the north-east trending axial surface trace of the main synmetamorphic folds in Bergslagen (cf. Stephens et
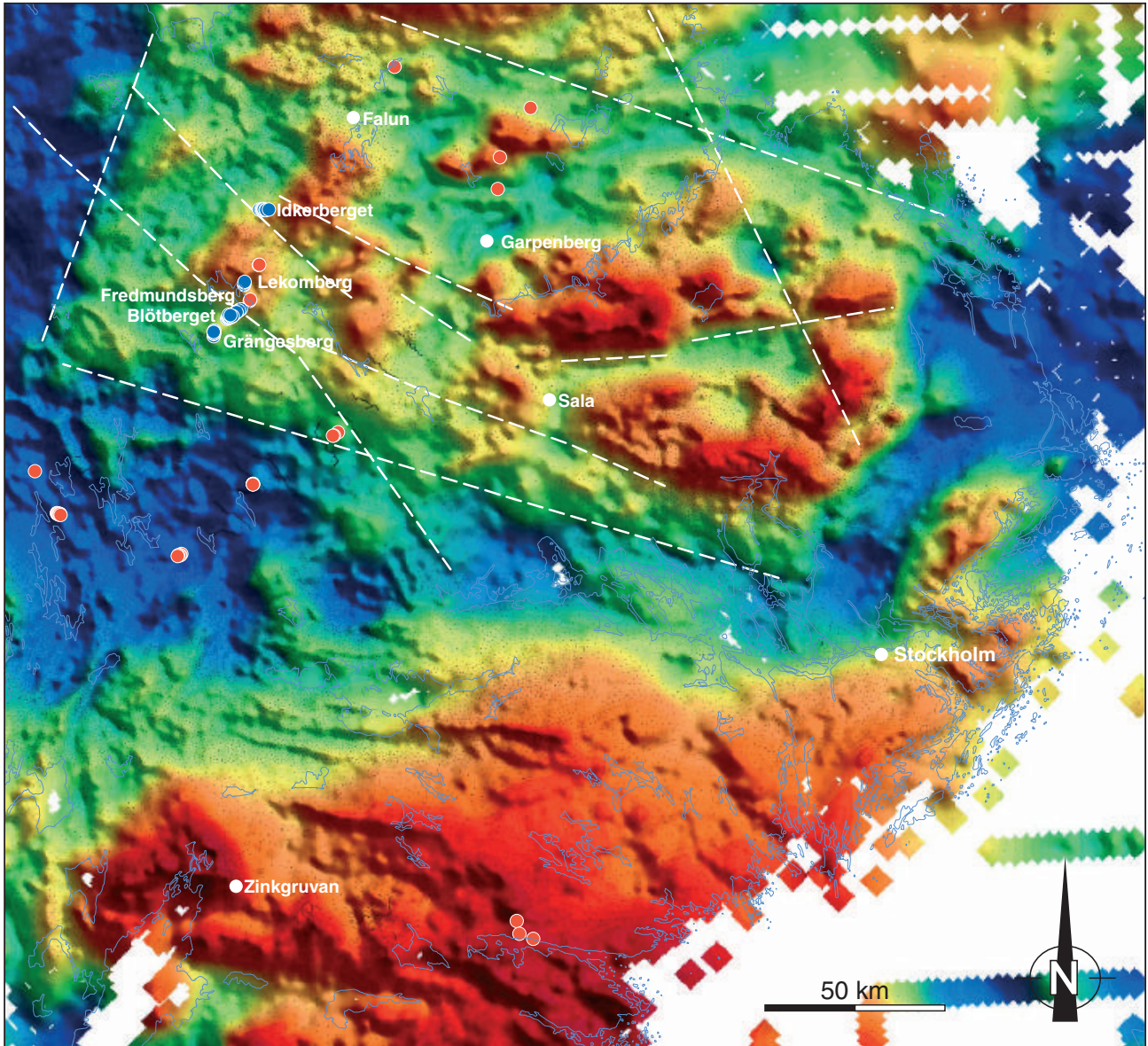
Fig. 2. Bouguer anomaly map of the Bergslagen area (modified from Stephens et al. 2000). Blue colour denotes low-density areas and red colour higher-density areas. Location of iron ores as in Figure 1. White broken lines denote interpreted lineaments.

al. 2000). This could imply that the ore-forming system somehow was controlled by synmetamorphic structures. On the other hand, all older rocks were more or less transposed into parallelism with these structures (see Fig. 1).

Ripa (2001) suggested that gold in the Bergslagen iron ores was related to metamorphic processes and synmetamorphic magmatic rocks. The geographic position of the gold-bearing iron ores (Fig. 1; and of the apatite-rich ores), however, suggests that not all of the younger plutonic rocks are interesting in the context. Both apatite-rich and gold-bearing iron ores tend to occur close to younger plutonic rocks of TIB-type in the westernmost part of the region. Thus apatite- or gold-bearing skarns have a spatial and possibly genetic relationship with synmetamorphic structures and TIB-type magmatism.

Conclusions

In our opinion, most of the geological data suggest that the traditional genetic interpretation of the apatite-rich iron ores is correct, i.e. they formed epigenetically through processes related to the intrusion of synvolcanic dykes and cryptodomes. However, definite evidence of a premetamorphic origin is lacking.

The skarn-altered rocks related to ore formation were modified during regional metamorphism, which more strictly should be referred to as metasomatism since extensive (further than grain-to-grain transport) mass movement was involved. To what extent skarn and ore minerals actually formed during metamorphism is unclear.

Acknowledgements

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Nickel exploration in northern Sweden
by the Outokumpu Oyj company

Christer Åkerman

Summary

Evaluation of data from Västerbotten County by the Outokumpu Oyj company, Finland, shows, like earlier studies, that most sulphide-rich mafic to ultramafic cumulates bear evidence of contamination by sulphide- and graphite-rich schists by having high contents of vanadium and molybdenum. The anomalous crystallization series: olivine–orthopyroxene–plagioclase–clinopyroxene existing in Rörmyrberget, Västerbotten, and Maniliden, southern Norrbotten, may also be the result of large-scale contamination processes. Some samples taken from the Ekträsk and Gissträsk layered intrusions in Västerbotten represent such a crystallization sequence. In both Ekträsk and Gissträsk there are samples (among which are most of the sulphide-rich cumulates) anomalously rich in vanadium. The parental magmas of the Rörmyrberget and Maniliden intrusions consisted of Mg-rich "basalts" with c. 13% MgO and were more primitive than comparative ultramafic to mafic intrusions in Finland, whereas the Inner-Åträsket magma with c. 10% MgO is similar to the Finnish ultramafic to mafic intrusions.

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Introduction

This paper is a general summary of reconnaissance and exploration work with focus on mineralisations in ultramafic to mafic intrusions in northern Sweden performed by the Outokumpu Oyj company in the years 1990 through 2001. While that work was in progress I had the opportunity to meet with the Outokumpu Oyj Exploration Manager at that time, Harry Rosenqvist, for discussions about prospects within the framework of the previous Swedish nickel exploration project. Also, during that time I studied selected parts of the following Outokumpu Oyj company reports, which are the basis for this summary:

Jokela (1995, 1996), Lamberg & Liipo (1996), Lamberg & Ylander (1998, 1999), Liipo & Lamberg (1996), Rosenqvist (2001) and Rosenqvist & Pietilä (1999).

Chemistry, petrography and petrogenesis of nickel exploration samples from Västerbotten and southern Norrbotten

117 rock samples from 43 different nickel occurrences, of which 28 are treated to some extent in this paper (Fig. 1) have been used for a classification of rock types. The classification is mainly based on whole-rock analyses and CIPW normative mineral composition. The classification of samples is based on chemistry rather than on mineralogy since the number of thin sections was limited and the mineral parageneses mainly are metamorphic. The material was divided into the following main types and subtypes (numbers in weight percent):

1) Peridotite (MgO >30%)
2) Pyroxenite (MgO 20–30%)
2a) Clinopyroxenite (CaO >10%)
2b) Orthopyroxenite (CaO <10%)
3) Gabbro (MgO 12–20%)
3a) Gabbro (Al_2O_3 = 7–15%)
3b) Olivine gabbro norite (Al_2O_3 = 5–10%, CaO <10%)
4) Mesogabbro (MgO <12%, Al_2O_3 >10%)
5) Pyroxene porphyry
6) Country rocks

As mentioned, the present mineral parageneses are metamorphic and consist mainly of tremolite, orthopyroxene and olivine/serpentine. Based on true mineralogy the rocks can be classified as: a) serpentinite, b) metapyroxenite, c) amphibole rock, d) metagabbro, and e) porphyry. Despite the overprinting caused by amphibolite facies metamorphism, relict cumulus textures can be recognised in some samples. The present mineralogies correlate poorly with the chemical rock types.

Most of the studied intrusions seem to consist of cumulates representing either the so-called Rörmyrberget (RÖR) or the Inner-Åträsket (INÅ) type of crystallization sequences. The Rörmyrberget type refers to crystallization sequences from olivine through orthopyroxene and clinopyroxene to plagioclase with the production of the following cumulates:

– olivine orthocumulate (oOC) with MgO >42%
– olivine-bronzite cumulate (obC) with 38–40% MgO
– bronzite-olivine cumulate (boC) with 33–38% MgO
– bronzite cumulate (bC) with 18–33 % MgO
– augite-bronzite cumulate (abC) with 20–25% MgO

– plagioclase-augite cumulate (paC) with 12–16% MgO
– bronzite-plagioclase cumulate (bpC) with 10–12% MgO
– plagioclase cumulate (pC) with <10% MgO

A calculated forsterite content of 86–88% implies a parental magma of high magnesium basalt containing between 14 and 18% of MgO. The magma is further characterized by low CaO/Al$_2$O$_3$ (0.3–1) and high Al$_2$O$_3$/TiO$_2$ (20–40) ratios.

The fractionation assemblage of Inner-Åträsket differs from the one in RÖR in that clinopyroxene appears earlier as a cumulus mineral, at c. 27% MgO. The following cumulates have been identified:

– olivine cumulate (oC) with >38% MgO
– olivine-bronzite cumulate (obC) with 31–38% MgO
– bronzite-olivine cumulate and bronzite cumulate (boC and bC) with 28–31% MgO
– bronzite-augite-olivine cumulate (baoC) with 24–28% MgO
– augite-bronzite cumulate (abC) with <24% MgO.

The mineral assemblages in INÅ are not as well defined as those in RÖR and the continuation from abC is not known. The highest calculated normative forsterite content of olivine from INÅ-type magma is 80–81%, implying a magma with c. 10% MgO. The CaO/Al$_2$O$_3$ ratio is slightly above 1 and the Al$_2$O$_3$/TiO$_2$ ratio is around 15. The magma has tholeiitic affinity and is similar to magmas of Svecofennian ultramafic to mafic intrusions in Finland (Lamberg & Liipo 1996).

Mineralised samples, with more than 0.5% Ni, from eight occurrences were included, i.e. the Maniliden, Grannäs, Gårkälen, Ultervattnet, Långbacka, Vallen, Källmyrberget, and Kälen occurrences (Fig. 1). The most Ni-rich samples were collected at Källmyrberget (1.53% Ni$_{tot}$, 1.39% Ni$_{sph}$) and Maniliden (1.51% Ni$_{tot}$, 1.27% Ni$_{sph}$), of which the latter are olivine-bronzite cumulates and, compared to non-mineralised samples with the same MgO content, richer in CaO and poorer in Al$_2$O$_3$. Evaluation of data shows, as in earlier studies (see Papunen & Gorbunov 1985), that most sulphide-rich cumulates bear witness to contamination with sulphide- and graphite-rich schists by high contents of vanadium and molybdenum. The anomalous crystallisation series olivine–orthopyroxene–plagioclase–clinopyroxene existing in Rörmyrberget and Maniliden may as well be the result of large-scale contamination processes. Some 30% of the samples from the Ekträsk and Gissträsk layered intrusions in Västerbotten represent that kind of crystallisation sequence. In both areas there are samples, among which are most of the sulphide-rich cumulates, which are anomalously high in vanadium.

Taking into account the nickel depletion features (total Ni, Ni/(Ni + Co) and Ni content versus MgO), the degree of primitivity of magma from which cumulates have crystallised, the coherency of the fractionation series, and total nickel content, the Maniliden, Kälen, Holmsvattnet, Brännarträsk, and Gårkälen deposits are ranked as the most promising targets. Generally speaking, the RÖR-type seems more prosperous, due to crystallisation from a more primitive magma, than the INÅ-type. The Maniliden prospect of the Blåliden area seems to be at least equally interesting as the ones in Västerbotten County.

The RÖR-type intrusions differ from Svecofennian ultramafic to mafic intrusions in Finland (Lamberg & Liipo 1996) by having crystallised from more primitive magmas, as indicated by higher MgO contents and pertaining to other series of crystallisation. The lack of olivine adcumulates and mesocumulates and the few olivine orthocumulates in Västerbotten and Blåliden raises the question: have those parts of the intrusions not been encountered yet or do they not exist at all? This is a most critical question since nickel ore almost always is located in or below olivine adcumulates or mesocumulates in ultramafic rocks (see Papunen & Gorbunov 1985).

The cotectic order of mineral frequency is qualitatively: plagioclase, clinopyroxene, ortopyroxene, olivine, ilmenite, magnetite, apatite, and chromite (Lamberg & Liipo 1996). Therefore, the amount of olivine, pyroxene and plagioclase should be more than 25% by weight when they occur as cumulus minerals. The cumulates are divided in ortho-, meso- and adcumulates (Irvine 1982). The exact percentage limits of postcumulus material that can be used for each type may vary somewhat depending on the number and type of cumulus minerals, as well as the grain size and texture of the rock, but as a rule, postcumulus minerals constitute 25–50% by volume in orthocumulates, 7–25% in mesocumulates and 0–7% in adcumulates (Irvine 1982). The abbreviations are OC, MC and AC, respectively. The boundary between ultramafite and gabbro was set at 25% of plagioclase (instead of 10% as suggested by Streckeisen 1976). Gabbro plagioclase should be as cumulus mineral and if there is plagioclase in ultramafic rock it must be as an intercumulus mineral.

Intrusive Svecokarelian rocks have normally been given names according to traditional conventions, even though they in some cases have been described as cumulates. Lamberg (1990) was probably the first to consistently use cumulate terminology and, for the Porrasniemi intrusion in Finland, he elaborated a sub-division in three principal zones based on cumulus stratigraphy of the layered series as follows:

- Peridotite zone defined by cumulus olivine [o(c)C, oaC, obC, aboC, baoC]
- Pyroxenite zone defined by cumulus pyroxene [abC, baC, b(a)C]
- Gabbro zone defined by cumulus plagioclase (bpC, pC, phmC)

The MgO content is >20% and Al_2O_3 <5% in the Peridotite zone, MgO <15% and Al_2O_3 >10% in the Gabbro zone.

Selected prospects in Västerbotten county

Ekträsk and Gissträsk intrusions

The evaluation of the prospecting potential for nickel sulphides is based on 176 whole rock analyses performed between the years 1990 and 1998. An Automatic Petrological Evaluation (APE) program (Lamberg & Ylander 1998) was used to calculate several parameters from rock analyses data in order to enable comprehensive petrological analyses. Cumulate names were given to the samples according to CIPW normative mineral composition. Chemical composition for parental magmas were calculated, crystallization paths were defined, and the degree of openness of the system was calculated. Contamination and sulphide segregation features were studied.

Ekträsk

The intrusion is 10 km long and 2–3 km wide. 51 samples from outcrops, boulders, and two drill cores were studied. The highest encountered nickel value is c. 0.35%. The parent magma was relatively evolved, basaltic, with c.10% MgO. The nickel content in relation to degree of magma evolution indicates a certain amount of sulphide segregation. The fact that both sulphide-rich and sulphide-poor cumulates are included in the groups of nickel depleted and nickel undepleted samples indicates that processes may have been large-scale. In a possible situation with sulphide enrichment, the nickel content may, at the best, slightly exceed 5% in the sulphide phase. As a whole, the Ekträsk intrusion is sufficiently interesting in order to motivate more field-work. Especially a north-easterly located ultramafite with the most primitive olivine cumulate and where contamination and signs of sulphide segregation are indicated, should be studied in more detail. The relationship between ultramafic boulders and the gabbroid main body is unsolved and calls for further investigation.

Drilling on anomalies at Kalvtjärn, at the western part of the body, resulted in the discovery of ultramafic rocks, pyroxenite and serpentine pyroxenite, as well as gabbro. It appeared that the magnetic anomaly is caused by magnetite in serpentinite. A chain of magnetic anomalies in the northern part should be surveyed by drilling as they may be caused by ultramafic bodies.

Gissträsk

Surface dimensions of the intrusion at Gissträsk are 5 x 2 km. 125 samples have been studied, partly from six diamond drill cores performed by SGAB and the Outokumpu Oyj company in the years 1990–1992, partly from percussion drilling. Maximum nickel content encountered is c. 0.45%. The parent magma is relatively evolved, basaltic, containing 11–12% MgO. Sulphide-bearing cumulates are depleted in nickel whereas nickel-poor cumulates are not. This implies small-scale, local ore formation processes. The potential is considered mediocre. The most interesting part is the south-western contact of the body.

The Rörmyrberget intrusion

The investigation of rocks from Rörmyrberget showed scattered relict cumulus textures. The mineral assemblage olivine–orthopyroxene–tremolite/Mg cummingtonite is of metamorphic origin and demonstrates amphibolite facies conditions. The following cumulates were identified (volatile- and sulphide-free MgO content within parentheses):

oC (MgO >42%), obC (MgO = 38–40%), boC (MgO = 33–38%), bC (MgO = 18–33%), abC (MgO = 20–25%), paC (MgO = 12–16%), bpC (MgO = 10–12%), pC (MgO <10%).

According to the CIPW normative mineral composition they are ortho- or mesocumulates.

The parental magma of Rörmyrberget is somewhat less primitive than that of ultramafic rocks of the Thompson nickel belt, Canada. The crystallisation series olivine–orthopyroxene–clinopyroxene–plagioclase in Rörmyrberget differs from the series olivine–clinopyroxene–plagioclase in the Thompson belt and from that of Svecofennian ultramafic to mafic intrusions of Finland. Important and significant differences between the intrusivie rocks of Västerbotten and the Blåliden area on the one hand, and Stormi, Hitura and the Thompson belt on the other hand, are the lack of olivine meso- and adcumulates and the low frequency of olivine orthocumulate in the Swedish prospects.

The formation of nickel sulphide enrichment at a large scale necessitates access to nickel from considerable amounts of magma and this in turn requires turbulent
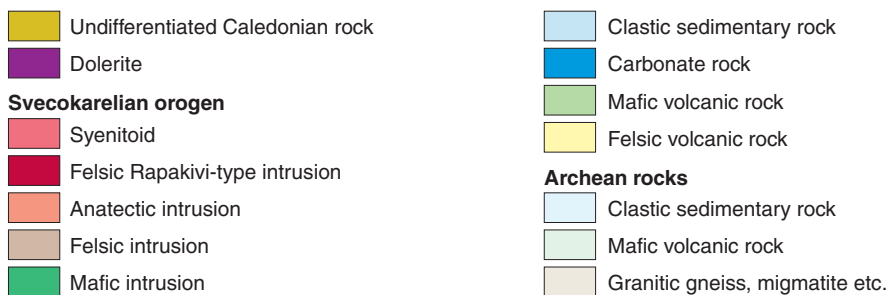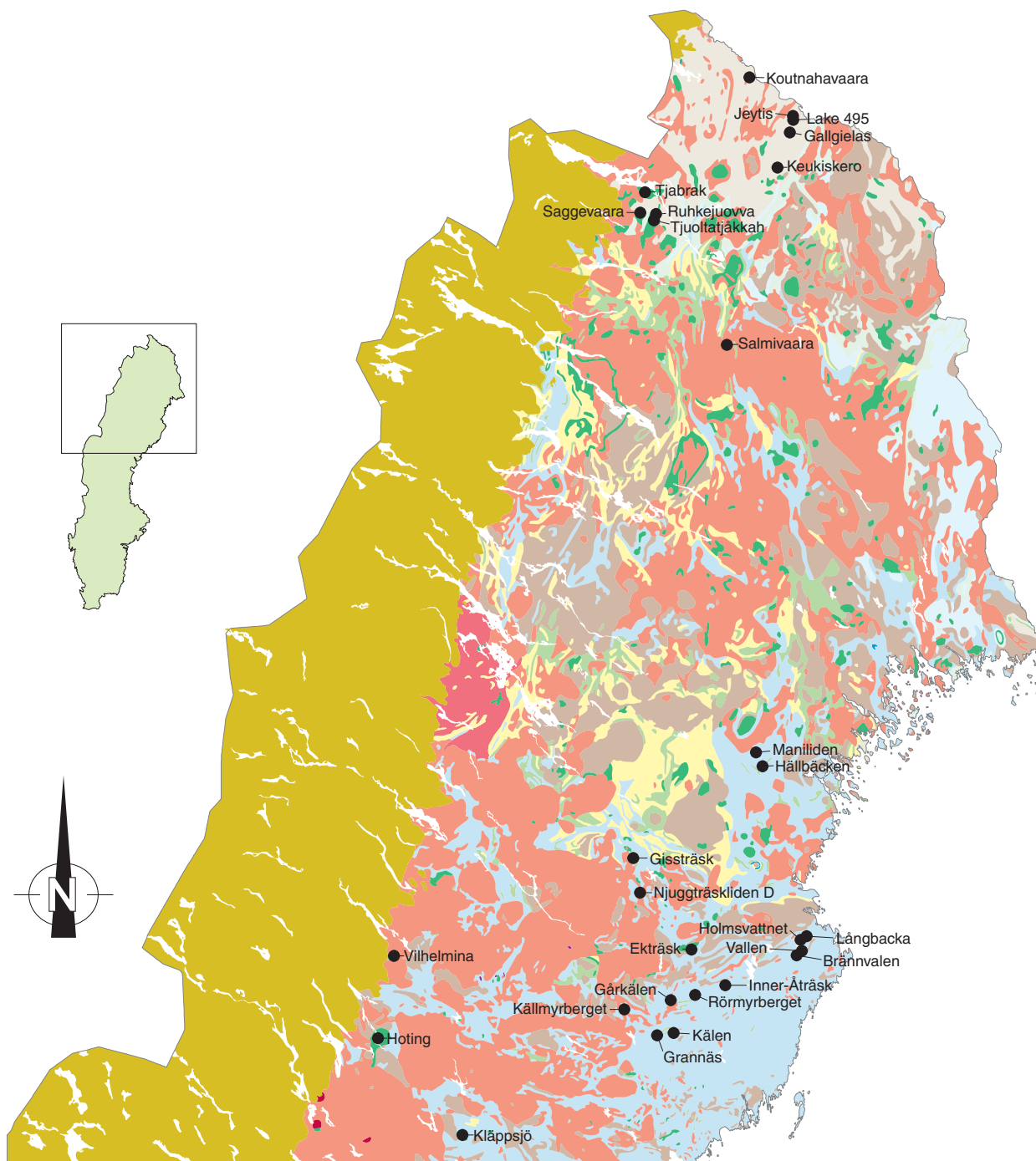
Fig. 1. Geological bedrock map of northernmost Sweden (simplified from Lundqvist 1994) showing the locations of some Ni occurrences.

flow of a relatively primitive magma during the time sulphide saturation for some reason is achieved.

The mineral paragenesis is metamorphic and consists largely of tremolite, orthopyroxene, and olivine/serpentine. On the basis of the present mineralogy they are classified as serpentinites, metapyroxenites, amphibole rocks, metagabbro, and porphyry.

The crystallisation sequence of the Rörmyrberget type is olivine-orthopyroxene, clinopyroxene to plagioclase. The forsterite content, calculated to 86–88% Fo, shows that the parental magma was a Mg-rich basalt ("high Mg basalt") with 14–18% MgO and characterised by low CaO/Al_2O_3 ratios (0.3–1) and high Al_2O_3/TiO_2 ratios (20–40).

After additional diamond drilling, evaluation suggests the existence of 0.7 million tons of a mineralisation containing 0.76% nickel. Two boreholes cut through the mineralisation at 600 m depth where the ultramafic rocks are about 400 m thick.

Inner-Åträsk

The crystallisation sequence of Inner-Åträsk differs from the one in Rörmyrberget in that clinopyroxene appears earlier as cumulus mineral, at c. 27% MgO. The highest calculated Fo content of olivine is 80–81% which implies a primary magma of about 10% MgO. The ratio CaO/Al_2O_3 is somewhat above 1 and Al_2O_3/TiO_2 about 15. This tholeiitic melt is similar to those encountered in Finnish, Svecofennian ultramafic to mafic intrusions (Lamberg & Liipo 1996).

Gårkälen

Several new, but small intrusions have been discovered at Gårkälen. The largest intrusion, with surface dimensions of about 250 x 100 m, exhibits jackstraw texture at the foot wall contact and adjacent to an orbicular peridotite. The thickness of the body is c. 75–100 m and mineralisation is poor, but the development towards depth is unknown. Geophysical anomalies of the area are difficult to interpret. It is possible that prospecting will continue here.

Långbacka

A gravimetric anomaly at Långbacka was tested by means of three bore holes, of which two contained 13 m and 8 m of ultramafic rock respectively, but without sulphide mineralisation. It is likely, however, that the major part of the anomaly is caused by some "greenstones". The chemical and petrological features of ultramafic rocks from the bore holes do not prove prospective. For instance, the magma does not appear to be sufficiently primitive. A positive feature was the thin overburden at the site of two drill holes – just a few meters.

Brännvalen, Njuggträskliden, Vallen and Holmsvattnet

The outcome of the various exploration activities (drilling, sampling, geological and geophysical interpretations) on the Brännvalen, Njuggträskliden, Vallen and Holmsvattnet prospects was not encouraging enough to motivate further efforts.

Selected prospects in Norrbotten county

Maniliden, Blåliden area

The occurrence at Maniliden is situated west of Piteå in southern Norrbotten. Since the discovery of sulphide-mineralised ultramafic boulders containing up to 1.5% nickel in 1995, the area has been surveyed by the Outokumpu Oyj company during several periods until 2001. The area has been geophysically measured by airborne slingram and radiometric methods by the company. Interpretations have been followed up by ground geophysics and diamond drilling. An initial testing of geophysical anomalies within an area of about 3 km^2 comprised 18 drill holes in 1997. This was followed two years later by a limited exploration drilling program of 7 bore holes within a restricted area and which successfully located sulphide mineralised ultramafic rocks. More than 1% Ni was encountered in meter-wide intersections and 0.4% Ni in a 10 meter section. Follow-up geophysical measurements, including down-hole surveys, outlined directions for further exploration and developed targets.

The nickel ore potential was tested by 6 diamond drill holes in 2001 in the central area of the prospect. The result was not encouraging. Intersected sulphide mineralised ultramafic rocks were too small and too poor in nickel, the best mineralisations being 7.45 m containing 0.41% Ni and 2.9 m containing 0.65% Ni. Pyrrhotite, pentlandite, and chalcopyrite occur as droplets and interstitial disseminations.

Drill cores delineate an ultramafic body (or bodies) which is at least 500 m long in direction NNW–NW with a maximum width of about 100 m. The ultramafic bodies, consist mainly of serpentine peridotite to metaperidotite and are tabular in shape and plunge to the west. They are locally cut by younger pegmatites. The country rocks are mainly mica gneisses with varying amounts of graphite and sulphides. They are paragneisses, converted

by metamorphism from greywackes and pelitic sediments. The serpentinites and pyroxenites in this area appear to be rather flatlying and are therefore difficult to discern from the overlying sulphide- and graphite-bearing sedimentary rocks by geophysical methods.

Hällbäcken

The sampled ultramafic rocks of the Hällbäcken area, not far south-east of Maniliden, do not seem to be prosperous. Furthermore, geological and geophysical interpretation indicate "narrow" conditions, meaning very limited possibilities for other, more prosperous ultramafic to mafic bodies.

Keukiskero–Jeytis area

In the summer of 1995, the Keukeskero–Jeytis area was investigated. Eighty observations on outcrops and 200 boulder observations were made and several hundreds of rock samples were taken for geochemical, mineralogical, and petrogeophysical analyses. Ultramafic rocks occur in a 40–50 km long and up to 4 km wide zone. In the Gardevait–Jeytis area, the width of the ultramafic zone varies between 500 m and 1 km. The dip varies between 50° and 75° towards NW and steep towards east. An anthophyllitic occurrence, at Keukiskero in the southern part of the area, looks less prospective than the northern part of the area, up towards Jeytis.

It was thought that komatiitic and gabbroic rock formations on the Finnish side of the national border would continue into Sweden, but that has not been confirmed.

A boulder of olivine-chromite mesocumulate, containing 0.9% Ni, was found just south of Jeytis. A 30 m thick overburden of till at the location of the boulder, suggests that its origin may well be from another rock sequence.

Karesuando area

Three areas (map sheet 31K) were studied during the summer of 1996: 1) Gallgielas, 2) Lake 495, and 3) Koutnahavaara. The two first areas are located in the northern part of the Keukiskero–Jeytis ultramafic belt, whereas Koutnahavaara lies about 30 km to the north-west of the Gallgielas area. Spinifex textures have not been observed in this region.

The Gallgielas study comprises a well exposed area of ultramafic cumulate rocks, approximately 1 x 2.5 km in size. The cumulates of the first main pulse are olivine (chromite) – meso-/adcumulate (?) – ocM/AC and olivine-chromite-bronzite-cumulate (ocbC). The cumulate of the second main pulse is olivine (chromite) orthocumulate. Augite

and rarely plagioclase have been observed as intercumulus minerals. Studies of the metamorphic alteration effects indicate serpentinisation (retrograde or prograde?), followed by prograde growth of anthophyllite in certain parts and renewed serpentinisation in other parts, all occurring under upper amphibolite facies conditions. Finally, there was a retrograde carbonatisation to various degrees. Strong carbonatisation is concentrated to young fissure and shear zones of various width (3–30 m) and where the cumulates locally are poorly mineralised by pyrrhotite or pyrite. Contact zones appear to be more magnetic than the central parts of the bodies.

The Lake 495 area comprises several sulphide-mineralised boulders of which one contains 0.65% Ni. It is a pentlandite-pyrrhotite mineralisation in olivine-chromite-mesocumulate (ocMC), also including some chalcopyrite and pyrite. There are also some boulders of sulphide-rich mica gneiss.

Kuotnahavaara, at the Finnish border, comprises ultramafic rocks in an Archaean granodiorite–tonalite gneiss and migmatised amphibolites with numerous dykes of metadiabase. The ultramafic bodies are probably small, less than 100–150 m in width, differentiated intrusions of metaperidotite, metapyroxenite, and metagabbro. Differentiation sequences are olivine-pyroxene, pyroxene, pyroxene-hornblende and hornblende cumulates. Some ultramafic rocks are locally very poorly mineralised by sulphides.

Geochemical and petrographical analyses of komatiitic rocks, samples mostly from boulders, but also some from diamond drill core (Keukiskero No 5), reveal that the primary magmatic texture is preserved in spite of intense alteration. Most samples are orthocumulates, and only a few may be classified as pure mesocumulates. In most cases olivine is preserved and metamorphic alteration began with intercumulus minerals. The following primary rock types may be discerned: 1) olivine-chromite orthocumulate, 2) olivine-bronzite±chromite orthocumulate, and 3) bronzite mesocumulate. The chemistry classifies them as Al-depleted komatiites. High Cr_2O_3 contents in olivine cumulate samples indicate that chromite may occur as a cumulus mineral, showing chromium saturation. Olivine-chromite orthocumulates from the Karesuvanto district resemble those of Forrestania, Western Australia, and differ from those of Ruossakero in northern Finland (Liipo & Lamberg 1996). The lack of pure olivine cumulates, such as olivine adcumulates and mesocumulates, in Karesuvanto is the main difference.

Selected gabbroic intrusions in northern Sweden

Some gabbroic intrusions were targeted by the Outokumpu Oyj company for evaluation of nickel exploration potential on the basis of lithogeochemistry and mineralogy. They were Saggevaara, Ruhkejuovva/Tjuoltajåkkah, Tjabrak, Salmivaara, Vilhelmina, Kläppsjö, and Hoting. The degree of geological knowledge of the studied areas varies a great deal, from information gathered during short excursions and sampling visits to thorough mapping and sampling.

Chemical analyses of 176 samples from the Rensjön area and 14 from Vilhelmina were done on 40 elements. 25 analyses from Hoting were made by SGU between 1985 and 1986. Samples from Kläppsjö have been analysed in different laboratories, 70 samples in Finland, 102 by SGU. Analyses of reference cases at Ekträsk and Rörmyrberget were performed between 1990 and 1998.

APE program was used in calculating several parameters from the whole rock data in order to enable extensive petrological analysis. Cumulus names were given for the samples according to CIPW normative mineral composition and IUGS names and ultramafic volcanic names were given for the samples according to Basaltic norm – normative mineral composition. Chemical compositions of the parental magmas were estimated, crystallisation series and orders were defined, and the openness of the magmatic systems was evaluated. Contamination and sulphide segregation features were studied. The Ekträsk and Rörmyrberget occurrences were used as reference cases.

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