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Cordierite-mica-quartz schists in a Proterozoic volcanic iron ore-bearing terrain, Riddarhyttan area, Bergslagen, Sweden

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Abstract

The Riddarhyttan Proterozoic predominantly felsic, alkali-enriched metavolcanic rocks have been affected by extensive synvolcanic hydrothermal Mg-alteration. After amphibolite facies metamorphism and deformation this is reflected in the occurrence of large elongated zones of tourmaline-bearing cordierite-mica-quartz schists, spatially related to numerous volcanogenic-exhalative iron formations. Geochemical evidence suggests that seawater-based fluids caused substantial mobilization of both major and trace elements, resulting in the formation of Fe-depleted and Fe-enriched Mg-schists. The latter is commonly gradational to cordierite-anthophyllite wall-rocks. The geochemical pattern is compatible with subseafloor hydrothermal circulation leaching iron and minor amounts of base metals from the felsic volcanic rocks, the emerging fluids precipitating these elements close to exhalative vents.

Introduction

The ore-bearing felsic volcanic complex of the Riddarhyttan-Norberg region, Bergslagen, Sweden is a part of the Proterozoic, Svecofennian, 1.8–1.9 Ga old orogenic volcanic belt. A review of the general geology of this belt has been given by Gorbatschev & Gaal (1987). The present study concentrates on the Riddarhyttan enclave of amphibolite-facies metavolcanic rocks (Fig. 1). Soon after their formation, the Riddarhyttan volcanic rocks were affected by two kinds of regional metasomatism: alkali metasomatism and Mg-metasomatism. A later phase of regional metamorphism turned the rocks into keratophyric metavolcanic rocks and cordierite-mica-quartz schists.

Alkali metasomatism altered the volcanic rocks into sodic and potassic varieties showing extreme enrichment of one of the alkali elements over the other. These rocks constitute the least altered and texturally best preserved meta-rhyolites in the Riddarhyttan area, and are the parent rocks of the cordierite-mica-quartz schists. Their mineralogy, chemistry and alteration textures have much in common with keratophyres as described by Battey (1955) and Hughes (1972, 1973, 1975).

Regional Mg-metasomatism in the Riddarhyttan area resulted in extensively developed cordierite-mica-quartz schists. They resemble the spotted 'dalmatianite' rocks of the Noranda district, Quebec (Wilson, 1935; De Rosen-Spence, 1969; Riverin & Hodgson, 1980) and silicic hornfels rocks reported from Newfoundland by Upadhyay & Smitheringale (1972). In the Noranda district, cordierite-bearing rocks constitute distinct alteration pipes underlying massive sulphide ores, while the Rid-

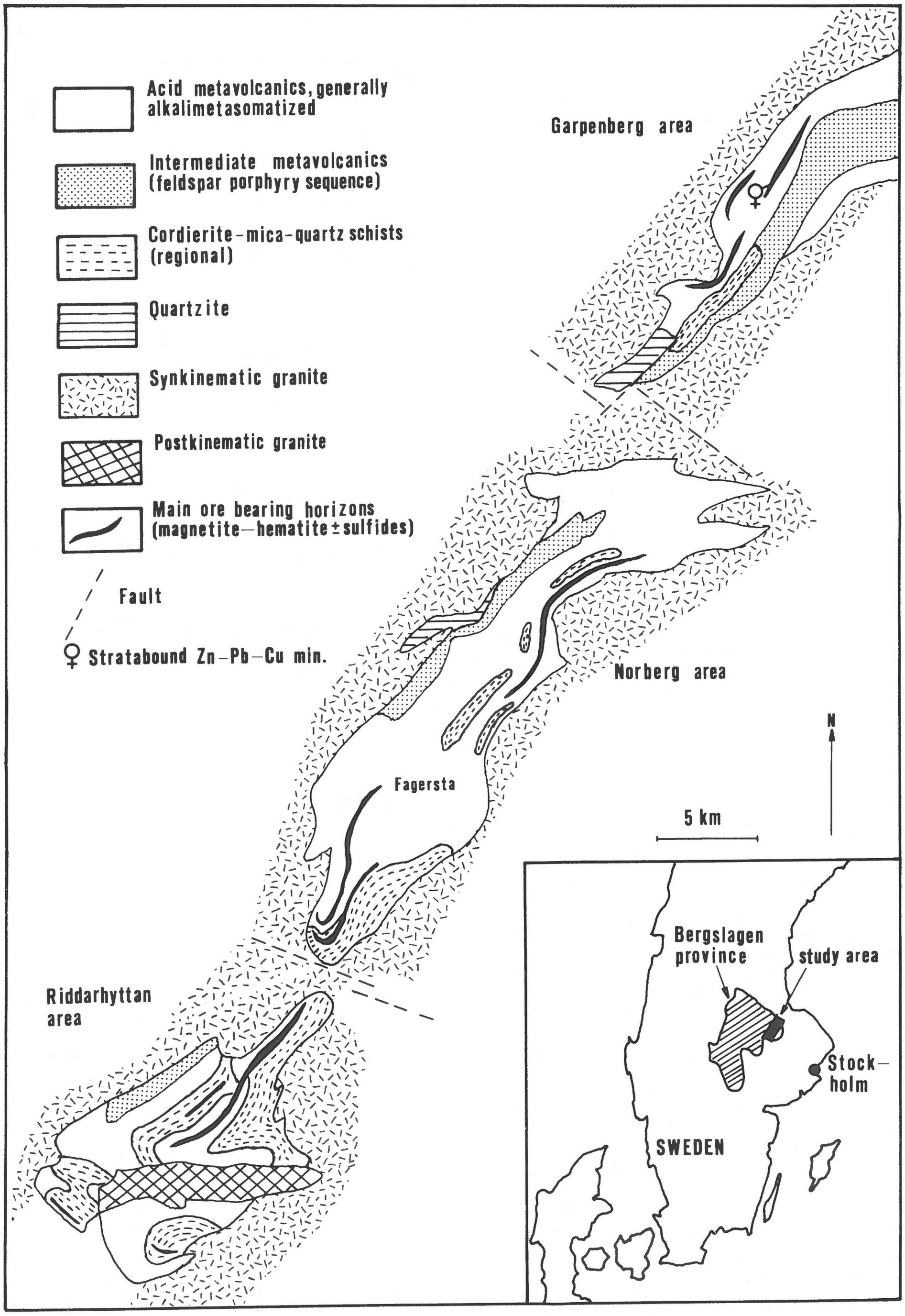

Fig. 1. General map of the Riddarhyttan-Norberg-Garpenberg enclaves showing the occurences of regional cordierite-mica-quartz schists and their spatial relation to iron-ore formations.

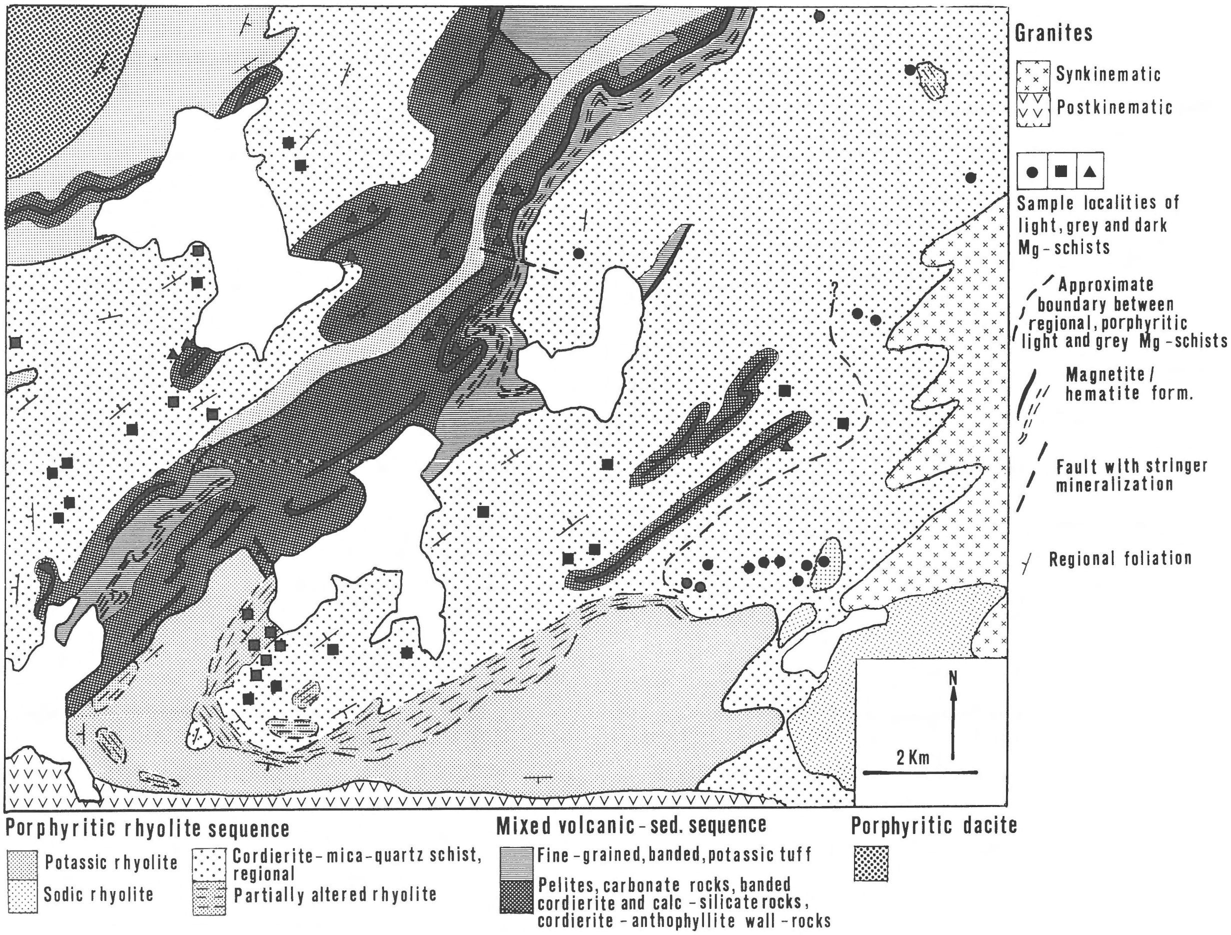

Fig. 2. Geology of the Riddarhyttan area. (Modified after Geijer (1923), Ambros (1983) and unpublished survey material from P.Ihre, SGAB. Dots, squares and triangles indicate sample localities for cordierite-mica-quartz schists.

darhyttan cordierite-mica-quartz schists occur as extensive, vaguely bounded zones of Fe-leaching and enrichment in a region dominated by iron formations. In greenschist facies terraines in western Bergslagen, similar cross cutting Mg-schistose zones occur as chlorite-mica-quartz schists (Baker & De Groot, 1983a) underlying a large volcanogenic-exhalative iron ore horizon (Baker & De Groot, 1983b).

Numerous volcanogenic-exhalative magnetite-hematite formations, sometimes enveloped by local cordierite-anthophyllite wall-rocks, occur throughout the Riddarhyttan area. However, the main ore-bearing strata are located within a NE-SW striking zone in the central part of the area (Fig. 2).

This paper discusses the chemistry of regional alterations, in particular Mg-metasomatism. Some 150 outcrop samples of cordierite-mica-quartz schists and keratophyres were collected and analyzed for major and trace elements using standard XRF-techniques.

Geological setting

General

The geology of the Riddarhyttan area has been reviewed in detail by Geijer (1923), Geijer & Magnusson (1944) and later by Ambros (1983). The stratigraphic column in Fig. 3 is based on Geijer's

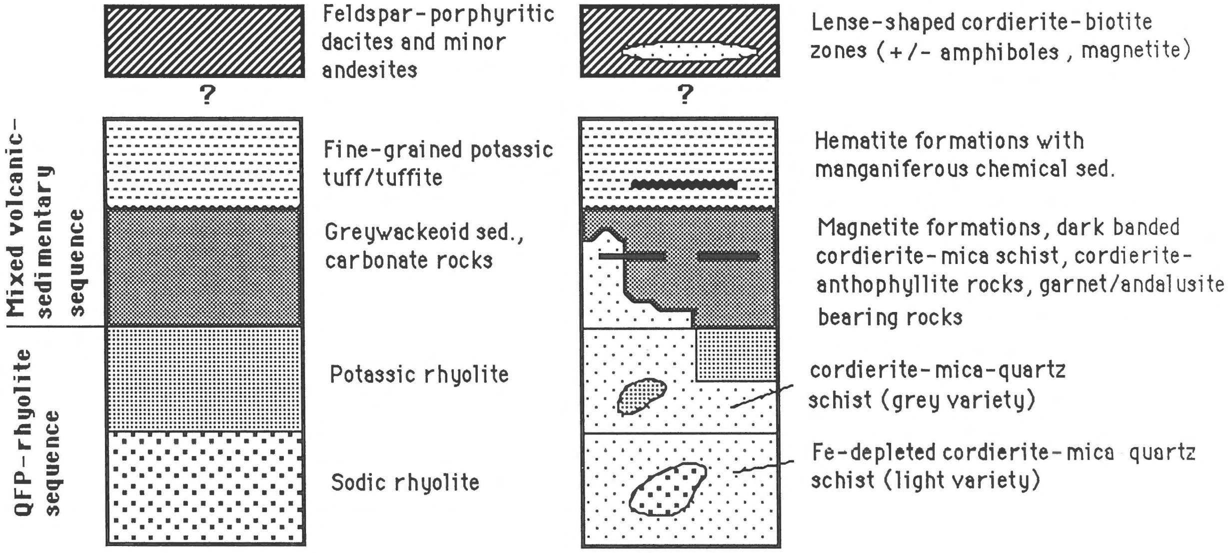

Fig. 3. Schematic stratigraphic sequence of the Riddarhyttan area and its relationship to regional Mg-metasomatism and iron formations.

descriptions and new field observations. A section showing regional alteration as related to stratigraphy has been added. The volcanic rocks consist predominantly of recrystallized felsic pyroclastic rocks, such as rhyolitic-, crystal- and ash tuffs, deposited in submarine environments. Fine-grained pelitic and psammitic sediments which probably represent redeposited tuffs, are resticted to the central NE–SW striking ore zone, which also comprises exhalative and carbonaceous sediments. This mixed volcanic-sedimentary sequence is flanked on both sides by regional cordierite-mica-quartz schists. Close to the northwestern margin of the studied area (Fig. 1), dacitic and subordinate andesitic pyroclastic rocks exist. The exact stratigraphic position of these rocks is still uncertain. The metavolcanic sequence is bordered and intruded by an early Svecofennian granitic complex. Granites from this group, located to the SW, have U–Pb zircon ages of 1870–1850 Ma (Åberg *et al.* 1983a, b).

The metavolcanic rocks of the Riddarhyttan area have been affected by regional alkali metasomatism producing keratophyres in the sense of Hughes (1973, 1975), with compositions plotting outside the igneous spectrum (Fig. 4). Generally it has been established that the potassic meta-rhyolites occupy higher stratigraphical levels than the sodic meta-rhyolites (Sundius, 1923; Geijer, 1936). Rocks unaffected by alkali exchange are very rare. The Na/K ratios may vary, but generally one of the alkali elements dominate strongly over the other. Extreme varieties with up to 6–7 wt% K_2O or Na_2O are common. Although a broad spatial association of potassic rhyolites with mineralizations exist (generally fine-grained, banded sequences), large areas of medium-grained, porphyritic, potassic rhyolites are not significantly mineralized (Lagerblad & Gorbatschev, 1985; Hellingwerf, 1986).

Regional alkali metasomatism of the porphyritic volcanic rocks was essentially a process of mimetic replacement of primary feldspars, which to a large extent preserved the original texture of the rock. The replacement is in most cases so complete that original feldspars were completely pseudomorphosed and recrystallized to albite or K-feldspar. However, a chequer structure in albite phenocrysts is common, indicating incomplete readjustment of the original feldspar crystals (Battey 1955). These rocks are texturally and chemically the least altered in the Riddarhyttan area and are overprinted by Mg-metsomatism. The term 'least altered' is here

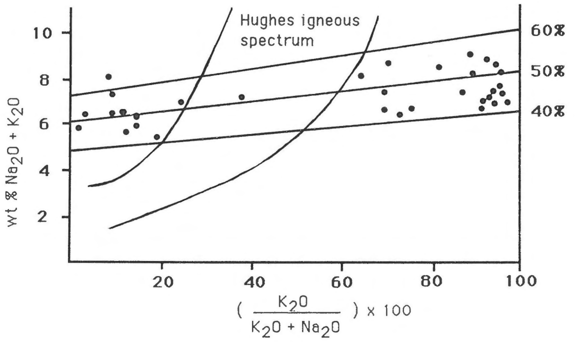

Fig. 4. Hughes diagram (1973) showing the general alkali-enrichment of the least altered quartz-feldspar porphyritic, felsic metavolcanics. The lines across the diagram show the percent of alkalis equivalent to a given percent of alkali feldspar in the rock.

used for rocks which have most of their original feldspar content left (see also Fig. 4), and were affected mainly by alkali exchange in feldspars. Regional porphyritic sodic metavolcanic rocks are taken to be evidence of early, relatively low temperature (>150° C according to calculations by Jasiński *et al.,* 1985) spilitic-type of seawater-rock interaction. Similar early Na-enrichment of felsic volcanic rocks has been demonstrated from Archaean alteration systems in Canada (Parry & Hutchinson 1981). However, alkali metasomatism also post-dated mineralization and burial metamorphism has been suggested (Cita *et al.,* 1981).

Lithologies

On the basis of texture and composition of the least altered rocks, the volcanic pile can be subdivided into three main sequences. From the bottom upwards, these are: (1) A medium-grained, quartz-feldspar porphyritic, partly rhyodacitic, rhyolite sequence (QFP-keratophyres). (2) A fine-grained banded sequence with intercalations of greywackoid and carbonaceous meta-sediments (mixed volcanic-sedimentary sequence) and, (3) A medium-grained, feldspar-porphyritic dacite sequence (FP).

The QFP-rhyolite sequence. This sequence predominantly contains medium-grained pyrolastic rocks with numerous recrystallized quartz and feldspar phenocrysts. These rocks are interpreted as lithic and crystal tuffs due to the high content of phenocrysts or fragments relative to matrix. Two varieties can be distinguished according to the compositions and structures of the feldspar phenocrysts. A quartz-microcline porphyry (potassic meta-rhyolite) dominates over a quartz-albite porphyry (sodic meta-rhyolite).

The microcline phenocrysts in the potassic meta-rhyolite are often recrystallized to aggregates of subgrains in a matrix consisting of quartz, microcline and variable amounts of biotite and plagioclase. Plagioclase is, however, often absent. Common accessory minerals are magnetite, zircon and sphene.

The quartz-albite porphyry contains albite phenocrysts occurring both as single laths showing ordinary polysynthetic twinning, and as composite grains, each consisting of a few crystals with disrupted twin lamellae (chequer structure). Chequer structure has been described as a common feature of alkali-metasomatized rocks (Battey 1955). The groundmass shows irregular grain-size distribution. It is dominated by albite and quartz and also contains minor amounts of biotite, chlorite, and epidote.

The mixed volcanic-sedimentary sequence. This sequence predominantly comprises fine-grained, banded, rhyolitic tuffs and tuffites. Phenocrysts are rare or absent, and the matrix predominantly consists of quartz, micas and potassic feldspar. Locally, bands richer in either quartz or feldspar can be distinguished. Thin layers of hematite and magnetite formations are common. In addition, the sequence includes greywackeoid sediments, marbles and chemical sediments such as jasper, chert ('quartzite'), and banded calc-silicate rocks ('skarn'), which are spatially and genetically closely associated with magnetite and hematite formations.

The mixed volcanic-sedimentary sequence has been tightly folded along NE–SW striking fold axes (D1). Towards the core of a synclinal structure, the iron formations are hosted by tuffaceous greywackeoid sediments showing increased maturity and marked graded bedding.

These rocks were deposited contemporaneously with widespread exhalative activity, indicated by the occurrence of banded magnetite and hematite formations. The hematite formations are situated stratigraphically just above the magnetite formations and are often intercalated with manganiferous chemical sediments containing spessartine garnet and rhodonite. The magnetite-rich ores commonly associate with cordierite-anthophyllite rocks and/or calc-silicate bands, but are also finely interbanded with quartz. Locally, some magnetite deposits carry disseminated chalcopyrite and pyrite as well as minor amounts of molybdenite, cobaltite and fluorite, which can be taken as an indication of proximity to stringer zones.

The FP dacite sequence. In the northwestern part of the Riddarhyttan area, the acid volcanic rocks are bordered by a sequence of presumably overlying fairly coarse, mainly dacitic pyroclastic rocks. The exact stratigraphic position of this sequence is still uncertain. Geijer (1936, 1967) considered these rocks to lie above the rhyolites in the Norberg region. These rocks contain large amounts of plagioclace phenocrysts mostly consisting of oligoclase crystals of variable grainsize. The matrix comprises plagioclase, quartz and biotite. Common accessories are magnetite and sphene. The FP sequence has locally been affected by Mg-metasomatism occurring in elongated, lens-shaped zones containing cordierite-bearing biotite schist (+/− amphibole, magnetite). In the less altered parts, the feldspars have a 'cloudy' appearance due to minute sericite and epidote inclusions. The FP-dacite sequence continues into the Norberg and Garpenberg areas (Fig. 1), where narrow Mg-metasomatic, schistose zones are common, sometimes occuring close to small iron formations.

Whole-rock analyses of samples from such a zone are included in Table 1.

Metamorphism

Mineralogical and textural evidence indicates that at least two phases of metamorphism had affected the supracrustal rocks of the Ridarhyttan area after sub-seafloor hydrothermal alteration. The earlier of these two phases of metamophism was prograde and produced mineral assemblages of the amphibolite facies such as cordierite-biotite-muscovite, cordierite-anthophyllite, andalusite – mica and garnet – andalusite. This phase of metamorphism was probably related to the emplacement of the early Svecofennian, partly synvolcanic granitic complex which intruded the volcanic pile. According to Geijer (1923), the granitic intrusions are coeval with at least one phase of deformation in the volcanic rocks which is marked by tight folding along NE–SW trending fold axes (D1).

The amphibolite-facies mineral assemblages were partly retrograded to lower grades during a later phase of metamorphism. The retrograde assemblages contain sericite/muscovite, chlorite and epidote. Frequently, cordierite has been altered to a fine-grained mass of sericite and chlorite. Overgrowths of biotite around cordierites along cross-cutting cleavage planes have been observed. This metamorphic event probably correlates with a younger phase of deformation (D2: open folding) which caused depressions and culminations along fold axes approximately perpendicular to D1.

In the central ore zone of the Riddarhyttan area, small domains of andalusite-bearing rocks occur in the cordierite-bearing mica schists. The occurrence of andalusite suggests that pressures in the Riddarhyttan area cannot have exceeded approximately 4 Kb during the prograde metamorphic event. In order to produce the present cordierite-anthophyllite assemblages which form the wall-rocks to mineralizations, temperatures of 550–600° C must have been attained. This estimate is based on data published by Akella & Winkler (1966) on the reaction: chlorite + quartz $\rightleftharpoons$ cordierite + anthophyllite + H_2O.

Distinct fields of microcline porphyries and albite porphyries occurring as less altered 'islands' in cordierite-mica-quartz schists of the Riddarhyttan area (Fig. 2), as well as the existence of small domains of andalusite or garnet-bearing rocks, suggest that metamorphism was essentially isochemical.

Thin sections from Mg-schistose zones occurring in greenschist facies terraines in western Bergslag-

Table 1. Whole-rock analyses of the Riddarhyttan felsic metavolcanic rocks and their altered equivalents. Major elements in wt% oxide and trace elements in ppm. Gains and losses calculated in the form of a depletion/enrichment factor (cf. Vivallo 1985a). QFG-quartz feldspar porphyritic.

	Least altered QFP-rhyolites		Cord.-mica-qtz. schist (grey)			Cord.-mica-qtz. schist (dark)			Noranda QFP-rhyolites[1]			
	$\bar{X}$	S	$\bar{X}$	S	gained lost	$\bar{X}$	S	gained lost		un-altered	spotted facies	giant spots
SiO_2	76.38	1.71	78.52	2.73	+ 0.08	76.21	1.51	− 0.02		76.56	76.96	74.47
TiO_2	0.13	0.06	0.11	0.05	− 0.11	0.11	0.02	− 0.17		0.29	0.27	0.26
Al_2O_3	11.36	0.88	10.80	1.31		11.62	1.25			12.08	12.01	11.41
Fe_2O_3	2.30	0.62	1.50	0.27	− 0.31	3.44	0.80	+ 0.46	FeO	2.22	3.31	5.54
MnO	0.02	0.03	0.01	0.01	− 0.63	0.01	0.01	− 0.66		–	–	–
CaO	0.25	0.22	0.11	0.05	− 0.54	0.10	0.05	− 0.61		1.10	0.28	0.39
MgO	1.05	0.40	3.92	0.84	+ 2.93	3.41	1.09	+ 2.93		1.18	1.97	2.24
Na_2O	0.82	0.76	0.18	0.19	0.77	0.19	0.11	− 0.77		3.64	0.75	0.59
K_2O	6.71	0.93	2.79	0.51	− 0.56	3.31	1.10	− 0.52		2.30	2.60	2.39
LOI	0.83	0.40	1.94	0.52		1.54	0.52					
TOT.	99.82		99.89			99.96						
Zn	6	6	5	5	− 0.12	9	7	+ 0.40	No. of			
Cu	7	7	3	6	− 0.55	2	2	− 0.72	analyses	9	12	17
Pb	5	4	4	4	− 0.15	4	3	− 0.22				
Rb	150	48	87	46	− 0.40	95	43	− 0.38				
Sr	19	15	5	3	− 0.72	2	3	− 0.90				
Y	45	14	37	11	− 0.14	43	16	− 0.07				
Zr	170	44	196	32	+ 0.26	181	29	+ 0.04				
Ba	754	380	174	90	− 0.75	151	103	− 1.00				
No. of analyses		20	20			18						

	Least altered QFP-rhyolites		Cord.-mica-qtz. schist (light)		gained/ lost	FP-dacite unaltered	Narrow zone of cord.-biotite schist[2]
SiO_2	77.21	1.70	77.77	2.00	+ 0.06	66.30	66.28
TiO_2	0.18	0.06	0.14	0.06	− 0.18	0.63	0.61
Al_2O_3	12.73	0.69	11.71	0.80		15.13	14.34
Fe_2O_3	0.95	0.27	0.50	0.20	− 0.44	5.78	6.67
MnO	0.01	0.01	0.01	0.01	+ 0.06	0.07	0.10
CaO	0.52	0.49	0.07	0.05	− 0.86	4.55	1.06
MgO	1.25	0.36	4.80	0.67	+ 3.06	2.25	4.44
Na_2O	5.55	0.69	0.31	0.21	− 0.94	2.71	1.83
K_2O	0.86	0.73	2.30	0.52	+ 1.83	2.00	2.63
LOI	0.75	0.49	2.28	0.64		0.63	1.68
TOT.	99.68		99.91			100.19	99.76
Zn	4	3	2	2	− 0.53	86	73
Cu	3	3	1	1	− 0.65	20	5
Pb	7	8	4	3	− 0.40	13	7
Rb	31	24	65	23	+ 1.22	75	82
Sr	56	51	7	5	− 0.87	364	96
Y	40	10	43	14	+ 0.14	24	25
Zr	238	93	214	31	− 0.05	164	170
Ba	160	116	144	61	− 0.04	680	462
No. of analyses		11	24			2	2

[1] From Riverin and Hodgson 1980. Calculated to 100 wt% oxide.

[2] Spatially associated with small calc-silicate banded iron formations (Norberg area).

Fe203 = Fetot.

en, were found to contain colourless chlorite blasts in a quartz and mica-rich matrix. Chemical analyses of these rocks are almost identical to analyses of light-coloured regional cordierite-mica-quartz schists in the Riddarhyttan area. This further indicates isochemical metamorphism and suggests a chlorite/clay precursor mineralogy to the regional cordierite-bearing rocks in the Riddarhyttan area. It is therefore suggested that the metamorphic mineral assemblages mirror the chemical patterns created by earlier hydrothermal alterations. The early hydrothermal alterations can thus be mapped by outlining the present occurrence areas of the metamorphic parageneses.

Mg-metasomatism and the Mg-metasomatic rocks

General

The large size of the Mg-alteration zones in the Riddarhyttan area is quite unique for Bergslagen. The extremely wide extension of these zones is probably enhanced by the fact that they constitute anticlinal ridges (Geijer 1923). On a regional scale, the Mg-schists appear to be conformable with the NE–SW striking surrounding alkali-enriched metavolcanic rocks, but on a smaller scale it is evident that Mg-metasomatism was discordant, cutting across the boundaries between K- and Na-enriched rocks. Petrographical and geochemical results show that Mg-metasomatism progressively altered both sodic and potassic rhyolites (see also Fig. 5). Along the boundaries between potassic or sodic rhyolites and cordierite-mica-quartz schists, initial alteration is indicated by succesive feldspar destruction and increasing amounts of micas (biotite, muscovite, and phlogopite). Towards the interior of the Mg-alteration zones, cordierites occur as poikiloblasts with increasing Mg-contents and Mg/Fe ratios. The boundaries between metavolcanic rocks only affected by alkali metasomatism and the Mg-schists are often diffuse, in some cases up to 100 m wide transition zones containing muscovite, biotite and quartz ± feldspars. These cordierite-free, mica-rich transition zones are most extensive along the boundaries with fairly coarse-grained volcanics (QFP-rhyolites). Locally, Mg-metasomatism followed fissures and developed pseudo-conglomerates or breccia-like patterns containing fragments of less altered metavolcanic rocks in a matrix of mica schist.

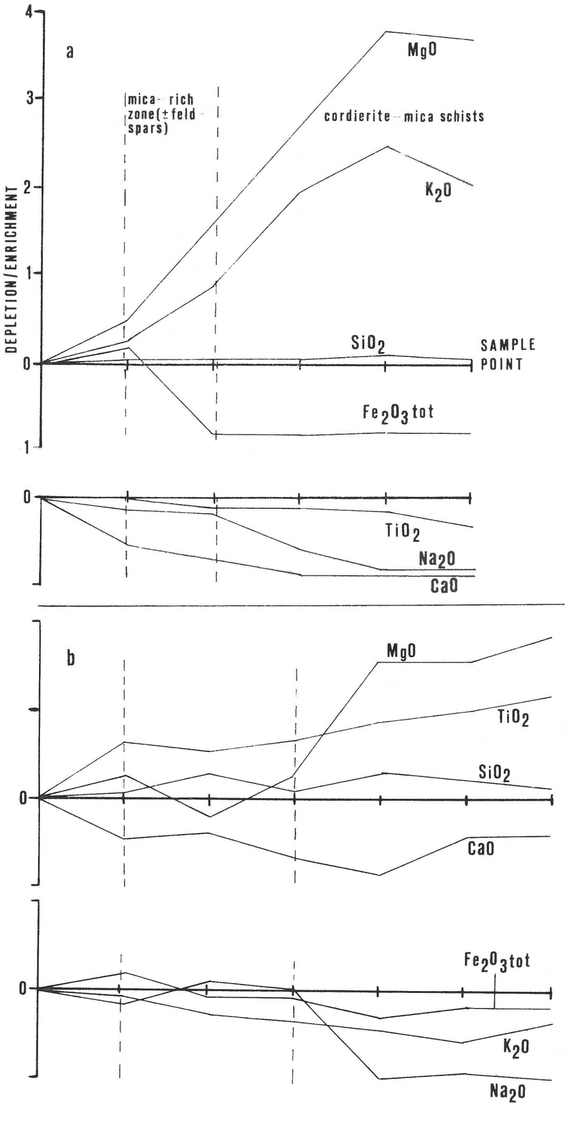

Fig. 5 (a). Sample profile from quartz-feldspar porphyritic sodic rhyolites to fully developed cordierite-mica-quartz schists of the light variety. (For calculation of depletion/enrichment fator see text). (b). Sample profile from quartz-feldspar porphyritic potassic rhyolite to fully developed cordierite-mica-quartz schists of the grey variety.

The interiors of the Mg-alteration zones consist of uniform and extensively developed cordierite-mica-quartz schists, which are the final and metamorphosed, alteration product of the volcanic rocks.

Three varieties of cordierite-mica-quartz schists with silica contents between 72–78 wt% can be distinguished. A light, almost white regional variety occurring transitional to porphyritic sodic rhyolite consists of colourless micas and has a very low Fe-content (<1 wt% Fe_2O_3 tot). A grey regional variety, often transitional to porphyritic potassic rhyolite, contains approximately 1–2 wt% Fe_2O_3 tot, and biotite and muscovite. A third, finer-grained and often cordierite banded, darker variety contains abundant biotite and higher Fe-contents (3.5–5 wt% Fe_2O_3 tot). The latter is most prominent in the central mixed volcanic-sedimentary sequence and usually developed locally in the vicinity of mineralized strata. It often contains magnetite. Regional light and grey varieties are widely distributed distal to the mineralizations.

An approximate boundary between regional light and grey varieties of Mg-schists, as mapped out in the field and determined from chemical profiles, is shown in Fig. 2, which also indicates the sampling localities for each variety of Mg-schist. Chemical profiles across boundaries between alkali-enriched porphyritic rhyolites and regional Mg-schists are shown in Fig. 5.

Regional, discordant, Mg-metasomatism predominantly affected the quartz-feldspar porphyritic rhyolites of the QFP-sequence, stratigraphically underlying the mixed volcanic-sedimentary sequence, while the mixed volcanic-sedimentary sequence contains stratiform, banded cordierite-magnetite bearing rocks. However, some magnetite formations, located outside the central ore-bearing zone, show a transition from local cordierite-anthophyllite wall-rocks almost directly to regional cordierite-mica-quartz schists, at both footwall and hangingwall sides. These observations indicate that regional Mg-metasomatism occurred or continued after the deposition of at least some of the iron formations. In some cases, remnants of less altered feldspar-bearing rhyolite exist close to these deposits.

Petrography

The Mg-schists have been affected strongly by regional deformation (D1; tight folding). The micas are orientated along foliation planes striking NE–SW or follow marked lineations. A later phase of deformation (D2; open folding) is indicated by micas overprinting older textures along crosscutting cleavage planes. The cordierite prophyroblasts, which range from one to more than 10 cm, are often developed as ellipsoids orientated parallel to the regional foliation. This gives the rocks a spotted texture. During Mg-metasomatism, the original volcanic textures were destroyed and only some recrystallized, embayed quartz phenocrysts remain. The cordierites show pleochrism from light yellow to colourless and contain numerous inclusions of quartz, muscovite and biotite. They have often been partly retrograded to fine-grained pinitic masses of light chlorite and sericite, developed along grain margins and intragranular fissures.

A common accessory mineral in all three varieties is a light green tourmaline which sometimes occurs in significant amounts as inclusions in cordierites and micas.

The dark banded and the regional grey-coloured varieties of Mg-schists contain parallel intergrowths of dark brown or occasionally greenish biotite and muscovite. The micas occur both as envelopes around cordierites and in the quartz-dominated matrix. The regional grey-coloured Mg-schist variety contains roughly equal amounts of biotite and muscovite, while the dark banded varieties show less muscovite and sometime contain magnetite porphyroblasts.

The regional light-coloured variety of Mg-schist contains abundant muscovite intergrown with a light yellowish to brown phlogopitic mica. In rare cases muscovite pseudomorphs of feldspars have been observed, but generally deformation has destroyed such textures.

Baker & De Groot (1983a) demonstrated that the widespread Mg-chlorite-mica-quartz schists in western Bergslagen develop in two sequential stages. An initial stage of feldspar replacement by sericite and/or clay minerals, was succeeded by the development of Mg-chlorite with increasing MgO-contents at the expense of the earlier formed phyllosilicates. Tourmaline was also recorded as a common accessory mineral.

Together with these results, the observations in the Riddarhyttan area suggest that regionally developed cordierite-mica-quartz schists, had originally been formed by sequential sericitization and choritization of the volcanic rocks. The initial stages of this process are documented by cordieritfree mica-quartz schist zones (± feldspars) transitional to volcanic rocks unaffected by Mg-metasomatism, whereas the more central, now cordierite-mica-bearing parts of the Mg-metasomitized areas reflect both original seritization and chloritization. Alternatively it is possible that some of the cordierite may have formed directly through metasomatic processes (e.g. Didier & Dupraz, 1985).

Geochemistry and element mobility

Averages of whole-rock analyses of each Mg-schist variety in the Riddarhyttan area are given in Table 1. After comparing element ratios from the least altered parent rock and the metasomatic equivalent according to Gresens (1967), it was concluded that Al was essentially immobile during alteration. Al is therefore used for calculating chemical gains and losses from the bulk chemical compositions according to:

$$x = \frac{\text{(given element/immobile element) altered}}{\text{(given element/immobile element) unaltered}} - 1$$

where x is the depletion/enrichment factor (cf. Iijima 1974). Two sample profiles, of approximately 100 m length, running from sodic and potassic rhyolites to fully developed regional cordierite-mica-quartz schists are shown in Fig. 5. The element variation along the sample point axis reflects successive feldspar subtraction and increasing mica and cordierite contents. The sodic rhyolites of the QFP-sequence lost Na, Ca, and Fe and gained Mg and K, while Al, Ti and Si were essentially immobile. This led to the formation of the light-coloured Mg-schists.

The potassic rhyolites of the QFP-sequence lost K, Fe, Na, Ca and Mn and gained Mg, while Al, Si and Ti were immobile as the grey-coloured Mg-schists were formed.

The dark banded variety, developed in the vicinity of iron formations, lost K, Ca, Na and Mn and gained Mg and Fe. Their compositions appear to have been influenced by metalliferous brines as they show Fe-enrichment (magnetite) and increasing Fe/Mg ratios, whereas the more widespread light- and grey-coloured varieties of Mg-schists, formed at a distance from the ores show Fe-depletion.

The variation of Fe/Mg ratios is illustrated by the AFM-plot in Fig. 6. The development of cordierite-mica-quartz-schists from potassic and sodic rhyolites is illustrated in Fig. 7.

Amongst the trace elements, Zn, Cu and Pb show little mobility with a tendency for Cu to be depleted. The array of Zn-analyses has a high standard deviation, but commonly the dark variety of Mg-schists have elevated Zn-contents. The dark and grey varieties show a loss of Ba, Rb and Sr. The light variety of Mg-schists lost Sr and gained Rb. In all three varieties Zr and Y were essentially immobile.

Morton & Nebel (1984) proposed the following reactions to account for chemical changes during the sericitization and chloritization of sodic felsic volcanic rocks:

$$\text{Albite} + K^+ + H^+ \rightarrow \text{sericite} + \text{quartz} + Na^+ \quad (1)$$

$$\text{sericite} + (Mg, Fe)^{2+} + \text{quartz} + H_2O \rightarrow \text{chlorite} + K^+ + H^+ + H_4SiO_4 \quad (2)$$

or

$$\text{sericite} + (Mg, Fe)^{2+} + \text{quartz} + H_2O \rightarrow \text{chlorite} + \text{pyrophyllite} + K^+ + H^+ \quad (3)$$

This suggests that fluid-rock interactions changed the compositions and pH-parameters of the fluids into the stability fields of either sericite or chlorite.

Discussion and conclusions

The cordierite-mica-quartz schists of the Riddarhyttan area are chemically and texturally similar to certain rock types found in the Archaean Noranda alteration pipes, known as 'dalmatianite' rocks, due to the occurrence of cordierite porphyroblasts.

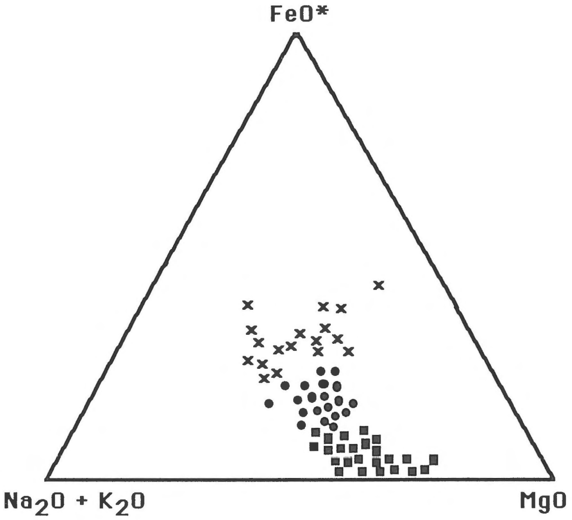

Fig. 6. Whole-rock analyses plotted in AFM diagram for the most altered Mg-schists. Squares = light variety, dots = grey variety, crosses = dark variety. The rocks show a general trend from Fe-depletion to Fe-enrichment. Values in wt%.

Samples from the Millenbach mine are included in Table 1 for comparison (Riverin & Hodgson, 1980). Similar Mg-metasomatism, associated with the Ordovician volcanogenic Gullbridge copper deposit and iron formation in Newfoundland, developed a cordierite-bearing silicic hornfels rock on the footwall side of cordierite-anthophyllite rocks (Upadhyay & Smitheringale 1972). This suggests a close relationship between Mg-metasomatic rocks and ore formation, and Mg-metasomatism due to the volcanogenic hydrothermal circulation of fluids derived from seawater has been proposed for these formations.

The frequent occurrence of tourmaline as inclusions in cordierites and micas indeed indicates that the fluid responsible for Mg-metasomatism was derived from boron-rich marine water.

Hajash & Chandler (1981) investigated seawater-rhyolite reactions and found that Mg was lost from the fluid to alteration minerals, such as hydrous Mg-silicate, most efficiently at temperatures of approximately 300° C, while the fluid leached Fe, Mn and Si from the rocks. The experiments demonstrated that large scale seawater-rock interaction could considerably change the chemistry of seawater, and produce large bodies of altered rock with associated ore deposits.

Such a process is in accordance with the geochemical variation seen in the Riddarhyttan Mg-enriched schists, where the regional light and grey varieties show depletion in Fe and Mn relative to the rhyolites and thus are likely to represent leaching zones. The Fe and Mn removed presumably formed iron deposits in the upper parts of the Riddarhyttan volcanic pile, of which the hematite formations are Mn-rich.

Similarly, the dark banded Mg-schists occurring close to ores apparently represent zones of Fe-enrichment. The geochemical data and the field relationships in the Riddarhyttan area thus suggest that evolved circulating seawater mobilized almost all major elements in the underlying volcanic rock pile, the fluids emerging at the surface subsequently precipitated Fe, minor amounts of base metals and Mn close to exhalative vents on the paleo-seafloor.

The large extension of the NE–SW striking central ore-bearing zone, with its numerous iron formations indicates the widespread, unfocused, exhalative activity of a vent field. Repeated hydrothermal alteration and exhalation probably allowed the early-formed iron formations, situated outside the mixed volcanic-sedimentary sequence, to be enclosed in large areas of generally barren Mg-rich schists. Such ore lenses often have narrow aureoles of dark Mg-schists grading rapidly into cordierite-anthophyllite wall-rocks. On a large scale, this multi-stage process created a pattern where iron formations are hosted both by Fe-depleted Mg-schists derived from porphyritic volcanics of the QFP-sequence, and by the mixed volcanic-sedimentary sequence (see Fig. 2). Accordingly, the style of hydrothermal circulation in the Riddarhyttan area created large diffusely bounded zones of Fe-depletion and more resticted zones of Fe-enrichment, and subsequently numerous iron formations at various stratigraphic levels. Sulphide-rich magnetite formations and associated small pyrite bodies probably comprise the proximal facies of iron formations and are commonly associated with cordierite-anthophyllite wall-rocks. Such cor-

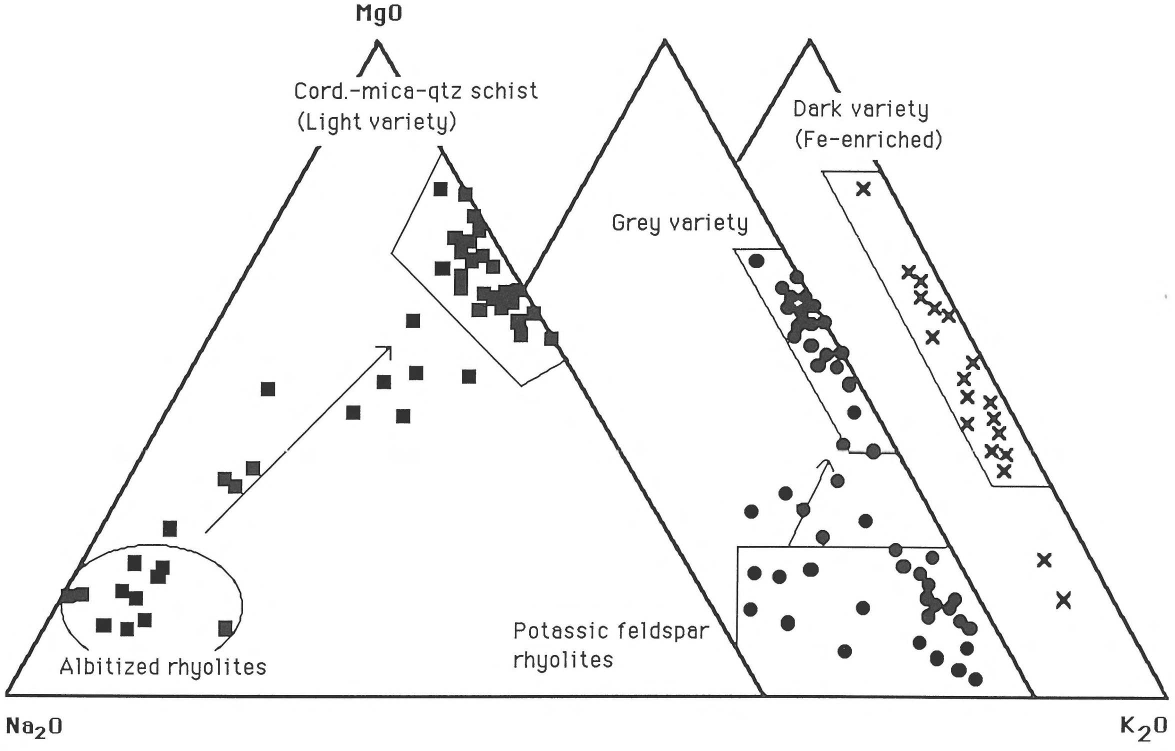

Fig. 7. MgO–Na_2O–K_2O diagram for whole-rock analyses from the Riddarhyttan area. Transitional samples between the least and the most altered rocks were collected along profiles across zones showing successive feldspar subtraction and mica and cordierite addition. Values in wt%.

dierite-anthophyllite wall-rocks, interpreted as chloritic pipe alterations are known from large massive sulphide deposits in Bergslagen and in North America. The Garpenberg (Vivallo, 1985a, b) and Falun (Koark, 1962) ores in Sweden and the Noranda deposits in Canada (De Rosen-Spence 1969, Riverin & Hodgson 1980) are well known instances.

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References

Åberg, G., Bollmark, B., Björk, L. & Wiklander, U. 1983a A radiometric dating of the Horrsjö granite, South Central Sweden – Geol. För. Förh. 105: 78–81.

Åberg G., Levi, B. & Fredrikson, G. 1983b Zircon ages of metavolcanic and synorogenic granitic rocks from the Svärdsjö and Yxsjöberg areas, South Central Sweden – Geol. För. Förh. 105: 199–203.

Akella, J. & Winkler, H.F.G. 1966. Orthorombic amphibole in some metamorphic reactions – Contrib. Mineral. Petrol. 12: 1–12.

Ambros, M. 1983 Beskrivning till berggrundskarten Lindesberg NO – Sver. Geol. Unders. af 141: 1–75.

Baker, J.H. & De Groot, P. 1983a Proterozoic seawater-felsic volcanics interaction W. Bergslagen, Sweden. Evidence for high REE mobility and implications for 1.8 Ga seawater compositions – Contrib. Mineral Petrol. 82: 119–130.

Baker, J.H. & De Groot, P. 1983b Proterozoic submarine-exhalative iron ores from Hjulsjö, leached from felsic volcanics by modified seawater (Abstract) – Terra Cognita 3: 167.

Battey, M.H. 1955 Alkali metasomatim and the petrology of some keratophyres – Geol. Mag. 92: 104–126.

Cita, N., Arvanatidis & D.T. Rickard 1981 REE-geochemistry of an early Proterozoic volcanic ore district, Dammberg, Bergslagen, Central Sweden. In: Rickard, D.T. (ed.) – Ann. Rept Ore Res. Group, Stockholm Univ.: 105–135.

De Rosen-Spence, A. 1969 Genese des roches a cordierite-anthophyllite des gisements cupro-zinziferes de la region de Rouyn-Noranda, Quebec – Can. J. Earth Sci. 9: 1339–1345.

Didier, J. & Dupraz, J. 1985 Magmatic and metasomatic cordierites in the velay granitic massif (French massif central). In: The Crust – the significance of granites, gneisses in the lithosphere – Theophrastus Publ. (Athens): 35–78.

Geijer, P. 1923 Riddarhytte malmfält. Kommerskollegium och Sver. – Geol. Unders. 343 pp.

Geijer, P. 1936 Norbergs berggrund och malmfyndigheter – Sver. – Geol. Unders., Ca 24: 162 pp.

Geijer, P. 1967 The precambrian quartzite in the Norberg district, central Sweden, and its iron-sand beds – Sver. – Geol. Unders. Ser. C 619: 36 pp.

Geijer, P. & Magnusson, N.H. 1944 De mellan svenska järnmalmernas geologi. Sver. – Geol. Unders. Ca 35: 654 pp.

Gorbatschev, R. & Gaal, G. 1987 An Outline of the Precambrian evolution of the Baltic Shield – Precamb. Res. 35: 15–52.

Gresens, R.L. 1967 Composition-volume relationships of metasomatism – Chem. Geol. 2: 47–65.

Hajash, A. & Chandler, G.W. 1981 An experimental investigation of high temperature interaction between seawater and rhyolite, andesite, basalt and peridotite – Contr. Mineral. Petrol. 76: 240–254.

Hellingwerf, R.H. 1986 Regional and localized hydrothermal alterations during sub-seafloor metamorphism in Western Bergslagen. Implications for metal prospecting – IAGOD Abstract, session 9.

Hughes, C.J. 1972 Late Precambrian volcanic rocks of Avalon New Foundland – a spilite/Keratophyre province: Recognition and implications – Can. J. Earth Sci. 10: 272–282.

Hughes, C.J. 1973 Spilites, keratophyres and the igneous spectrum – Geol. Mag. 6: 513–527.

Hughes, C.J. 1975 Keratophyre defined – N. Jb. Miner. Mh.: 425–430.

Iijima, A. 1974 Clay and zeolitic alteration zones surrounding Kuroko deposits in the Hokuroko district, northern Akita, as submarine hydrothermal-diagenetic alteration products – Soc. Min. Geol. Japan. Min. Geol. Spec. Iss. 6: 267–289.

Jasínski, A.W., Baker, J.H. & De Groot, P.A. 1985 Thermodynamic aspects of the Mg-clorite – alkali feldspar – sericite – kaolinite system: applications to the fossil sub-seafloor hydrothermal system at Hjulsjö, Bergslagen, Sweden – GUA Pap. Geol. ser. 1, 21: 159–188.

Koark, H.J. 1962 Zur Altersstellung und Endstehung der Sulphiderze von Typus Falun – Geol. Rundsch. 52: 123–145.

Lagerblad, B. & Gorbatschev, R. 1985 Hydrothermal alteration as a control of regional geochemistry and ore formation in the central Baltic shield – Geol. Rundsch. 74: 33–49.

Morton, R.L. & Nebel, M.L. 1984 Hydrothermal alteration of felsic volcanic rocks at the Helen siderite deposit, Wawa, Ontario – Econ. Geol. 79: 1319–1334.

Parry, S.E. & Hutchinson, R.W. 1981 Origin of a compex alteration assemblage, Four Corners Cu-Zn Prospect, Quebec, Canada – Econ. Geol. 76: 1186–1201.

Riverin, G. & Hodgson, D.J. 1980 Wall-rock alteration at the Millenbach Cu–Zn mine, Noranda, Quebec – Econ. Geol. 75: 424–444.

Sundius, N. 1923 Grythyttefältets geologi – Sver. – Geol. Unders. ser. C: 312 pp.

Upadhayay, H.D. & Smitheringale, W.G. 1972 Geology of the Gullbridge copper deposit, New Foundland: Volcanogenic sulfides in cordierite-anthophyllite rocks – Can. J. Earth Sci. 9: 1061–1073.

Vivallo, W. 1985a Subseafloor hydrothermal alteration during the Early Proterozoic at Garpenberg. Central Sweden – Mineral Deposita 20: 33–42.

Vivallo, W. 1985b The geology and genesis of the Proterozoic massive sulfide deposit at Garpenberg, Cental Sweden – Econ. Geol. 80: 17–32.

Wilson, M.E. 1935 Rock alteration at the Amulet mine, Noranda district, Quebec – Econ. Geol. 30: 486–492.