Geologie en Mijnbouw 67: 189–202 (1988)

The metasediments associated with stratabound base metal mineralization, Ljusnarsberg District, Central Sweden

IUGS
UNESCO IGCP 247

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Received 3 August 1987; accepted in revised form 17 January 1988

Key words: Lower Proterozoic, Sweden, metasediments, hydrothermal alteration, strata-bound mineralization, base metal sulphides.

Abstract

An extensive suite of exhalites of sub-economic potential occurs in a succession of Lower Proterozoic quartzofeldspathic gneisses in the Ljusnarsberg district, central Sweden. Previously economic varieties include Fe-Mn oxides, silicates, and carbonates, Cu–Pb–Zn bearing and W bearing rocks all of which have been mined in the past.

The stratigraphic succession of the Ljusnarsberg-Ställdalen area is conformable and changes from a lower metavolcaniclastic pile of >5 km thickness (the Kumlan Group) to a mixed metavolcanic and metasedimentary sequence (the Ställdalen Group). To the east the mixed metavolcanic and metasedimentary succession (the Wigström Group) is thought to be stratigraphically equivalent to the Upper Kumlan Group and Lower Ställdalen Group.

The Kumlan Group is dominated by primary rhyodacitic volcaniclastic material partly subaerial. The rapid decline in volcanism is coeval with an increase in the sedimentary component and marks the conformable contact of the upper and lower groups. The dominantly stratabound mineralization is concentrated in two main ore horizons in the upper group: (1) a lower Cu–Pb–Zn sulphide-rich horizon with some magnetite and (2) an upper Fe-Mn enrichted horizon. The ore deposits are spatially associated with the metamorphic equivalents of a variety of clastic and chemical sediments including quartz-feldspar-biotite rocks, with minor calcite, hornblende, garnet, pyroxene, epidote and magnetite; quartz-K feldspar-plagioclase-garnet-amphibole-pyroxene-calcite-epidote- biotite rocks with minor chlorite, apatite and sphene; and pyroxene-epidote-K feldspar rocks.

The varied chemistry of both ores and barren chemical sediments suggests the palaeoenvironment was continental with minor basinal development. Composition and pathways of the circulating fluids were restricted causing sharp changes in chemical precipitation. Clastic sediments are not common and reflect a low energy environment starved of sediment. Subsidence seems to have been the overriding tectonic trend.

Introduction

The close association of complex exhalite horizons, the exogenous end-products of syndepositional hydrothermal activity (Oftedahl, 1958; Hutchinson, 1982) with stratiform base metal sulphide deposits and hydrothermal alteration processes are characteristic of Broken Hill-type mineralization (Plimer, 1984, 1986; Rickard, 1987; Parr & Rickard, 1987). The exhalites are of the sulphide, oxide, carbonate and silicate facies and have been affected by hydrothermal alteration, diagenesis and metamorphism to varying degrees. Exhalites of the silicate facies include cherts, magnetite-calc-silicates, W-calc-silicates, quartz-garnet rocks and mixed silica-carbonate facies. Ba rich calc-silicates, gahnite-quartz rocks and B, Mn, and F enriched rocks are amongst other exotic mineralogies reported for the Broken Hill exhalites (Plimer & Lottermoser, 1987). The deposits commonly coincide with major changes in the depositional environment. Most commonly they occur at the waning stages of felsic and felsic-mafic bimodal volcanism and the onset of quiescent (subaqueous) conditions. Proterozoic examples include the Broken Hill deposit itself (Barnes, 1980); Gamsberg and Aggeneys, Namaqualand (Ryan *et al.,* 1982); Salida, Colorado (Boardman 1986, Boardman & Condie 1986) the Blacklite Prospect. New Mexico (Fulp & Renshaw, 1985) and the Dammberg deposit and Älvlången-Vikern areas in western Bergslagen (Arvanitidis & Rickard, 1981; Hellingwerf *et al.,* 1988).

Arvanitidis & Rickard (*op. cit.*) suggest ore deposition in these environments is a function of preservation potential rather than deposition. Metalliferous rocks are found, therefore, where deposition (precipitation) exceeded erosion. Also concentration of the ore is dependent on relative rates of rock deposition: high rates of sedimentation, for example in volcanically active areas, will cause dissipation of the metalliferous precipitates (C.J. Carlon, pers. comm., 1987).

The metasediments associated with an example of Early Proterozoic base metal sulphide mineralization from the Ljusnarsberg-Ställdalen district are considered in this paper. They occur at the stratigraphically conformable contact between a lower felsic volcanic pile and an upper mixed metasedimentary and bimodal metavolcanic sequence. The metasediments are stratigraphically equivalent to a thin metalliferous horizon consisting of lenses of Fe–Cu–Pb–Zn sulphides with locally concentrated magnetite and scheelite.

Regional geology

The Bergslagen Ore Province has been regarded as the southernmost terrain accreted to the Archaean nucleus to the northeast during the Svecokarelian orogeny (2.2–1.75 Ga) resulting in the formation of the Fennoscandian Shield (Hietanen, 1975; Rickard, 1979: Fig. 1). It is bounded to the southwest by a belt of younger granitoids, the Trans-Scandinavian Belt which defined the shield margin during the Middle Proterozoic (1.7–1.6 Ga; Nyström, 1982; Gaal & Gorbatchev, 1987). To the north the province is bounded by the migmatised greywackes and late orogenic S-type granitoid massifs of the Bothnian Basin. The ore province (*sensu lato*) can be extended across the Baltic Sea into that of southwest Finland (Lundström & Papunen, 1986; Lundström, 1987) which includes the Orijärvi deposit.

Bergslagen is dominant by granitoid intrusives. They have been subdivided into older primorogenic (syn-volcanic) and younger serorogenic intrusions dated between 1.8–1.9 Ga (Åberg *et al.,* 1983, 1984; Welin *et al.,* 1980). There appears to be a continuous history of magma intrusion throughout this time and they can no longer be regarded as separate groups (Baker *et al.,* 1987). The Bergslagen supracrustal series, as defined by Oen *et al.,* (1982), are preserved as enclaves of varying size caught up in the intrusives and consist of volcanosedimentary successions; they are commonly mineralized and contain deposits worked since at least medieval times e.g. Falun and Sala. One such supracrustal enclave in western Bergslagen is the Ljusnarsberg-Ställdalen district.

The Ljusnarsberg-Ställdalen district lies 10 km south of the Grängesberg magnetite-apatite deposit, and 30 km southeast of the Yxsjöberg scheelite deposit. No deposits are currently worked but several mines have been important at different times. Fe–Mn (magnetite) ores were worked at Ställberg and Ställdalen by the Stora Kopparberg AB until 1978 and were iron ore producers for 110 years (Grip, 1978). Base metal sulphide deposits, owned by Boliden AB, were worked at Ljusnarsberg (until 1975) and Kaveltorp (until 1974); Ljusnarsberg boasts the first Swedish mine map (Grip, *op. cit.*). The Finngruvan Cu–Fe deposit was a major Cu ore

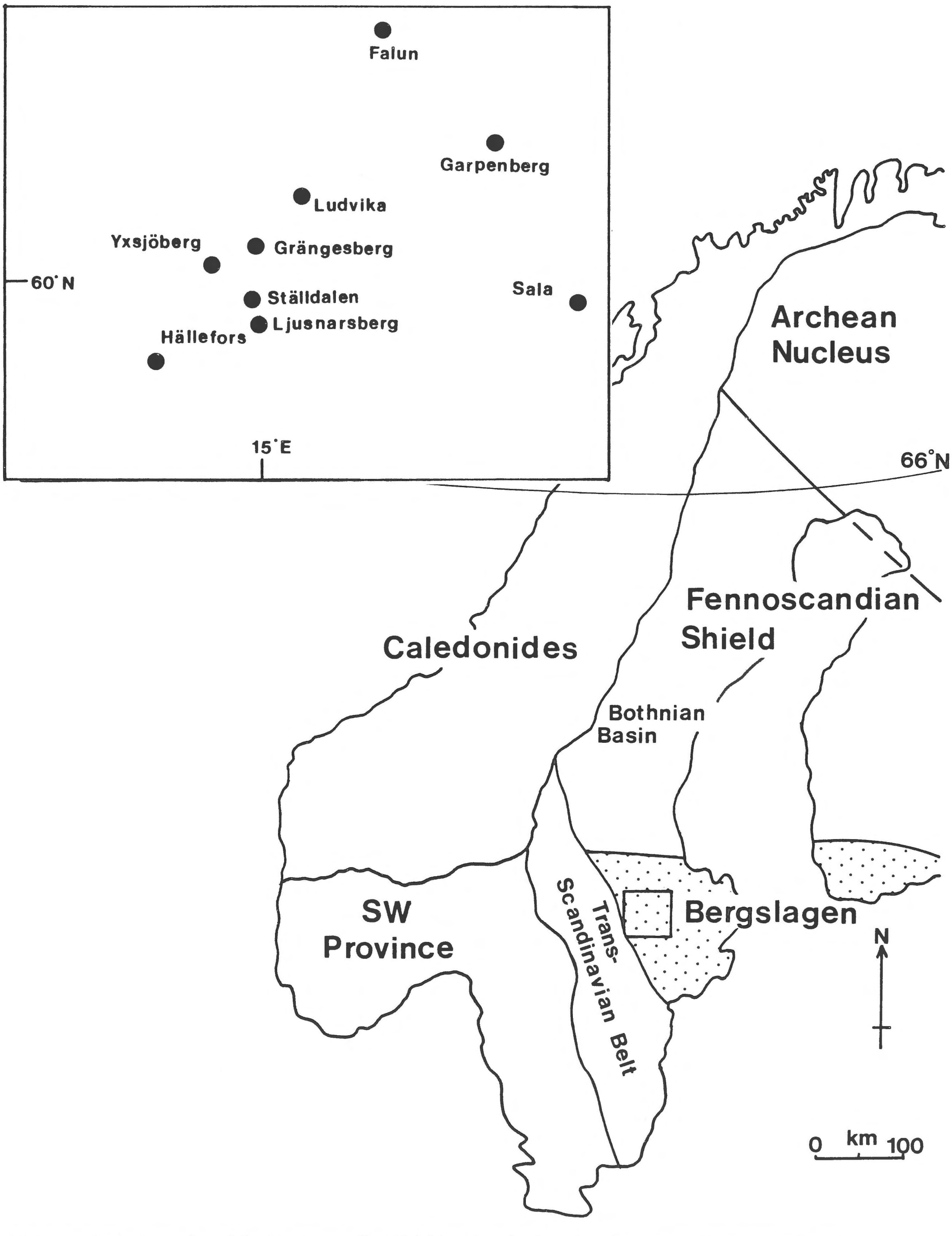

Fig. 1. Major geological terrains of the Fennoscandian Shield and major locations in western Bergslagen (inset).

producer for central Sweden in the medieval times but work ceased in 1876 (Carlborg, 1934). Recently tungsten has become the most economic resource in the area as scheelite and the small deposits at Wigström (1978–1981) and Älgfall (1970–1971) were exploited briefly. The ores were economically viable because of the proximity of the mill at Yxsjöberg.

Local geology

The stratigraphic succession in the Ljusnarsberg district is approximately 15 km thick and is dominated by a fault bounded syncline (Fig. 2). The tight F_1 fold which defines the syncline (Lundström, 1985) has a near horizontal axis doubly plunging and closing to the north and south (Nisca, 1981; in Lundström, 1985). It is cut by a major sub-parallel N/S lineament which can be traced for some distance (C.J. Carlon pers. comm., 1986). The extent of vertical and lateral movement along the zone of faulting is unknown but several small NW/SE faults of limited dextral slip are thought to be associated with it (Fig. 2). F_2 folds are more open and have steeply dipping east-west axes, they are associated with some faulting (there is minor shear movement along fault planes).

Two major lithostratigraphic groups have been recognised (Parr & Rickard, 1987; Parr, in press): a lower metavolcanic dominated group, the Kumlan Group, and an upper mixed metasediment and metavolcanic group, the Ställdalen Group (Fig. 3). Metamorphic grade increases from west to east from upper greenschist to lower amphibolite facies. East of the synclinorium and the zone of N/S faulting lies a more complex mixed metasediment-metavolcanic group, the Wigström Group. This group was intruded by the post-orogenic Malingsbo Granite and was subject to upper amphibolite facies metamorphism and intense deformation. Stratigraphically the status of the Wigström Group is uncertain but its succession of metavolcanic to metasediment dominated rocks suggests it is equivalent to the upper part of the Kumlan Group and lower Ställdalen Group and is coeval with the base metal mineralization in the lower Ställdalen Group (cf. Lundström, 1985).

The Kumlan Group is dominated by a 5 km thick pile of felsic volcanic material with occasional minor mafic episodes and rare intercalated metasediments. The lower part of the Kumlan Group is dominated by massive pyroclastic deposits with few depositional bedforms and probably represents several episodes of major ash fall or flow during a very active volcanic episode. The upper part of the group, the Abborrtjärn Tuff Member, (Fig. 4) is interpreted as subaerial (Parr & Rickard, 1987) and has been correlated tentatively with a major subaerial unit, the Holmsjö Formation to the east near Malingsbo (Ambros, 1983).

The Abborrtjärn Tuff Member contains both massive and planar beds. Contacts between beds, which are 10–40 mm thick, are sharp and are defined by changes in quartz and feldspar crystal size (recrystallised) and composition i.e. biotite content (aligned to schistosity). Fine laminations are absent and internal sorting of beds is rare. Primary quartz eye phenocrysts are abundant. They are concentrated in, but show no sorting within, individual horizons. There does, however, appear to be an overall trend of upwards thinning of horizons and an increase in biotite content of the rock. Erosional surfaces, indicative of a high energy environment are not common but do occur in the lower succesion suggesting some topographic relief at that time. Primary textures and structures observed in the member indicate volcanism was explosive and built up a thick pile of rhyodacitic tuffaceous material fairly rapidly. They are interpreted as subaerial pyroclastic fall deposits of minor or distal Plinian volcanism (Sutheren, 1985; Parr & Rickard, 1987).

Metasediments within the Kumlan Group occur as minor lens-like horizons spatially and temporally restricted within the stratigraphy. They plausibly represent pauses in volcanic activity and are frequently metalliferous: Fe (magnetite-pyrrhotite), Cu–Fe. The Kumlan Group is overlain by the Ställdalen Group (Fig. 3), the contact being gradational over 250 m. The stratabound mineralization occurs above this contact (Fig. 3).

The distinct change in environment of deposition is reflected in the change in lithologies, from the metavolcanics of the Kumlan Group to the metavolcanics and metasediments of the Ställdalen Group. It appears to have been crucial for the formation and preservation of the metalliferous deposits (cf. Arvanitidis & Rickard, 1981). Almost immediately above the contact region there is a marked increase in thin ironstones (as defined by Klein, 1973) finely interbedded with other metasediments. The contact region between the groups is characterised by finally bedded metasediments

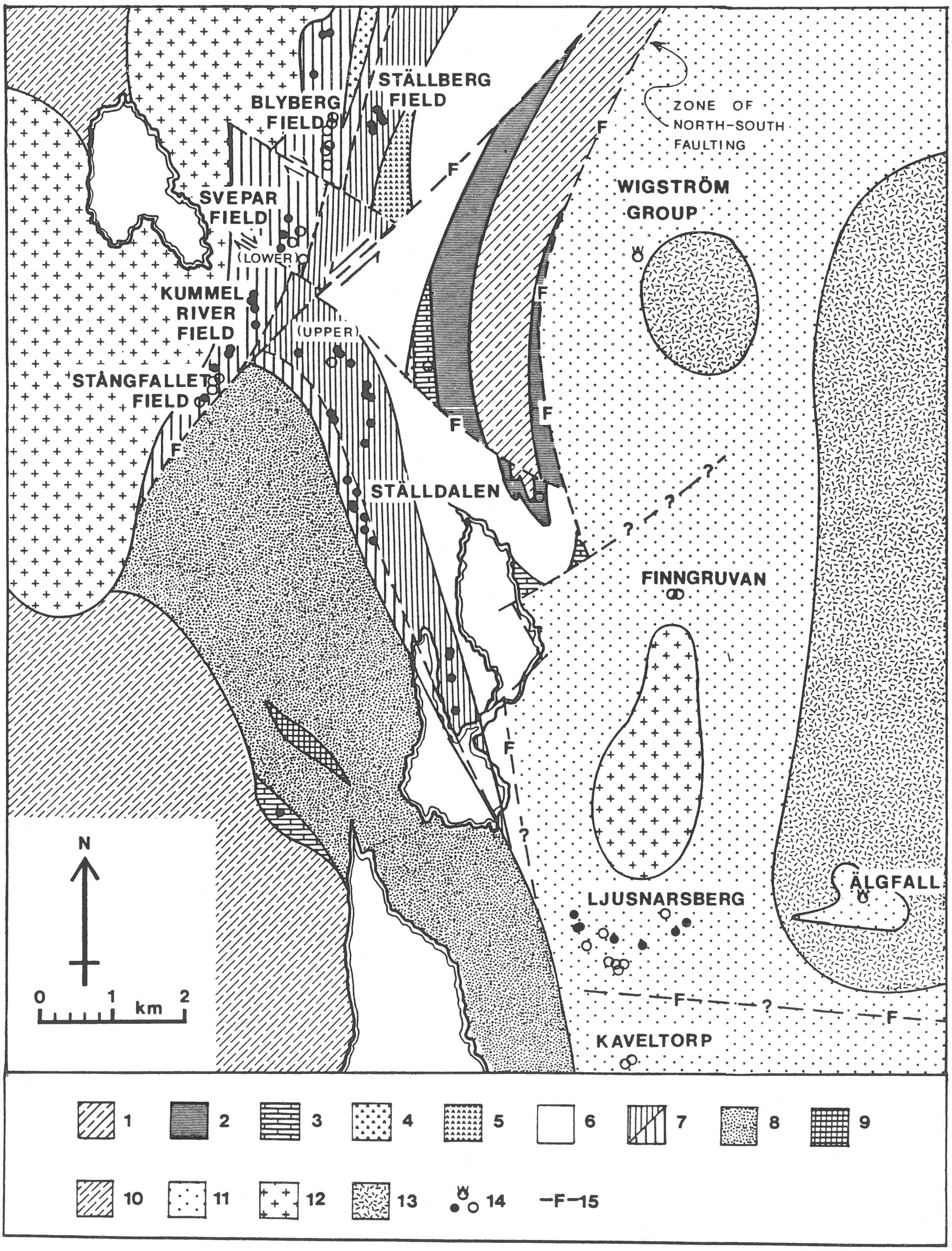

Fig. 2. Geology of the Ljusnarsberg-Ställdalen district showing the Ställdalen Mineralized Zone. Key: (1) Andalusite schist; (2) meta-argillite; (3) Carbonate; (4) Coarse pyroclastics; (5) Amphibolite; (6) Fine-grained, mixed metavolcanic and metasedimentary rocks; (7) Ställdalen mineralized zone Upper/Lower; (8) Abborrtjarn tuff member; (9) Biotite schist; (10) Lower Kumlan Group; (11) Wigstrom Group; (12) Early-orogenic granite; (13) Late-orogenic Malingsbo granite; (14) Tungsten, magnetite, sulphide deposits; (15) Faults.

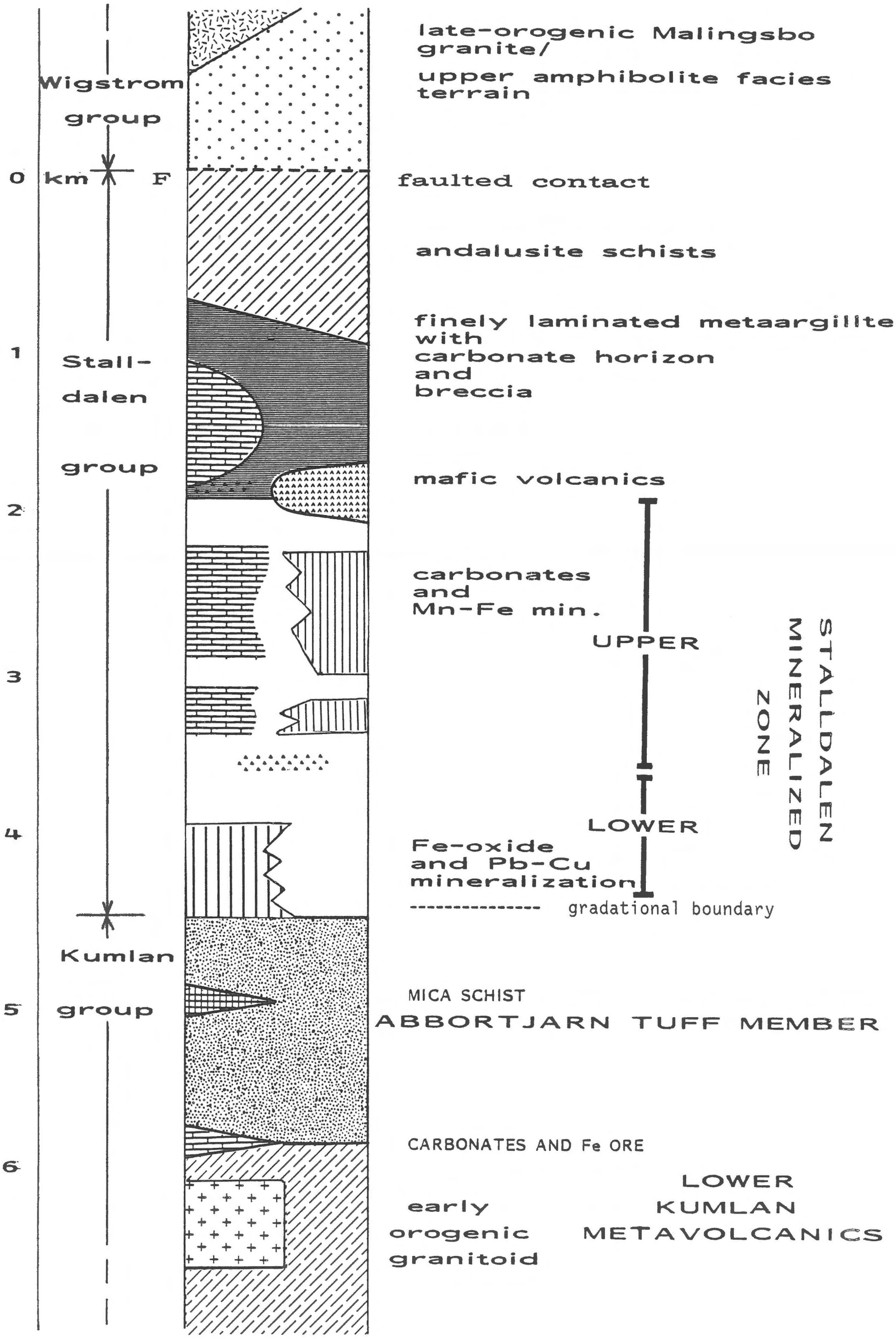

Fig. 3. Lithostratigraphy of the Ljusnarsberg-Ställdalen district.

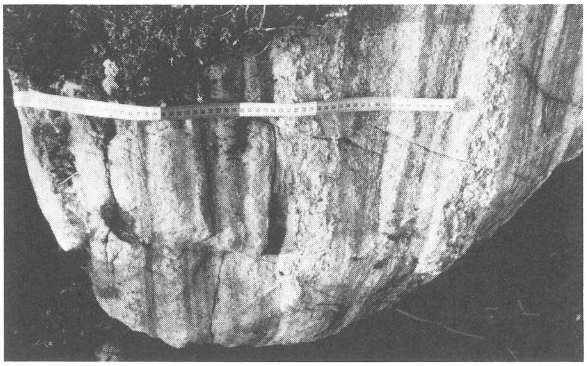

Fig. 4. Subaerial pyroclastic fall deposits, east of Lake Ljusnarn. The beds are unsorted, planar and have sharp contacts. Beds are defined by relative contents of biotite.

of both clastic or detrital origin and chemically precipitated rocks. It is these rocks which are described below.

Commonly the rocks fluctuate between clastic and chemically precipitated metasediments on a centimetre scale. The precise changes in mineral assemblages, from quartz-feldspar-biotite (+/− zircon) horizons (frequently <1 mm thick) to carbonate and calc-silicate dominated horizons (Fig. 5), and the concentration of zircons interpreted as detrital (see below), suggests the banding is primary sedimentary bedding. Chemically precipitated metasediments (in particular calc-silicate-rich assemblages) are volumetrically most important near regions of ore deposition. In these regions post depositional alteration (hydrothermal) processes are most intense. These beds mark the beginning of the Ställdalen Group. The sedimentary component increases in importance up stratigraphy and culminates in an alumina-rich meta-argillitic horizon (andalusite schist; Fig. 3). Volcanism decreases and is increasingly bimodal in composition. Bimodal composite intrusives of limited extent (<3000 m^2) also occur (compare also with the occurrence of composite dykes at Grängesberg to the north: Back, pers. comm., 1985).

Two major occurrences of concordant stratabound mineralization occur in the lower part of the Ställdalen group, they are:

(1) a lower Cu–Fe–Pb–Zn–(W–Mo) sulphide-rich zone composed of small lenses of carbonate and calc-silicate hosted base metal sulphide ores, and
(2) an upper Fe–Mn oxide (magnetite) dominated zone of larger extent and thickness.

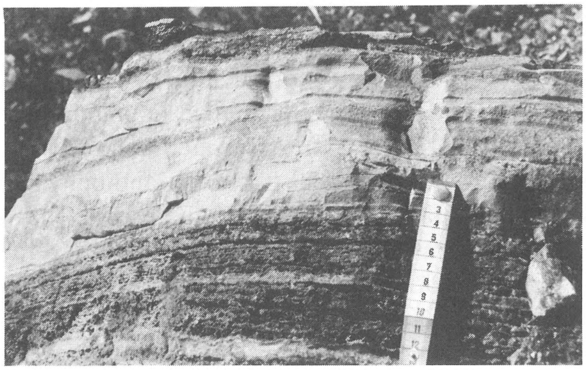

Fig. 5. Very finely banded clastic sediments intercalated with chemically precipitated carbonates. Clastic material is derived from the underlying volcanic pile; it marks the onset of quiet shallow subaqueous conditions and the waning of explosive volcanism.

Primary depositional structures preserved in the rocks associated with the lower zone of mineralization indicate mineral deposition was in a shallow subaqueous environment associated with hydrothermal activity. Such a view is supported by petrographic and geochemical evidence, and is discussed in more detail below. The upper zone has few primary depositional structures but the dominant carbonate-magnetite rock indicates deposition was in an aerated subaqueous environment.

Other mineralized occurrences are found throughout the stratigraphy and include the base metal deposits at Finngruvan, Kaveltorp and Ljusnarsberg, and the W-skarn deposits at Wigström and Älgfall dicussed above.

The Lower Mineralized Zone

The ore deposits of the lower zone are commonly hosted in carbonate rocks and are locally tectonically lensoid in form (the Stångfallet deposit is a typical example: 25 × 15 × 50 m). The metalliferous sulphide-rich rocks have varying proportions of pyrite, pyrrhotite, chalcopyrite, galena and sphalerite with minor molybdenite, arsenopyrite, and reported boulangerite, native antimony and bismuth (Hübner, 1968). Associated wall rocks include garnet-biotite schists, garnet-anthophyllite rocks and quartz-K feldspar-epidote rocks.

The mineralized lenses are truncated by several minor faults orientated at 45° to a major D_2 NE/SW fault zone (Fig. 2). The stratigraphic extent of the zone is unclear: deposits in the Hörken-Yxjöberg (W-Mo) ore field to the north are dispersed and there has been remobilisation of the sulphide ores (Parr, 1988). To the south the zone is cut by the D_2 NE/SW fault zone (Fig. 2). Its possible continuation, however, may be represented by the Kaveltorp and Ljusnarsberg base metal sulphide deposits (Fig. 2; Parr, 1988).

Metal ratios vary within the mineralized zone, Cu–Zn–Pb ores occur towards the northern (Blyberg) and southern margins (Stångfallet; Fig. 2). Both are associated with garnet-biotite-anthophyllite rocks and the metasediments described below (in particular groups 2 and 3; see below). The 'central' part of the zone, as it occurs now, is enriched in Fe and Cu. Fe is as magnetite with only minor pyrrhotite. These metalliferous rocks are commonly associated with hornblende-rich rocks. The zoning observed here is similar to that noted for the Early Proterozoic stratiform base metal exhalative deposit at Pegmont, Australia (Stanton & Vaughan, 1979). Stanton & Vaughan (*op. cit.*) suggested the changes defined a palaeobasin with changing depositional environments away from the centre. It must also reflect distance, or relationship to, or variation of, the circulating hydrothermal fluids.

Metasediments associated with the Lower Mineralized Zone

The deposits are underlain and interspersed with metasedimentary rocks of three main types:

(1) very finely banded quartz-feldspar-biotite-(calcite-hornblende-garnet-pyroxene-epidote) with some magnetite-rich beds <20 cm thick (Fig. 5).
(2) well banded rocks of variable mineralogy. Bands consist of differing amounts of quartz-K feldspar-plagioclase-garnet-amphibole-pyroxene-calcite-epidote-biotite-chlorite-apatite-sphene (Fig. 6).
(3) distinctly banded pink and green rocks consisting of K feldspar, epidote and quartz (Fig.7).

Rocks of the first group are most commonly, though not exclusively, the furthest away from mineralized occurrences. They are particularly fine grained (0.01–0.1 mm). Fine scale compositional banding (0.2–1.0 mm); Fig. 5) is interpreted as primary bedding because of the very fine layering, graded bedding and rare symmetrical ripple structures which are observed. They indicate deposition was in a shallow subaqueous, quiescent environment. The rocks have a simple mineralogy; they are predominantly quartz-feldspar-biotite with minor horizons rich in calcite (Fig. 5), amphibole (hornblende), zircon and magnetite. Relict quartz eye phenocrysts and zircon crystals are interpreted as detrital. The metasediments of the first group are, therefore, probably derived by reworking of the underlying metavolcanic rocks.

Well banded rocks with more variable mineralogies of the second group occur stratigraphically below and laterally equivalent to rocks of the first group. They are dominated by Ca-rich minerals, in particular calcite and calc-silicates such as epidote, Ca amphiboles., Ca pyroxenes and garnets.

Banding in the rocks of the second group is again due to compositional and grain size changes (Fig. 6). However, the paragenesis is a metamorphic one: crystals have equilibrium textures and there is porphyroblastic development of magnetite. Microprobe analyses indicate that the amphiboles are ferroactinolite to hornblende, indicating that metamorphism was at greenschist to amphibolite grade. The are rich in Ca, Fe and Mn and are aligned parallel to schistosity. Pyroxenes are less common ~5%) but are enriched in Ca and Fe; they are ferrosalitic to hedenbergitic. The garnets are pale red in colour and are enriched in Ca and Mn.

Although the mineralogy is a metamorphic one, banding (which is as fine as 0.25 mm) is interpreted as primary bedding. Crude grading is evident in

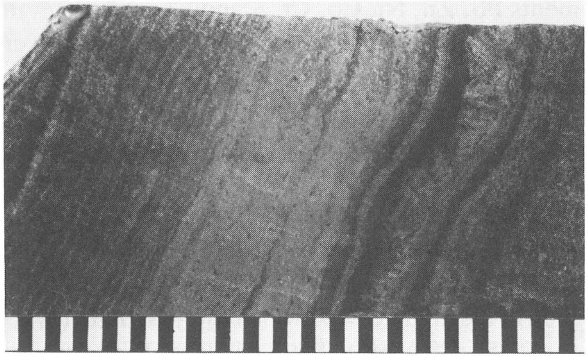

Fig. 6. Well banded carbonate rich rock with variable mineralogy including amphibole, pyroxene and epidote. *In situ* brecciation of individual layers (right of picture) is interpreted as synsedimentary deformation. Bars measure 2 mm wide each.

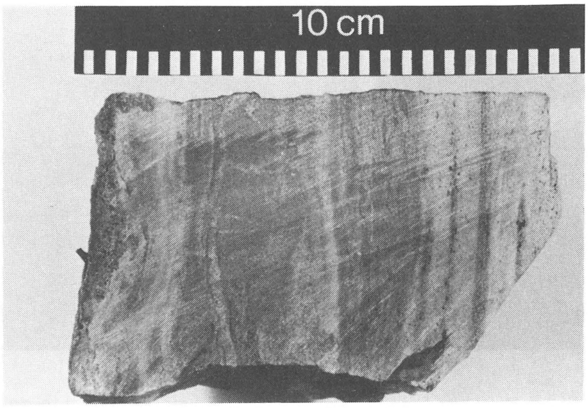

Fig. 7. Distinctly banded K feldspar-epidote-quartz rocks interpreted as hydrothermally altered metasediments (sample 580; see text).

thicker bands on a scale of 20–50 mm from Fe-rich to Fe-poor and is reflected in the epidote content of the carbonate bands (Fig. 6). Garnets commonly form crystalline layers ~5–15 mm thick and have a bulbous concretionary morphology (Fig. 8). The garnet layers are mantled stratigraphically above by variable quartz-feldspar-ferroactinolite layers but do not disturb the quartz-K feldspar-carbonate layers below. Perpendicular microfractures crosscut the garnet and are filled with quartz and feldspar. Other bands are not fractured suggesting extensional brittle failure was concentrated in the garnets, or their precursors, either as post lithification extensional movement associated with regional deformation along a preferential layer, or brittle failure during diagenesis of a partially lithified colloidal accumulation of, for example, Fe–Mn silicate gels (Stanton, 1976). The bulbous textures observed on the upper surface of the garnet layer are similar to those seen in primary evaporitic deposits (Kendall, 1984).

The two rock groups (1) and (2) above are closely related in the field and in places are intercalated. They are interpreted as representing fluctuating periods of clastic sediment input overprinting probably continuous chemical precipitation. The chemical precipitates observed, therefore, formed during periods of sediment starvation, brine concentration and/or increased hydrothermal activity. The presence of barren carbonate horizons (Fig. 5) reflects the apparent indepedence of carbonate precipitation of metal enriched exhalative solutions and the depandence on *additional* pulses of hydrothermal activity for the formation of metalliferous precipitates.

Banded rocks consisting of K feldspar, epidote and quartz (group 3) are considered to be chemical sediments which have been subject to potassic hydrothermal alteration (Browne, 1978; Rose & Burt, 1979). The fine banding observed reflects primary compositional bedding so that these rocks are thought to be the hydrothermally altered equivalent of the clastic and chemical sediments described above. The bands have sharp contacts and show some cyclicity (Fig. 7). They can be divided into two main mineral assemblages: quartz-K feldspar-epidote (+/−fluorite-Fe Ti oxides) and epidote-pyroxene (hedenbergite). Bands are not equigranular and do not show equilibrium textures although epidote rich bands tend to be coarsest and are made up of subhedral crystals.

Epidote in group (3) rocks are very Fe-rich containing up to 12.5 wt% Fe_2O_3; there is also enrichment in Ca (<23.8 wt% CaO: Parr, unpub. data). They are pale green in colour and form subeuhedral prismatic crystals. The pyroxenes are ferrosalitic in composition and are Ca enriched (<16.6 wt% CaO). They are anhedral and commonly altered along their margins to a Ca-rich material. K feldspar is fine to coarse grained microcline. It is anhedral and porphyroblastic (some in-

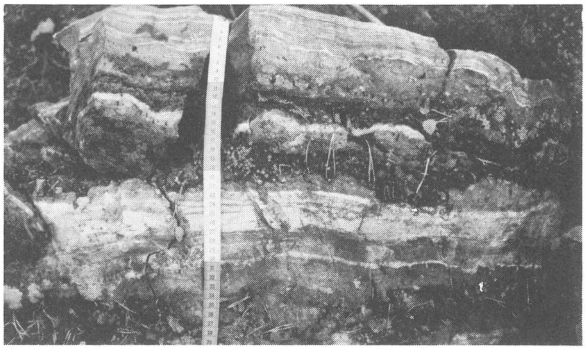

Fig. 8. Well banded calc-silicate rock consisting of garnet, hornblende, epidote, pyroxene, calcite, quartz and feldspar (sample 106; see text).

clusions of epidote and quartz) to fine grained. Unlike K feldspar, quartz is nearly all fine grained and has recrystallised as a function of metamorphism; it shows no undulose extinction or other strain indicator.

Geochemistry of the metasediments

For this study twelve samples were selected from a large set of specimens taken from the Ljusnarsberg-Ställdalen area: four for each rock group. They were analysed using the XRF spectrometer (Philips PW1400) at University College, Cardiff. Major elements were determined using fused beads and minor elements with pressed powder pellets. All iron data were measured as Fe_2O_3 (Table 1). Attempts were made to select representative samples despite the variable mineralogy and in some cases subdivisions were made according to varying dominant mineralogy within the rock specimen (sample 106: 1062 & 1066, sample 580: 5801 & 5802: Table 2).

Metasediments of group (1) have major element chemistries dominated by silica (average 70.16 wt% SiO_2) and alumina (average 12.19 wt% Al_2O_3) and this is reflected in their most common quartz-K feldspar-biotite mineralogy. The rocks have total alkali contents reflecting their high feldspar content (although lower than rocks of group (2)). Group (1) rocks also have trace Cu unlike the more altered rocks in groups (2) and (3). The elements Pb, Zn, Ni, Co, Cr, S and Cl are present in significant amounts compared to rocks of the other groups (Table 1).

Rocks from group (2) have lower silica (average 58.24 wt% SiO_2) and alumina (average 11.86 wt% Al_2O_3) than those of group (1). The observed calcite, calc-silicate-rich mineralogy is reflected in the high Ca content (average 13.73 wt% CaO). The calc-silicates are Fe (−Mn) enriched and this is seen in the high Fe (6.91 wt% Fe_2O_3) and Mn (average 0.85 wt% MnO). Total alkali contents are also high compared to the other metasediments studied. Elevated trace element contents of Zn and Y are contrasted by relative depletions in Pb, Co, Cr, and V (Table 1).

Table 1. Average whole rock geochemical analyses of metasedimentary groups described in the text). (Total Fe as Fe_2O_3).

(wt%)	Group 1 (no. = 4)	Group 2 (no. = 4)	Group 3 (no. = 4)
SiO_2	70.16	58.24	71.95
TiO_2	0.25	0.21	0.14
Al_2O_3	12.19	11.86	10.96
Fe_{tot}	4.23	6.91	4.81
MnO	0.10	0.85	0.16
MgO	1.02	1.19	0.82
CaO	8.22	13.73	7.97
Na_2O	1.65	2.23	1.14
K_2O	2.26	3.90	3.14
P_2O_5	0.04	0.06	0.25
Total	100.12	99.18	101.34
(H_2O^-)	0.75	1.29	0.76
(ppm)			
Pb	51	9	15
Zn	62	122	20
Cu	6	0	0
Ni	15	11	12
Co	81	59	79
Cr	70	24	83
B	499	758	1118
Rb	118	115	111
Sr	52	56	89
Y	30	51	32
Zr	220	258	267
Nb	13	14	21
S	1861	384	226
Cl	293	233	134
V	20	0	0

The highly variable mineralogy of rocks in group (2) corresponds to observed large trace element variations on a centimetre scale within individual rock samples. For example two analyses are given for sample 106 (1062 and 1066). They are both taken from the upper 15 cm of Fig. 8 and are separated by approximately 8 cm. The mineralogy of sample 1066 is dominated by the calc-silicates actinolite, epidote and garnet, with only minor K feldspar and quartz. 1062 contains the above calc-silicates but has more K feldspar, quartz and plagioclase. Selected trace element concentrations are shown in Table 2; large variations are noted. Elevated values of the base metals Cu, Zn and Pb are observed for sample 1066, only Zn was detected in 1062. Similarly sample 1066 is enriched in Ba by a factor of ~1.5 (observed as very rare baryte crystals), and Rb and Sr by a factor of ~3. Variations in these elements, though significant locally, is not unusual because of their mobility in both hydrothermal and metamorphic processes (Pearce & Cann, 1973). More noteable are the large variations in the so-called 'immobile' elements (Cann, 1970; Field & Elliot, 1974; Table 2). Y and Zr increase from 1062 to 1066 by factors of 2.4 and 2.7 respectively but the ratio Y/Zr remains approximately constant (Table 2). Nb, however, increases 6.9 times between 1062 and 1066 and the ratios Nb/Zr and Nb/Y are doubled between analyses (Table 2).

Table 2. Selected trace element concentrations and ratios for four analyses taken from two rock samples. Rock sample 106 (group 2): analyses 1062 and 1066; rock sample 580 (group 3): analyses 5801 and 5802.

(ppm)	1062	1066	5801	5802
Pb	0	14	11	15
Zn	41	216	18	25
Cu	0	13	0	0
Ni	8	12	12	12
Co	53	83	77	79
Cr	4	4	86	83
Ba	611	920	1052	1185
Rb	79	259	77	140
Sr	35	104	80	92
Y	40	95	23	39
Zr	172	467	219	257
Nb	6	27	16	22
S	205	65	148	162
Cl	224	202	122	198
V	0	0	0	0
Y/Zr	0.23	0.20	0.11	0.15
Nb/Y	0.15	0.28	0.70	0.56
Nb/Zr	0.03	0.06	0.07	0.09

The petrography of the rocks of group (2) suggests the observed banding represents primary bedding (see above). The measured changes in element concentration, particularly Zr, Y and Nb, are, therefore, interpreted as primary depositional chemical trends preserved in individual lithological units. Extreme changes over short stratigraphic distances are, therefore, recorded in the pre-metamorphic chemistry of the rocks.

Metasediments of group (3) are the most altered. They are enriched in silica (average 71.95 wt% SiO_2) and potassium (average 3.14 wt% K_2O) reflected in the quartz-K feldspar mineralogy. P_2O_5 is also elevated relative to the metasediments in groups (1) and (2). If phosphorus was introduced during alteration it may suggest hydrothermal solutions were of sea water origin. MnO on the other hand is relatively depleted. As a group they have elevated Ba, Zr and Nb values and have low Cl (Table 1). But, like group (2) rocks, element concentrations vary over small distances. Two analyses are given for rock sample 580 (5801: epidote > quartz > K feldspar and 5802: K feldspar >> quartz > epidote; Fig. 7): they are separated by approximately 5 cm. Factors of enrichment are not as extreme as those observed in group (2) above but significant changes are observed in Rb (enrichment factor ~2), S (1.6) and in the 'immobile' elements Y (1.7), Zr (1.2) and Nb (1.4). Immobile element ratios are relatively consistent compared to those for group (2) (Table 2).

Discussion

The rocks described in groups (2) and (3) above form part of the larger group of calc-silicate dominated 'skarn' mineralogies (Einaudi *et al.*, 1981). Skarn assemblages have been documented by many authors in association with mineralization (e.g. Stanton & Vaughan, 1979; Barnes, 1980;

Stanton, 1982b; Plimer, 1984; Fulp & Renshaw, 1985); In Bergslagen, specifically, the association has been described by authors too numerous to list but they include Magnusson (1940) for the Ljusnarsberg-Ställdalen area, Hedström (1984) for the Hällefors deposit and Hellingwerf (1984) for the Gruvåsen deposit.

At Mount Misery, Queensland, assemblages of Ca garnets, Ca pyroxenes, amphiboles and epidote, with accessory calcite, fluorspar and scapolite, and locally dominant magnetite are described in association with a Fe–Cu–Zn–Pb sulphide mineralization (Stanton, 1982a). They are interpreted as exhalative sediments precipitated as localised aprons in hydrothermally active regimes. The absence of any granitic material precludes a contact metamorphic origin for the rocks; Stanton (*op. cit.*) suggested that regional metamorphism of suitable precursor calc-silicate gels might be responsible.

Possible primitive silicates might include Fe–Ca–Mn–Mg–Na–K silicates and alumino-silicates. Mn chamosite, ferriferous illite, and chert (Stanton & Vaughan, 1979).

Despite the proximity of the synorogenic granites to the rocks described in this paper (100–500 m), there is no apparent spatial relationship of the calc-silicate-rich rocks with distance from the intrusion: indeed the same complex mineralogies are found at least 1 km away from the contact. The rocks are, however, intimately spatially associated with the mineralized horizons, in particular, the lower base metal sulphide horizon.

Delicate but well defined compositional banding seen in the rocks of groups (1) and (2) in particular, reflects possible periodic pulses and fluctuations in hydrothermal fluid temperature, Eh, pH, FO_2, and chemistry (Hutchinson *et al.*. 1980). A distinct zoning can be developed away from the exhalative centre in regions of exhalative precipitation (Stanton & Vaughan, 1979). At Gruvåsen, Hellingwerf (1984) recognises sulphide zonation in areas of intense potassic alteration and interprets the zoning in terms of distance from a hydrothermal vent below the sea floor. Cu–Fe, Cu–Zn, Cu–Pb–Zn–Fe, Fe-oxide and W–Mo enriched lenses can be distinguished in the lower mineralized horizon of the Ljusnarsberg-Ställdalen district and can be interpreted as reflecting distances from hydrothermal centres, or changes in hydrothermal solutions away from their point of exhalation, or both. The metasediments between mineralized zones also show potassic alteration in rocks nearest the mineralization (group 3 rocks). Metasediments deposited stratigraphically away from the mineralized rocks have highly variable mineralogies and whole rock chemistries which change drastically over centimetres (group 2 rocks). At greater distances the metasediments have simple quartz-feldspar-rich mineralogies (group 1 rocks), they lack the chemical variations observed in metasediments of groups (2) and (3).

The end of a felsic volcanic succession (The Kumlan Group) with only minor sediments, is marked by the rapid onset of quiet shallow subaqueous conditions (Fig. 3). Sundius (1923) suggested subaqueous development was as 'shallow ephemeral lakes' and this might be expected in the transition from subaerial volcanism (the Kumlan Group) to subaqueous sedimentation (the Ställdalen Group). Magmatism in the lower Ställdalen Group is compositionally bimodal. Fulp & Renshaw (1985) suggest mafic magmatism may be responsible as a heat source for the circulating hydrothermal fluids in the Blacklite Prospect, New Mexico. Hellingwerf (1984) came to the same conclusion for the marble-hosted Cu–Zn–Fe–Pb–As(–W–Mo) sulphides at Gruvåsen.

The apparent pre-deformational confinement of supracrustals in the Bergslagen district (e.g. the Ljusnarsberg-Ställdalen, Grythyttan (Oen *et al.*, 1982), Garpenberg (Vivallo, 1985), and Sala districts) suggests depositional basins were, at least initially, separate. In the upper stratigraphy, however, chronological units can be recognised on a more widespread scale and represent the connection of the basins. The regional occurrence of large Fe (magnetite) ores may, therefore, signify the onset of regional subaqueous conditions.

Conclusions

The stratigraphic succession in the Ljusnarsberg-

Ställdalen district can be divided into two main lithostratigraphic groups. A lower metavolcanic sequence, the Kumlan Group, comprising felsic, partly subaerial, rocks dominated by pyroclastic deposits. An upper mixed metavolcanic and metasedimentary sequence, the Ställdalen Group, which includes two stratbound zones of mineralization: a lower series of base metal sulphide enriched lenses and an upper, more dominant, Fe oxide rich horizon.

The lower mineralized horizon occurs at a change in the depositional environment. It is associated along strike with chemically variable metasediments (group 2: Fig. 6). Petrological, mineralogical and chemical evidence suggest they are Fe–Ca–Mn enriched exhalative chemical precipitates with some clastic input. Close to the small lensoid ore occurrences the metasediments have been subject to potassic hydrothermal alteration resulting in quartz-K feldspar-epidote assemblages (group 3: Fig. 8). At greater distances along strike the metasediments are very finely bedded clastic sediments with only occasional thin barren carbonate horizons (group 1: Fig. 5): they are apparently unaffected by any syndepositional alteration.

Major element chemistry reflects the petrography of the rocks studied. Least altered rocks (group 1) are Si and Al-rich. Variable rocks of group (2) have Ca, Fe and alkali-rich chemistries. The most altered rocks (group 3) are enriched in Si and K, and also have significant P and Ba. Trace element concentrations, however, are less predictable. They vary over centimetres in the more altered rocks. In particular the 'immobile' elements show distinct concentrations.

The spatial relationship of the altered metasediments to the lower mineralized zone indicates the most altered rocks occur nearest the mineralized rocks. They represent zones of potassic alteration due to hydrothermal activity.

Acknowledgements

This work forms part of a Ph.D. research project under the supervision of Professor David Rickard, his guidance is appreciated. I gratefully acknowledge the support of B.P. Minerals International Ltd. The manuscript has benefitted from constructive critisism from several reviewers including P.T Leat, Per Hedström, and Chris Carlon.

References

Åberg, G., Bollmark, B., Björk, L. & Wiklander, U. 1983 Radiometric dating of the Horrsjö granite, south central Sweden – Geol. För. Förh. 105: 78–81.

Åberg, G., Levi, B. & Fredrikson, G. 1984 Zircon ages of metavolcanic and synorogenic granitic rocks from the Svärdsjö and Yxsjöberg areas, south central Sweden – Geol. För. Förh. 105: 199–203.

Ambros, M. 1983 Beskrivning till berggrundskartan Lindesberg NO – Sver. Geol. Unders. Af 141.

Arvanitidis, N. & Rickard, D.T. 1981 REE geochemistry of an Early Proterozoic volcanic ore district, Dammberg, central Sweden: a summary of results. – In: Rickard, D.T. (ed.): Ann. Rept. Ore Res. Group, Stockholm University, 1981: 105–135.

Baker, J.H., Hellingwerf, R.H. & Hammergren, P. 1987 Geochemistry of a Proterozoic high silica W–Mo granite from Västra Grashöjden, central Sweden – Geol. För. Förh. 109: 111–121.

Barnes, R.G. 1980 Types of mineralization in the Broken Hill Block and their relationship to stratigraphy. In: Stevens, B.P.J. (ed.): A guide to the stratigraphy and mineralization of the Broken Hill Block, New South Wales – NSW Geol. Surv. Rec. 20: 33–70.

Boardman, S.J. 1986 Early Proterzoic bimodal volcanic rocks in central Colorado, U.S.A. Part I: petrography, stratigraphy, and depositional history – Precamb. Res. 34: 1–36.

Boardman, S.J. & Condie, K.C. 1986 Early Proterozoic bimodal volcanic rocks in central Colorado, U.S.A. Part II: geochemistry, petrogenesis, and tectonic setting – Precamb. Res. 34: 37–68.

Browne, P.R.L. 1978 Hydrothermal alteration in active geothermal fields – Ann. Rev. Earth Planet. Sci. 6: 229–250.

Cann, J.R. 1970 Rb, Sr, Y, Zr, Nb in some ocean floor basaltic rocks – Earth Planet. Sci. Lett. 10: 7–11.

Carlborg, H. 1934 Ljusnarsberg malmtrakt, Historik.

Einaudi, M.T., Mienert, L.D. & Newberry, R.J. 1981 Skarn Deposits – Econ. Geol. 75th Anniv. Vol.: 317–391.

Field, D. & Elliot, R.B. 1974 The chemistry of gabbro/amphibolite transitions in south Norway – Contrib. Mineral. petrol. 47: 63–76.

Fulp, M.S. & Renshaw, J.L. 1985 Volcanogenic-exhalitive tungsten mineralization of Proterozoic age near Santa Fe, New Mexico, and implications for exploration – Geology 13: 66–69.

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

Grip, E. 1978 Sweden. In: Bowie, S.H.U., Kvalheim, A. &

Haslam, H.W. (eds): Mineral deposits of Europe 1. N.W. Europe – Inst. Min. Metall. Lond.: 93–198.

Hedström, P. 1984 Geological and genetic aspects of the Hällefors sulfide ores, Bergslagen, Sweden – Geol. För. Förh. 106: 151–166.

Hellingwerf, R.H. 1984 Paragenetic Zoning and Genesis of Cu–Zn–Fe–Pb–As Sulfide Skarn Ores in a Proterozoic Rift Basin, Gruvåsen, Western Bergslagen, Sweden – Econ. Geol. 79: 696–715.

Hellingwerf, R.,H., Lilljequist, R. & Ljung, S. 1988 Stratiform Zn–Pb–Fe–Mn Mineralisation in the Älvlången-Vikern Area, Bergslagen, Sweden. In: Baker, J.H. & R.H. Hellingwerf (eds): The Bergslagen Province, Central Sweden – Structure, stratigraphy and ore-forming processes. I.G.C.P. Project 247 – Geol. Mijnbouw 67: 313–332 (this issue).

Hietanen, A. 1975 Generation of potassium poor magmas in the southern Sierra Nevada and the Svecofennian of Finland – U.S. Geol. Surv. J. Res. 3: 631–645.

Hutchinson, R.W. 1982 Syn-depositional hydrothermal processes and Precambrian sulphide deposits. In: Hutchinson, R.W. & Franklin, J.M. (eds): Precambrian sulphide deposits. H.S. Robinson Memorial Volume. – Geol. Soc. Can. Spec. Pap. 25: 761–791.

Hutchinson, R.W., Fyfe, W.S. & Kerrich, R. 1980 Deep fluid penetration and ore deposition – Minerals Sci. Eng. 12: 107–120.

Hübner, H. 1968 Die Mineralparagenesen von Blyberg, Mittelschweden – Geol. För. Förh. 90: 401–416.

Kendall, A.C. 1984 Evaporites. In: Walker, R.G. (ed.): Facies Models, second edition – Geosci. Can. Repr. Ser. 1: 259–296.

Klein, C. 1973 Changes in mineral assemblages with metamorphism of some banded Precambrian iron formations – Econ. Geol. 68: 1075–1088.

Lundström, I. 1985 Beskrivning till berggrundskartan Lindesberg NV – Sveriges Geol. Unders. Af 140: 131 pp.

Lundström, I. 1987 Lateral variations in supracrustal geology within the Swedish part of the Southern Svecokarelian volcanic belt – Precambr. Res. 35: 353–365.

Lundström, I. & Papunen, H. 1986 Proterozoic geology of southwestern Finland and the Bergslagen Province, Sweden. In: Mineral Deposits of southwestern Finland and the Bergslagen Province, Sweden – Sveriges Geol. Unders. Ca 61: 6–11.

Magnusson, N.H. 1940 Ljusnarsberg malmtrackt. Berggrund och malmfyndigheter – Sver. Geol. Unders. Ca 30: 188 pp.

Nyström, J.O. Post 1982 Svecokarelian Andinotype evolution in central Sweden – Geol. Runsch. 17: 141–157.

Oen, I.S., Helmers, H., Verschure, R.H. & Wicklander, U. 1982 Ore deposition in a Proterozoic incipient rift zone environment: a tentative model for the Filipstad-Grythyttan-Hjulsjö region Bergslagen, Sweden – Geol. Runsch. 71: 182–194.

Oftedahl, C. 1958 A theory of exhalative-sedimentary ores – Geol. För. Förh. 80: 1–19.

Parr, J.M. 1988 The Interrelationships of Ore Types in the Proterozoic Supracrustals of the Ljusnarsberg District, Central Sweden – Unpub. Ph.D. Thesis, Univ. Coll., Cardiff.

Parr, J.M. & Rickard, D.T. 1987 Early Proterozoic subaerial volcanism and its relationship to Broken Hill-type mineralization. In: Pharaoh, T.C., Beckinsale, R.D. & Rickard, T.D. (eds): Geochemistry and mineralization of Proterozoic volcanic suites – Geol. Soc. Lond. Spec. Publ.: 81–93.

Pearce J.A. & Cann, J.R. 1973 Tectonic setting of basic volcanic rocks determined using trace element analysis – Earth Planet. Sci. Lett. 19: 290–300.

Plimer, I.R. 1984 The mineralogical history of the Broken Hill Lode, NSW – Aust. J. Earth Sci. 31: 397–402.

Plimer, I.R. 1986 Sediment-hosted exhalative Pb–Zn deposits – products of contrasting ensialic rifting – Trans. Geol. Soc. S. Africa 89: 57–73.

Plimer, I.R. & Lottermoser, B.G. 1987 Exhalites of the Willyama Supergroup, Broken Hill Block, Australia – Abstract IGCP 217 Mtg, Lund 3–6 June 1987.

Rickard, D.T. 1979 Scandinavian metallogenesis – GeoJournal 3.3: 235–252.

Rickard, D.T. 1987 Proterozoic volcanogenic mineralization styles. In: Pharoah, T.C., Beckinsale, R.D. & Rickard, D.T. (eds): Geochemistry and mineralization of Proterozoic volcanic suites – Geol. Soc. Lond. Spec. Publ.: 23–35.

Rose, A.W. & Burt, D.M. 1979 Hydrothermal alteration. In: Barnes, H.C. (ed.): Geochemistry of hydrothermal ore deposits. 173–235, John Wiley & Sons.

Ryan, P.J., Lawrence, A.L., Lipson, R.D., Moore, J.M., Paterson, A., Stedman, D.P. & Van Zyl, D. 1982 The Aggeneys base metal sulphide deposits, Namaqualand, South Africa – Econ. Geol. Res. Unit, Univ. Witwatersrand Inf. Circ. 160.

Stanton, R.L. 1976 Petrochemical studies of the ore environments at Broken Hill, New South Wales: 2-Regional metamorphism of banded iron formations and their immediate associates – Trans. Inst. Mineral. Metall. 85: B118–131.

Stanton, R.L. 1982a Metamorphism of a stratiform sulphide orebody at Mount Misery, Einasleigh, Queensland, Australia – Trans. Inst. Mineral. Metall. 91: B47–B80.

Stanton, R.L. 1982b Discussions and contributions on 'Genetic problems related to base-metal deposits in sediments' – Trans. Inst. Min. Metall. 93: B112–119.

Stanton, R.L. & Vaughan, J.P. 1979 Facies of Ore Formation: A preliminary Account of the Pegmont deposit as an example of potential relations between small 'Iron formations' and stratiform sulphide ores – Proc. Australas. Inst. Min. Metall. 270: 25–38.

Sundius, N. 1923 Grythyttefältets geologi – Sver. Geol. Unders. Ser C 312: 354 pp.

Sutheren, R.J. 1985 Facies analysis of volcaniclastic sediments: a review. In: Brenchley, P.J. & Williams, B.P.J. (eds): Sedimentology recent developments and applied aspects – Geol. Soc., Lond. Spec. Publ.: 123–146.

Vivallo, W. 1985 The geology and origin of the Zn–Pb–Cu Sulfide Deposit Garpenberg. Central Sweden – Ph.D. Thesis, Stockholms Uni. Geol. Inst. Nr. 257: 222 pp.

Welin, E., Wiklander, U. & Kahr, A.M. 1980 Radiometric dating of a quartz-prophyritic potassium rhyolite at Hällefors, south central Sweden – Geol. För. Förh. 102: 269–272.