

The geology and structural setting of the Håkansboda Cu-Co-As-Sb-Bi-Au deposit and associated Pb-Zn-Cu-Ag-Sb mineralisation, Bergslagen, Central Sweden



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Abstract

A complex sulphide mineralisation occurs within calc-silicate rich dolomite-calcite marble at Håkansboda, Bergslagen, Central Sweden. Exploration during 1980–86 has defined the distribution and nature of the mineralisation and its structural setting.

Three zones of mineralisation are identified. The central or B zone, with up to 900 m strike length and 80 m wide, is proven to a depth of 600 m. It forms an envelope around previously mined massive and streaky chalcopyrite-pyrrhotite and chalcopyrite-arsenopyrite-tennantite ore shoots, containing minor antimony, bismuth, gold and molybdenum. A similar, but lower grade mineralisation forms the A and C zones. The deposit is spatially associated with strongly altered felsic volcanic rocks and volcanoclastics, especially in the stratigraphic footwall, and areally extensive exhalite horizons with Pb-Zn-Cu-Ag-Sb sulphides and Mn-rich magnetite ores in the stratigraphic hangingwall.

The 'ore'-hosting sequence occurs on the overturned limb of a regional F_1 syncline and is refolded by steeply plunging F_2 folds. Brecciated host rock-sulphide lenses and the geometry of individual ore shoots indicate remobilisation and extension of the sulphides into pipe-like bodies parallel to local F_2 fold axes.

Background

The Håkansboda deposit is located on the eastern flank of the Storå valley in the formerly important iron mining area of Stråssa-Stripa, Western Bergslagen (Figs. 1 and 3). Copper-rich massive sulphide lenses, forming seven principal ore-shoots, were worked to a maximum depth of 212 metres, over 300 metres of N-S strike extension.

The mineralogy and its setting have been briefly described by Tegengren (1924), Koark (1960), Adolffson (1972) and Koark (1983). Note of the

deposit is made by Magnusson (1970, 1973), Zakrzewski et al. (1980), Lundström (1983) and Lundström & Papunen (1986). Frietsch (1975) classified the deposit as 'an ore of the Falu type' using the criteria of Magnusson (1960). A similar occurrence has been described in the Gruvåsen area by Hellingwerf (1984) and Zakrzewski et al. (1980).

Copper was worked at Håkansboda before 1600 (Tegengren, 1924), but the main periods of mining date from the 1700–1800's. Pits were opened up and extended into underground workings on the Norr, Lo, Smed, Commerce, Märr, Varp and Sör

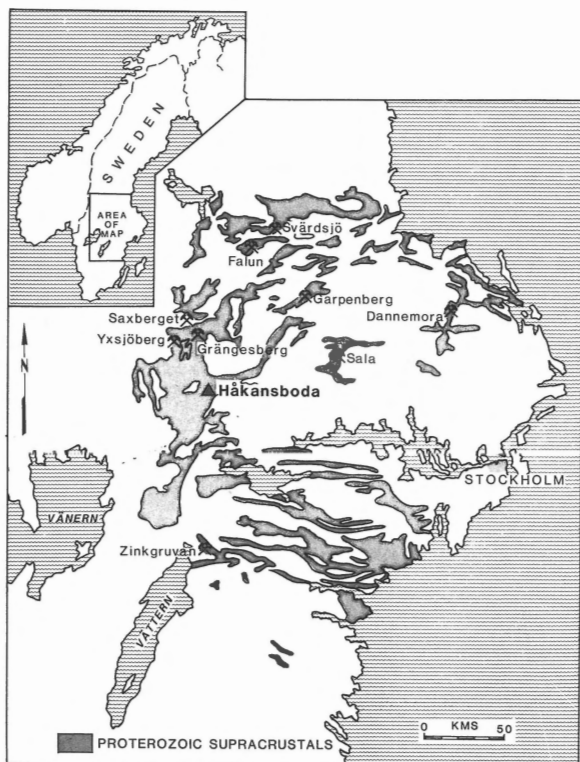


Fig. 1. Håkansboda: Regional location.

sulphide lenses. Underground development located the blind Cecilia and Lill-Cecilia sulphide 'ore-shoots' (Fig. 5).

Between 1741–1873 the mine produced 2,108 tonnes of copper from an estimated 42,000 tonnes of ore (5% copper) (Tegengren, 1924). A further 19,000 tonnes of 2.45% Cu were produced in 1916–1919. The deposit was re-examined in the 1950's and 1970's when extensive drilling was undertaken, and a 2.7 km long exploration level driven from Stråssa iron mine to intersect the sulphide lenses at a depth of 200 metres. This tunnel was plugged in 1984, and the Håkansboda workings are now flooded and inaccessible.

Geological mapping, diamond and percussion drilling, core logging and sampling were undertaken around the deposit in 1983–1986 and forms the background data to this paper, together with information obtained by the re-logging and sampling of older drillcore.

Regional lithostratigraphy

The Håkansboda mineralisation is one of many known sulphide occurrences within the Guldsmedshyttan Syncline, a NE-SW trending belt of 1.9–1.8 Ga. Lower Proterozoic supracrustals (Lundström, 1983). Detailed mapping in the Stråssa-Stripa area in 1983–84 has confirmed the presence of a major synclinal fold structure (F_1 , see Fig. 3). Although some structural breaks and/or repetitions occur within the sequence, the following lithostratigraphic succession may be recognised from east to west across the overturned eastern limb of the syncline (Fig. 2).

The oldest rocks are oligoclase-labradorite pyritic, intermediate metavolcanites with occasional relict quartz phenocrysts ('quartz-eyes'). They pass westwards into distinctly quartz pyritic, sericite-biotite, grey-pink, massive metavolcanites. Estimates are difficult due to deformation, but these units are at least 1,000 metres thick, and belong to the Storsjön Formation of Lundström (1983). Minor metabasite (gabbroic-dioritic) intrusives occur within, and appear restricted to, this lower volcanic sequence. They are foliated, and represent the oldest intrusives in the area, being possibly contemporaneous with the acid volcanic sequence in which they occur.

The quartz pyritic 'rhyolite porphyries' are magnetite, biotite, cordierite and sillimanite porphyroblastic in their upper part, passing into quartz banded haematite iron formation. This characteristic lithology can be traced around the Guldsmedshyttan Syncline from the area south and east of Håkansboda, through the Blanka and Stråssa mines to the mines on the western limb.

Quartz-hornblende-andradite-actinolite and minor epidote occur within this horizon, and minor Cu-Fe sulphides are noted (Geijer, 1927). Magnetite accompanies haematite within the iron formation particularly in areas of strong deformation. Massive quartz pyritic and aphyric, tuffaceous rhyolitic metavolcanites overlie the quartz-haematite marker. Stratigraphically below the Håkansboda deposit these rocks are altered to quartz-sericite-chlorite schists. Well banded, almost rhythmically layered diopside calc-silicates and

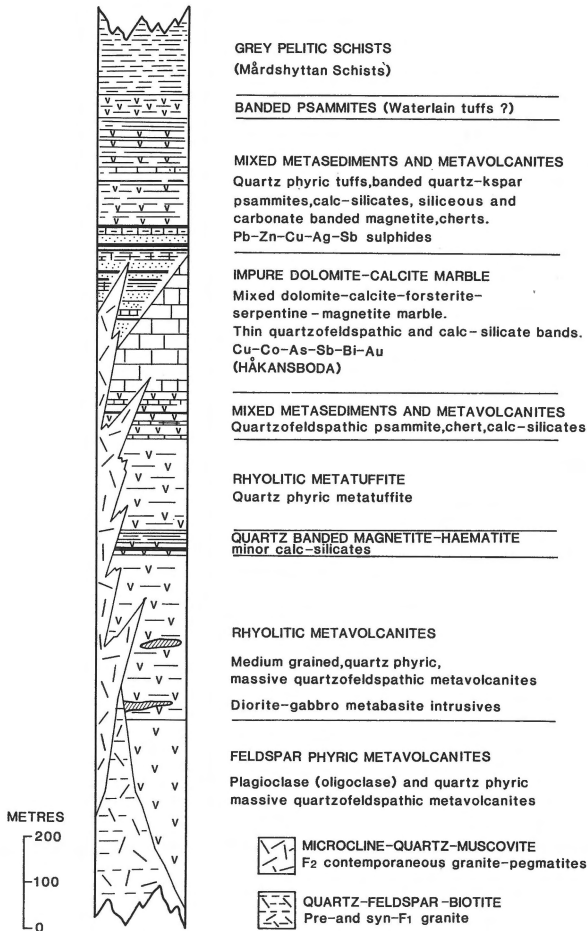


Fig. 2. Regional lithostratigraphic column.

fine grained quartz-feldspar 'cherts' and psammite overlie the metavolcanites. Thin garnet-biotite-hornblende layers contain massive and disseminated magnetite and minor pyrrhotite. The change from the massive metavolcanites to banded meta-volcanic rocks and metasediments (the Storsjön and Usken Formations of Lundström, 1983) is comparable with the Lower and Middle Leptite Groups of Oen et al. (1982).

Thin dolomite-calcite marble horizons appear near the top of the unit, becoming more abundant westwards passing into a 60–250 metre thick, mixed calc-silicate, dolomite-calcite marble with thin pyroxene-amphibole bands and quartz-feldspar 'cherts'.

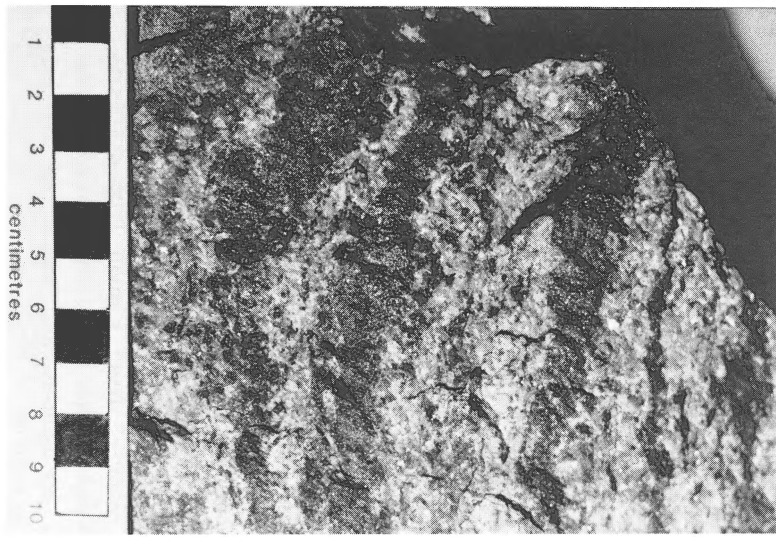
These lithologies host the Håkansboda mineral-

isation and display a mineral paragenesis typical of magnesian-iron skarns (Einaudi et al. 1981). On the western limb of the Guldsmédshyttan Syncline equivalent marble horizons are dominantly calcitic, but on the eastern limb in the Håkansboda area they are dominantly dolomitic. In the immediate area of the sulphide mineralisation, however, they become mixed calcite-dolomite marble crowded with serpentine pseudomorphs after forsterite and humite group minerals (the 'camgite' or ophicalcite of Koark, 1960) (Plate 1B).

A prograde development of tremolite-biotite-phlogopite and forsterite-calcite-diopside-magnetite-spinel and chondrodite/clinochumite is recognised with a late-stage hydrous, retrograde alteration producing serpentine-talc and sericite.

Minor interbanded, fine grained granoblastic quartz-microcline 'cherts', quartz-sericite-calcite marble and diopside-hornblende-K feldspar-grossularite calc-silicates are enclosed within the main marble formation. By contrast, thin marble horizons below the main carbonate are typically mafic silicate poor, granoblastic dolomites with coarse red-black almandine, vesuvianite, epidote and wollastonite. These minerals are conspicuous by their absence or only minor occurrence in the mineralised marbles.

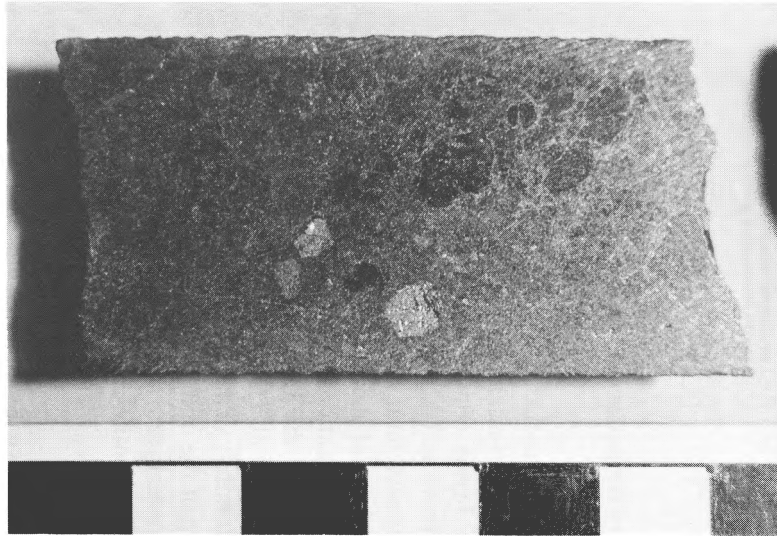
The main calcite-dolomite marble is overlain by very fine grained, recrystallised, well banded, quartzofeldspathic 'cherts' and coarser psammites containing rare relict quartz phenocrysts. These rocks also contain abundant sillimanite (up to 20 vol.%) and minor cordierite. They are interlayered with bands and laminae of magnetite-chert, grunerite-chert, magnetite bearing marble and calc-silicates containing diopside-cummingtonite K feldspar-biotite and garnet in various combinations. The magnetite horizons, containing up to 4% Mn, belong to the manganeseiferous iron ores (Magnusson & Geijer, 1944), typically found, as here, within potassic metavolcanites and mixed dolomite-calcite marbles and calc-silicates. These strata are interpreted as fine grained acid tuffs, possibly subaqueous deposits from Plinian type eruptions (Fisher & Schmincke, 1984), siliceous pelites, and siliceous, ferruginous and calcareous banded chemical sediments.



A



B



C



D

Plate 1A. Massive chalcopyrite streaks. Varv shoot-zone mineralisation, B-zone, Håkansboda 199 m level (cm scale); B. (Top). Dolomite-serpentine-diopside-forsterite-magnetite-calcite marble ('ophicalcite'). B-zone host rock (cm scale). (Bottom). A large diopside patch, containing chalcopyrite-pyrrhotite mineralisation, within unmineralised 'ophicalcite' marble. B-zone mineralisation (cm scale); C. Cobaltite porphyroblasts within pyrrhotite-chalcopyrite massive 'ball-ore' sulphides. Dark wall rock clasts are visible. A-zone mineralisation, drillhole 374, 355.40 m (cm-scale); D. Finely banded, microcrystalline chert and pyrrhotite-chalcopyrite-galena-magnetite laminae (middle of sample), with garnet porphyroblastic layers and remobilised sulphides. Elisabethgruvan, Håkansboda stratigraphic hangingwall (cm scale).

The mineral paragenesis with sillimanite, andalusite, cordierite, almandine, hornblende and oligoclase reflects regional metamorphism to amphibolite facies (Myashiro, 1973), with increasing temperature from west to east.

Structure

Mapping and structural analysis have identified the following structural elements.

The major structure of the area is the NE-SW trending Guldsmedshyttan Syncline (Lundström, 1983). The existence of this structure is indicated by lithological symmetries, a magnetic anomaly pattern outlining macroscopic fold closures, asymmetries of mesoscopic F_1 folds, and locally angular S_0 - S_1 relationships, although both S-surfaces are generally parallel to each other.

The axial surface trace of this regional structure can be followed for at least 15 kms. The steeply inclined syncline is overturned towards the northwest is tight to isoclinal in character and doubly plunging. The Stråssa-Håkansboda area is situated on a SW-plunging segment of this syncline, and the Håkansboda deposit occurs on the eastern, overturned limb (see Figs. 3 and 4).

NE of Stråssa the regional synclinal axis passes over a major culmination, NE of which, the Guldsmedshyttan syncline has a possible continuation in the Riddarhyttan structure. The culmination overlies a buried NNW-SSE trending, deep seated body, well displayed in the regional total field magnetic image. This correlates with the NW continuation of a known post- F_1 granite of Fellingsbro type which lies to the SE.

In the Stråssa-Håkansboda area, $S_{0,1}$ surfaces are reorientated around SE steeply plunging axes, indicating refolding of F_1 structures by a second (D_2) event. This is confirmed on a mesoscopic scale by abundant F_1 - F_2 overprinting structures. F_2 folds have subvertical NW-SE to NNW-SSE trending axial planes and plunge steeply to the SE. The D_2 event appears to coincide with the culmination of regional metamorphism, marked by, for example, the growth of cordierite and amphibole porphyroblasts along L_2 , and the intrusion of syn- F_2 granite pegmatites.

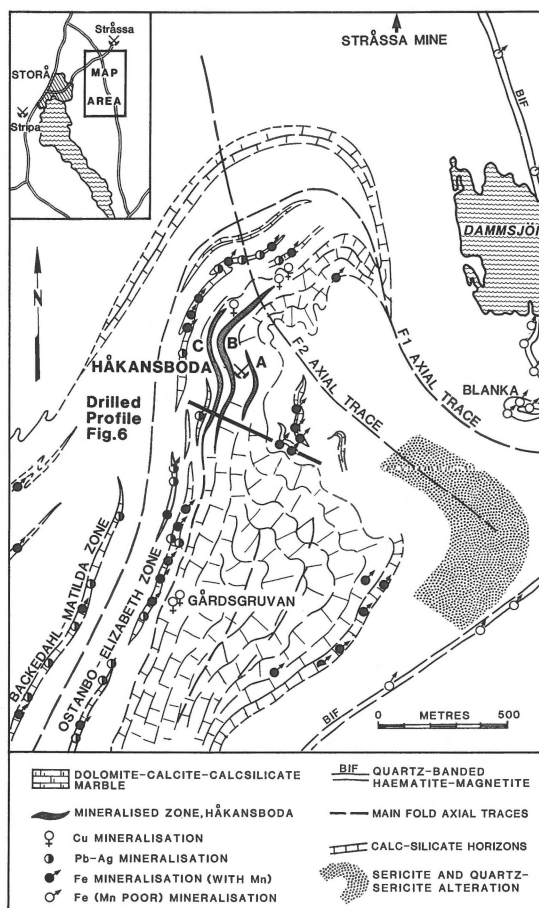


Fig. 3. Regional geology for the northern termination of the Guldsmedshyttan Syncline.

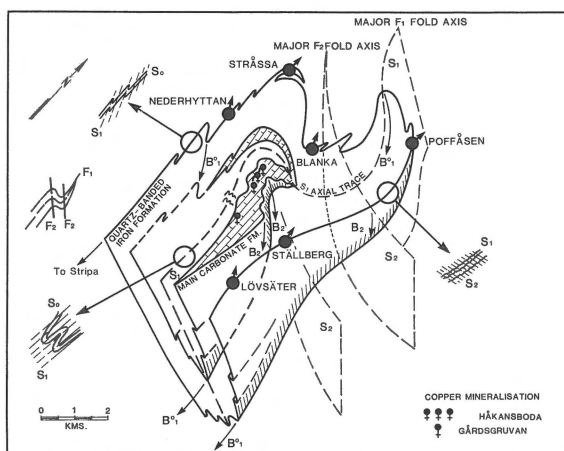


Fig. 4. F_1 - F_2 overprinting structures in the Håkansboda area, northern part of the Guldsmedshyttan Syncline.

L_2 lineations are a penetrative fabric element throughout much of the Stråssa-Stripa area and are developed as intersection, crenulation or stretching lineations parallel to mesoscopic F_2 fold axes. Two zones of intense F_2 folding trend NW-SE through Håkansboda and through Blanka (Fig. 4) (Geijer, 1927; Koark, 1960). These zones represent the axial surface traces of macroscopic F_2 folds.

The Håkansboda deposit is situated in the core of one of these F_2 folds, where extreme stretching parallel to F_2 fold axes has deformed individual ore bodies into pipe-like shoots, a common feature of Bergslagen sulphide zones (Koark, 1973). In addition, the fold axes of mesoscopic F_1 folds are rotated into near parallelism with F_2 axes, locally producing sheath folds. The macroscopic interference structure is depicted in Fig. 4. It should be noted that the Håkansboda F_2 fold dies out towards the SE, due to structural 'infilling' of the axial core-zone.

F_1 - F_2 folding has affected the entire region, although expressions of this deformation history are not everywhere as obvious as in the well layered metasediments with high competency contrasts seen for example around Håkansboda. In the rather monotonous metavolcanites which characterize the lower half of the volcano-sedimentary pile, the strongly developed S_1 foliation is the only manifestation of D_1 . Mesoscopic F_1 folds are rare, due to the lack of layering. F_2 may be developed as crenulations of S_1 but is generally of too large a wavelength for mesoscopic observation.

Drilling in the area west of Håkansboda (Carlson, 1986) has intersected stratabound shearing parallel to S_1 . Shear deformation, producing C-S fabrics (Berthé et al., 1979), tectonic slides, sheared out folds, complex sheath folding and boudinage structures occur around Håkansboda (Marten, pers. comm.). There is some indication that the F_1 isoclinal folds with upright axial planes, may be a continuous development from an earlier shear deformation along parallel transport directions. Where shearing occurs, left lateral movement is the dominant displacement.

The Sulphide Mineralisation

The calcite-dolomite-diopside-forsterite-clinohumite-magnetite-spinel-serpentine marble with minor quartz, grossular, sericite, tremolite and talc which hosts the mineralisation, displays a well developed mineralogical banding parallel to $S_{0,1}$ deformed around F_2 structures and extended down L_2 . Chemical analyses for the host rocks are given in Table 1. In general, trace metal contents are highest where calc-silicates are most abundant. Three zones of mineralisation are recognised. These are characterised by a heterogeneous dissemination of chalcopyrite, pyrrhotite and trace glaucodot, danaite and cobaltite. A very weak sulphide dissemination is found between the zones. The A-zone lies 20–40 metres above the strati-

Table 1. Whole rock analyses from the sulphide host rocks in Hole 86/001 Håkansboda.

	1	2	3	4
	%	%	%	%
SiO ₂	0.34	8.92	14.48	39.49
Al ₂ O ₃	0.36	1.00	0.81	8.62
TiO ₂	0.02	0.03	0.03	0.38
¹ Fe ₂ O ₃	4.00	3.87	4.25	7.26
MgO	16.89	16.16	16.13	10.63
CaO	34.08	31.26	30.32	14.13
NaO	0.04	0.08	0.04	2.21
K ₂ O	0.11	0.51	0.38	3.55
MnO	Not determined			
CO ₂	Not determined			
	ppm	ppm	ppm	ppm
Cu	6	20	44	98
Zn	7	10	11	75
Pb	5	5	5	36
Co	2	7	13	30
As	4	5	10	21
Sb	1	2	5	7
Bi	bd	3	3	7
Ba	14	22	78	330
Sr	16	20	17	350

1. Dolomite-calcite marble Hole 86/001 30 m depth.

2. 'Ophicalcite' marble Hole 86/001 70 m depth.

3. 'Ophicalcite' marble Hole 86/001 90 m depth.

4. Diopside-amphibole calc-silicate Hole 86/001 20 m depth.

Analysis by XRF on pressed powder pellets.

¹ Total Fe shown as Fe₂O₃.

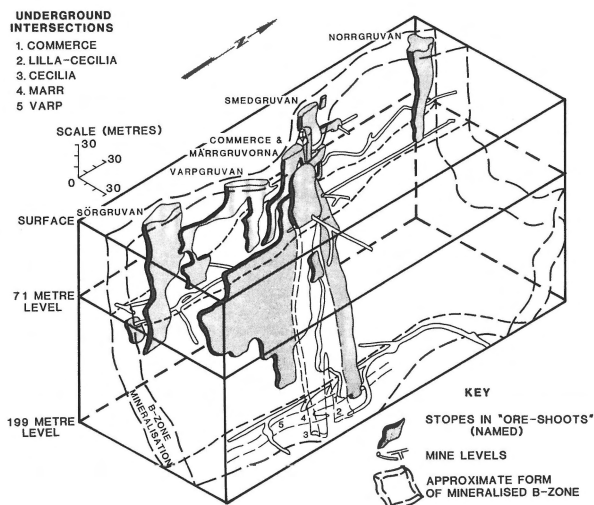


Fig. 5. Block diagram of the Håkansboda mine workings, B-zone mineralisation and ore-shoots.

graphic base of the host marble; the B-zone in about the centre of the sequence, and the C-zone at the stratigraphic top (Fig. 6). All three parallel the $S_{0,1}$ foliation. The B-zone forms the bulk of the deposit, extending for 900 metres along strike. Up to 80 metres wide, it dips at 65–85° E to 50 metres depth, and a consistent 60–65° E below this level (Fig. 5).

Both the A and C-zones are centrally situated with reference to the midpoint of the B-zone strike length, above and below the main ore-shoots in the B-zone. Neither the A nor C-zones have been exploited. The B-zone ore-shoots (Fig. 5) were previously mined as a series of stacked lenses over a strike length of 300 metres. The shoots plunge at 50–60° SE parallel to L_2 and are open in depth. They do not have well defined contacts but are marked by a progressive increase in sulphide content inwards:

1. *The B-zone envelope*: 30–40 metres average width with low grade mineralisation enclosing the shoot zones and massive sulphides. Table 2 lists typical B-zone drilled intersections.
2. *Shoot-zones*: 3–20 metres wide, disseminated and streaky sulphide with sulphide bands cm-dm thick, 0.2–1.5 m long, (Plate 1A). Several shoot zones can lie stacked within the B-zone. Table 3 lists drilled intersections within four

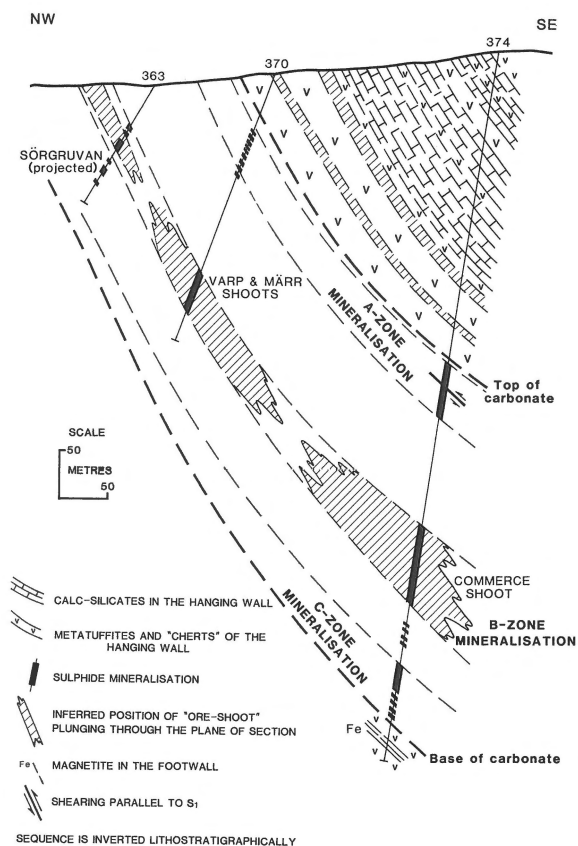


Fig. 6. NW-SE drill profile through the main ore-shoots and mineralised zones.

different shoot zones. Shoot-zones enclose.

3. *Massive bands*: Massive sulphide layers and lenses lying within shoot-zones. Individual bands are up to 20–30 m in length, 0.5–3 metres thick. Table 3 lists typical massive lens intersections.

Individual 'ore-shoots' or 'shoot-zones' are up to 30 metres long, average 6 metres wide and have pitch lengths of over 200 metres. They are separated by lower grade sulphide impregnations, frequently associated with diopside patches, (Plate 1B). The style of mineralisation corresponds to the structural types noted by Koark (1983). Disseminated or 'impregnation ore' is typical of the envelope; impregnation and schlieren sulphide being characteristic of the shoot-zones around the contained massive bands.

Mined out portions of the ore-shoots averaged

8% Cu (Tegengren, 1924). Representative intersections and grades are given in Tables 2 and 3. These show considerable variation in the width and grade of the B-zone mineralisation and the contained shoot zones and lenses. Individual lenses can be locally very high grade. Of note is the Märr intersection in hole 370 (Table 3) and the mineralisation in and around the Cecilia shoot which lies in

the hangingwall of the Commerce shoot (Tables 2 and 3; Fig. 5).

Massive sulphide lenses frequently display a 'ball-ore' structure (Geijer, 1971), the 'breccia-ore' type noted by Koark (1983), (Plate 1C). Rounded host rock clasts, often bearing a disseminated mineralisation, are enclosed within a massive sulphide matrix. These pass from matrix to clast supported

Table 2. Representative metal contents of four continuous sampled profiles through the B-zone, Håkansboda.

	Drillhole 370	Drillhole 374	Drillhole 377	Drillhole 602	Drillhole 371
Width (m)	30.00	40.36	33.25	36.67	62.95
Cu %	0.70	0.62	0.40	1.43	0.67
As %	0.27	0.22	0.35	0.52	0.24
Sb %	0.04	0.004	0.006	0.008	0.005
Bi %	0.01	0.01	0.01	0.006	0.007
Co %	0.01	0.01	0.06	nd	nd
Ag g/t	14	2	2	4	3
Au g/t	0.21	0.47	0.55	0.41	0.27
Ni ppm	43	22	32	nd	nd
Pb ppm	44	92	39	100	96
Zn ppm	72	18	21	38	17

Mo in sections analysed 0.02%; nd: not determined; Cu, As, Sb, Bi, Ag, Pb, Zn, Mo: AAS analysis; Co, Ni: XRF analysis; Au: fire assay.

Drillhole location: Holes 370, 374 (see Figs. 3 and 6). Hole 371. 134 m N. of hole 370 and parallel. Hole 377. 50 m S. of hole 374 and parallel. Hole 602. Underground hole from the 71 m level.

Table 3. Representative metal contents of the 'shoot-zone' and high grade sulphide lenses, B-zone, Håkansboda.

	'Ore-shoot' Drillhole 363 Sör		Drillhole 370 Märr		Drillhole 371 Commerce		Drillhole 374 Commerce		Drillhole 602 Cecilia
	Zone	Lens	Zone	Lens	Zone	Lens	Zone	Lens	Lens
Width (m)	5.88	0.45	3.00	0.55	13.39	2.78	6.40	2.72	2.25
Cu %	0.95	3.81	2.52	5.18	0.86	2.35	1.24	1.95	3.75
As %	0.27	2.42	0.64	2.40	0.56	1.23	0.42	0.26	0.46
Sb ppm	103	167	0.28%	1.36%	128	131	30	30	163
Bi ppm	274	600	219	760	168	98	122	120	132
Co ppm	372	0.24%	362	603	nd	nd	326	278	nd
Ni ppm	41	278	86	328	nd	nd	60	32	nd
Pb ppm	209	294	52	48	300	147	116	108	248
Zn ppm	43	144	473	0.17%	16	27	23	26	42
Ag g/t	9	19	112	434	6	10	4	6	12
Au g/t	0.35	0.96	0.45	1.36	0.53	0.74	1.12	1.61	3.18

nd: not determined; Cu, As, Sb, Bi, Pb, Zn, Ag: AAS analysis; Ni, Co: XRF analysis; Au: Fire assay.

Drillhole location: Holes 363, 370, 374: (see Figs. 3 and 6), Hole 371: 134 m N. of hole 370, Hole 602: Underground hole from the 71 m level.

bodies towards the contact, and into brecciated wallrocks with sulphide veins, sulphide cusps and 'piercement structures' (Maiden et al., 1986) cross-cutting the $S_{0,1}$ foliation. These features indicate that the sulphide layers have been remobilised and recrystallised subsequent to original sulphide deposition, calc-silicate formation and blastesis.

Mineralogy

The metal contents of the B-zone (Table 2) confirm that the usual reference to Håkansboda as a Cu-Co deposit (Adolfsson, 1977) is incorrect. Cobalt, while unusual, is not a major constituent of the

Table 4. Mineral species recorded from Håkansboda (after Koark, 1983).

Major species:	
CHALCOPYRITE	$CuFeS_2$
PYRRHOTITE	$Fe_{1-x}S$
ARSENOPYRITE	$FeAsS$
PYRITE	FeS_2
MAGNETITE	Fe_3O_4
MOLYBDENITE	MoS_2
TENNANTITE	$(Cu, Fe)_{12}As_4S_{13}$
TETRAHEDRITE	$(Cu, Fe)_{12}Sb_4S_{13}$
Minor species:	
CUBANITE	$CuFe_2S_3$
LÖLLINGITE	$FeAs_2$
GALENA	PbS
SPHALERITE	ZnS
BREITHAUPITTE	$NiSb$
KALLILITE	$Ni(Sb, Bi)S$
ELECTRUM	Au/Ag
NATIVE SILVER	Ag
NATIVE GOLD	Au
URANINITE	UO_2 (etc)
DANAITE	$(Fe, Co)AsS$
GLAUCODOT	$(Co, Fe)AsS$ (up to 14.2% Co)
COBALTITE	$CoAsS$
ARGENTITE	AgS
BOURNONITE	$CuPbSbS_3$
NATIVE BISMUTH	Bi
GUDMUNDITE	$FeSbS$
TETRADYMITE	Bi_2Te_2S
CHALCOCITE	Cu_2S
ALLARGENTUM	(Ag, Sb)

mineralisation. Mineral species noted from Håkansboda are listed in Table 4 (after Koark, 1983). Chalcopyrite, pyrrhotite, arsenopyrite and minor pyrite form the typical assemblage of the A, B and C zones. Minor quantities of glaucodot, danaite and cobaltite have been noted (Koark, 1983). The streaky massive mineralisation of the 'shoot-zones' displays:

1. Massive pyrrhotite and massive or granular chalcopyrite, occurring singly or in combination with either veining the other. Cubanite occurs in this association, possibly due to reaction between pyrrhotite-chalcopyrite.
2. Mixed chalcopyrite-tennantite with minor tetrahedrite. This assemblage produces for example the high grade Cu-As-Sb drilled in hole 370 (Table 3).
3. Massive streaks of arsenopyrite with either pyrrhotite or chalcopyrite, and as idiomorphic porphyroblasts in pyrrhotite. Koark (1983) notes arsenopyrite within tennantite.
4. Cubic and dodecahedral, 1–15 mm cobaltite porphyroblasts within massive pyrrhotite and less frequently in chalcopyrite (Plate 1C). (Koark, 1983) records cobaltite with tennantite. On textural evidence at least two phases of cobaltite deposition or growth are noted.
5. Rare orthorhombic glaucodot porphyroblasts occur within pyrrhotite and arsenopyrite.
6. Pyrrhotite, chalcopyrite, tennantite, arsenopyrite and cobalt minerals all occur within massive sulphide lenses and 'ball-ores'.
7. Koark (1983) records a late stage Pb-Sb-Cu-Bi-(Te) mineralisation with Au. Tellurium is mostly below detection (1 ppm) in the deposit, but occasionally reaches 3 ppm with elevated Co. Gold occurs as a native phase and with Ag in electrum in this paragenesis. Gold typically forms a positive correlation with Bi, As and Sb. However, at Håkansboda, no positive correlation can be seen with Au and Sb, As (Figs 7A and 7B) or Bi, and only a weak correlation in samples containing over 0.5 g/t Au and elevated Bi (Fig. 7D). This may reflect metamorphic remobilisation.
8. A Co versus Ni plot for samples within the shoot-zones (Fig. 7E) shows a general positive

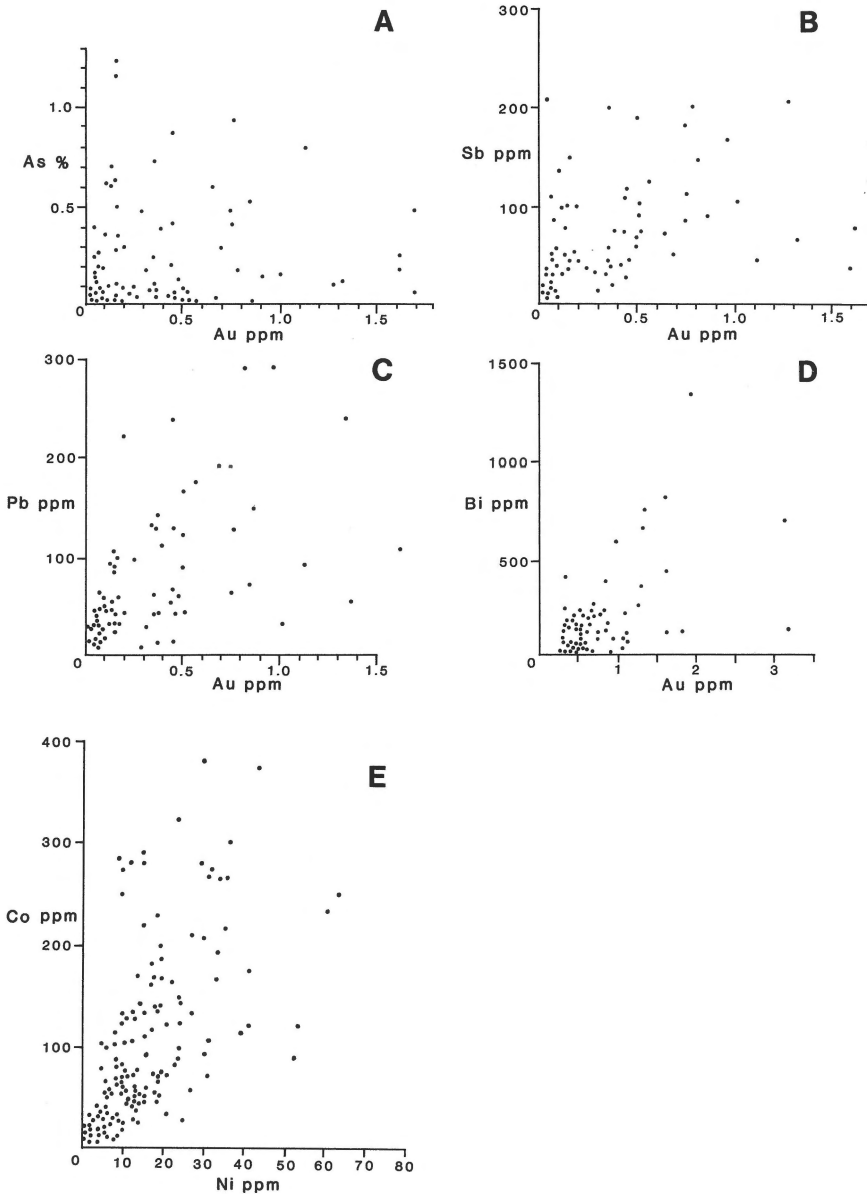


Fig. 7. As, Pb, and Bi versus Au plots for five continuous drilled and assayed sections of the B-zone (A–D), and Co versus Ni for the B-zone (E).

correlation. Ni and Co enrichments are due to cobaltite-pyrrhotite content and possible Ni-Co variations within these phases.

- De-dolomitisation of the host marble has produced a mixed calcite-dolomite marble generally banded parallel to $S_{0,1}$. Sulphides are typically associated with the calcite-dolomite mafic marble, and are sometimes seen to corrode the silicates.

It is evident that a simple paragenesis does not occur and that several phases of deposition and remobilisation are present.

Compositional heterogeneity within the deposit may be primary or the result of remobilisation. All ore-shoots are rich in chalcopyrite-pyrrhotite, but the latter is most common in the Varp, Märr and Commerce shoots accompanied by glaucodot.

Glaucodot also occurs in the Smed shoot. Cobaltite is most abundant in the Märr shoot which produced 710 tonnes of cobalt rich ore in 1836–1841 (Tegengren, 1924). Tennantite is noted in the deeper parts of the Commerce and Märr shoots. Galena and sphalerite are rare at depth but occurred at shallow depth in the Märr and Sör shoots. Pb-Zn values rarely exceed 100 ppm but sporadic high values are seen with tetrahedrite (see Hole 370, Table 3) high (400–500 g/t) Ag and elevated Au (1.5–1.6 g/t). There is a very weak correlation between Pb and Au (Fig. 7B). Pyrite and marcasite are common in and around the Norr-shoot. Uranium content is, as expected, low within the deposit. The enriched samples (up to 400 ppm) noted by Koark (1960) probably relate to NNW or NE uraninite veinlets noted by Welin (1964) and dated at 1585 m.y.

Genesis of the deposit

The geological setting of the Håkansboda deposit can be summarized as follows:

1. A complex Cu-Co-As-Sb-Bi-Au deposit, with trace Ag and Mo is hosted by magnesium-calcium-iron bearing calc-silicates and impure marble.
2. The deposit has been affected by two fold episodes, possibly preceded by an early shearing event, the deformation and accompanying metamorphism having remobilised the sulphides, with some recrystallisation and blastesis.
3. Acid metavolcanites stratigraphically below, but now structurally above, the deposit are altered to quartz-sericite-chlorite assemblages.
4. Fine grained siliceous, calcareous and ferruginous metasediments stratigraphically overlie, but structurally underlie, the deposit. These are characterised by abundant sillimanite and contain stratabound magnetite-sulphide mineralisation.

Dolomite-calcite marble hosted sulphide mineralisation is known from many areas of Bergslagen, notably Kaveltorp (Magnusson, 1940), Garpenberg (Vivallo, 1984) and Gruvåsen (Hellingwerf, 1984). In these areas sulphides are hosted by im-

pure dolomite-calcite marbles and calc-silicate bands containing various combinations of diopside-tremolite-phlogopite-biotite-chlorite-talc-spinel-chondrodite-magnetite and serpentine.

Initial investigations at Håkansboda suggest that the host rocks follow a calc-silicate paragenesis comparable with Gruvåsen (Hellingwerf, 1984). The early potassic alteration and magnesium addition identified at Gruvåsen may be represented at Håkansboda by the potassic quartz-microcline 'chert' bands within the mineralised zone, biotite-phlogopite growth in the main host marble, and the formation of early Mg-amphibole. These are followed by diopside-spinel-chondrodite/clinohumite, calcite, forsterite and magnetite.

The general trend is a compositional variation from K-Mg to Mg-Fe with Si and Al addition, comparable with stage 1 and 2 'skarns' at Gruvåsen (Hellingwerf, 1984), and infiltration, magnesian-iron skarns in general (Einaudi et al., 1981).

Sulphide mineralisation accompanied calc-silicate development, and throughout the Håkansboda zone trace metal contents are generally higher in the calc-silicate rich bands (Table 1). The low grade disseminated Cu-Co-As-Fe sulphides post-date much of the magnetite, some of which is associated with later serpentinisation. Increasing f_{S_2} may have moved the Fe-S-O system from magnetite to pyrite-pyrrhotite deposition (Large, 1977), accompanied by chalcopyrite, arsenopyrite, the Co-As and Co-As-Fe sulphides and trace Mo.

The occurrence of cobalt minerals at Håkansboda is not unique in Bergslagen. Oen et al. (1982) record cobaltite in a paragenesis with Pb-Zn-Ag-Cu-Fe at Sundsudden and in the Saxå area, Grythyttan. In addition Co is noted in mineralisation at Riddarhyttan (Tegengren, 1924), and at Gruvåsen, Getön, Nordmark and Gåsborn (Zakrzewski et al., 1980).

Deposition of Sb-Bi-Ag-Au-Pb-Zn appears to have followed Cu-Co-Fe-As at Håkansboda, producing cross-cutting and sheet-like replacement zones. Later structural and metamorphic remobilisation has obliterated much of the original paragenesis. Original crosscutting features have been transposed into parallelism with $S_{0,1}$, producing pinch and swell sulphide bands, 'ball-ore' breccias,

sulphide veined boudinaged calc-silicate bands and wallrock-sulphide vein-nets. The shoots themselves, as previously noted, parallel the F_2 fold axes.

Koark (1983) suggested that danaite and glaucodot formed at higher temperatures than arsenopyrite and cobaltite, though these minerals may have crystallised in several stages. It is evident that sulphide porphyroblasts have grown within the pyrrhotite-chalcopyrite 'ball-ores' with the occurrence of well formed arsenopyrite, glaucodot and cobaltite crystals, (Plate 1C).

The long known association of sulphide ores with Mg-rich host rocks in Bergslagen was originally related to 'magnesium-metasomatism' by metasomatic fronts advancing in front of rising early granitic intrusives (Geijer, 1917; Magnusson, 1936). Koark (1962) suggested that Mg enrichment was caused by hydrothermal activity related to sulphide deposition. Mg, Fe, Si enrichment is a common feature of inferred hydrothermal alteration zones in the footwall rocks of many massive sulphide deposits (Plimer, 1978; Franklin et al., 1981). A sub-seafloor hydrothermal origin for the magnesium alteration and sulphide mineralisation has gained acceptance in Bergslagen in recent years through the studies of Oen et al. (1982), Zakrzewski (1982), Baker & De Groot (1983), Wolter & Seifert (1984), Hellingwerf (1984), Vivallo (1985) and Lagerblad & Gorbatshev (1985).

Baker & De Groot (1983) suggested that the hydrothermal fluids were seawater derived and alteration proceeded in two stages from the breakdown of feldspar to clay minerals and their replacement by Mg-chlorite through seawater-rock interaction. The same process was advocated for the production of quartz-sericite-chlorite precursor minerals in cordierite-anthophyllite rocks at Falun in an inferred stockwork zone (Wolter & Seifert 1984).

The quartz-sericite-chlorite zone stratigraphically below the Håkansboda deposit could represent a 'feeder-zone' alteration system. There is also the possibility, as yet untested, that zones of sericite-chlorite and quartz-epidote mineralogy lying within the Storsjön Formation might represent a 'lower semi-conformable' type of alteration (MacGeehan & MacClean 1980).

Fine grained, well layered metasediments stratigraphically overlie the complex sulphide bodies at Håkansboda, occurring structurally below and immediately west of the deposit. The sequence contains thin, sporadic magnetite bands and a low grade pyrite-chalcopyrite-galena-tetrahedrite mineralisation (Plate 1D), with associated native silver and antimony minerals (gudmundite $FeSbS$, acanthite AgS , dyscrasite Ag_3Sb , allargentum $Ag_{1-x}Sb_x$, pyragyrite Ag_3SbS_3 , stephanite Ag_5SbS_4 , and freibergite $(Ag, Cu)_{12}(Sb, As)_4S_{13}$). Silver contents are in the range 300–600 g/t, and one silver bearing horizon lies immediately above the complex sulphides in the footwall (stratigraphic hangingwall) of the C-zone. Zinc bearing horizons also occur in the sequence with minor tourmaline, fluorite and scapolite (Carlson, 1987).

The abundance of sillimanite stratigraphically above the complex sulphide zone at Håkansboda, associated with minor cordierite and Pb-Zn-Cu-Ag-Sb sulphides, may reflect hydrothermal alteration, the production of precursor hydrous aluminosilicates, and prograde metamorphic breakdown to sillimanite-cordierite as proposed by Stanton (1983, 1984).

The juxtaposition of andalusite, cordierite and sillimanite, and the abundance of the latter spatially associated with the sulphides, suggests a pre-metamorphic clay mineral alteration. Most sillimanite forms fibrolite 'eyes' drawn out parallel to S_1 , and associated with biotite-quartz-garnet and minor spinel.

The geological setting of the Håkansboda mineralisation with a complex Cu-Mo bearing sulphide deposit stratigraphically below stratabound Pb-Ag follows a predicted thermodynamic pattern and established field relations (Large, 1977; Plimer, 1978). The change from pyrrhotite-chalcopyrite upwards into lead with minor zinc is as reported for the Heath Steele B-1 orebody in New Brunswick (Lusk, 1969) and is consistent with the typical copper rich base to Pb-Zn rich top zonations of many massive sulphides (Large 1977). Vivallo (1984) notes the same zonal arrangement at Garpenberg, and the occurrence of Ag-As-Sb (as arsenopyrite, boulangerite, bournonite and tetrahedrite) with Zn-Pb-Cu in the upper part of the deposit, which

are regarded as the stratabound ores above the Cu-rich 'stockwork' ores (Vivallo 1985).

Unlike the Gruvåsen deposit (Hellingwerf, 1984), which appears to be a contained 'feeder-zone' with no associated exhalites, it is proposed that Håkansboda represents a sub-seafloor hydrothermal system, underlying its own chemical sediments and exhalites. This system developed concurrent with shallow water sedimentation; induced calc-silicate formation, host rock alteration and sulphide deposition in the main carbonate, and clay-mineral alteration, calc-silicate formation, chert, iron and metal sulphide deposition in the overlying sediments.

Deposition, occurring at or below the sediment-water interface (Solomon & Walshe, 1979), produced the proximal to distal stratabound sulphide horizons now seen in the area. The term proximal is used here relative to the feeder system (Large, 1977) as opposed to a volcanic centre (Plimer, 1978).

Håkansboda is not the only possible 'feeder' system in the area. At Gårdsgruvan, (Fig. 3) 1 km along strike to the south, magnetite-chalcopyrite in the same mafic-dolomite-calcite marble unit may represent a smaller, less complex sulphide system. Ten kilometres along strike to the SW at Lejagruvan, a Cu-Mo sulphide deposit sits central to, and stratigraphically comparable with Zn-Pb-Ag-Cu-Sb-As stratabound mineralisation at Siggeboda (Bleeker, 1983).

These hydrothermal systems may have been generated by the rise of granitic magmas, now seen to the east of Håkansboda, as pre-F₁ (syn-volcanic) intrusives.

Subsequent deformation and metamorphism, culminating in the D₂ event, has produced the features of the deposit described above.

Granitic intrusives and microcline-perthite, quartz-muscovite pegmatites were introduced with the culmination of F₂ and local anatexis of the quartz-feldspar supracrustal sequence to the east.

A post D₂, retrograde metamorphic event has produced serpentine pseudomorphs after forsterite-chondrodite/clinohumite in the dolomite-calcite marbles, pinitisation of sillimanite-cordierite porphyroblasts, and breakdown of biotite to chlo-

rite. Serpentinisation has also produced minor magnetite. Faulting along NNW and NE trends formed pre-1585 M.a. as these fractures occasionally contain uraninite, described and dated by Welin (1964). Faulting along these trends has occurred subsequently, producing generally small throws within the Håkansboda deposit.

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