

ÅKE JOHANSSON

THE DALSLANDIAN  
SULPHIDE-BEARING QUARTZ VEINS OF  
DALSLAND AND VÄRMSKOG  
SOUTHWEST SWEDEN



UPPSALA 1985

SVERIGES GEOLOGISKA UNDERSÖKNING

---

SERIE C NR 809

AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 79 NR 3

---

ÅKE JOHANSSON

THE DALSLANDIAN  
SULPHIDE-BEARING QUARTZ VEINS OF  
DALSLAND AND VÄRMSKOG  
SOUTHWEST SWEDEN

UPPSALA 1985

ISBN 91-7158-333-5

ISSN 0082-0024

Kartorna godkända ur sekretessynpunkt för spridning  
Statens lantmäteriverk 1985-09-02.

Address:

Åke Johansson

Laboratory for Isotope Geology  
Swedish Museum of Natural History

Box 50007

S-104 05 STOCKHOLM

## CONTENTS

Abstract .....	4
Introduction .....	5
Geology and mineralogy of the veins .....	5
Geological setting .....	5
Vein mineralogy .....	11
Wall-rock alteration .....	14
Wall-rock geochemistry .....	16
Lead isotopes .....	20
Fluid inclusion thermometry on the Vegerbol vein .....	27
Sulphur isotopes .....	33
General discussion and conclusions .....	37
Acknowledgements .....	41
References .....	42
Appendices .....	44

## ABSTRACT

Johansson, Åke, 1985: The Dalslandian sulphide-bearing quartz veins of Dalsland and Värmskog, southwest Sweden. Sveriges geologiska undersökning, Ser. C No. 809, pp. 1-48. Uppsala 1985.

Quartz veins containing sulphides, sulphosalts, carbonates and occasionally fluorite, barite, chlorite, sericite, magnetite and/or hematite are found in Dalsland and Värmskog (southwest Värmland) in southwest Sweden. The Dalsland veins are hosted by rocks of the Åmål Complex and the Dalsland Group and the Värmskog veins by gneisses of the southwest Swedish gneiss complex (western 'Pregothian' unit) on the east side of the Gillberga synform. Geological and lead isotope evidence indicates a late Dalslandian age of around 1000 Ma for both vein groups, and a metamorphic or magmatic contribution to the ore-forming fluid may be indicated by the presence of CO<sub>2</sub> in fluid inclusions in quartz and sphalerite from the Vegerbol deposit in Värmskog. Fluid inclusion data indicate quartz deposition at a minimum temperature (no pressure correction added) of +190 to +330°C from a weakly saline (c. 4 eq. wt% NaCl) CO<sub>2</sub>-bearing hydrothermal solution, while the temperature of sphalerite deposition is more uncertain.

Wall-rock alteration with breakdown of feldspars and mafic minerals is common around the veins. In Värmskog, an inner quartz-sericite zone, sometimes containing calcite and pyrite impregnation, is followed outwards by chloritization of the gneiss. The sericitization led to a drastic decrease of sodium, as well as other chemical changes, in the wall-rocks, and could have released the silica and many of the other constituents now found in the veins. Although sulphide impregnation caused a local enrichment of ore metals and sulphur adjacent to the veins, lead isotope data suggest the surrounding rocks of the Åmål Complex and the southwest Swedish gneiss complex as the source of lead, and these rock units may well be the source of sulphur as well. Sulphur isotope data from Värmskog indicate a sulphur source with a composition close to zero per mil vs. CDT, typical for igneous sulphur, while lighter galena sulphur in Dalsland may indicate a contribution of light sedimentary sulphur to these veins, or a more oxidizing environment of galena precipitation in the Dalsland veins, something also suggested by their mineralogy. Quartz and sulphide deposition probably occurred at near-neutral pH (5-6 at +250°C) from a sulphide-dominated solution in Vegerbol (Värmland) and a solution containing both sulphide and sulphate in Slådekärr (Dalsland). Increase in pH, caused by wall-rock reactions, promoted sulphide and carbonate precipitation in the veins, and oxidation caused by mixing with ground water could have led to the precipitation of barite, magnetite and hematite found in some veins. Thus, the most important mechanism for ore deposition probably was the wall-rock alteration process, which precipitated quartz, released many other elements from the rocks and increased their concentrations in the hydrothermal solution, and increased the pH of the solution. Cooling and dilution with ground water may also have played a role, especially towards the later stages of deposition. Veins of different mineralogy may have formed at different stages of the development of a hydrothermal system, or may represent different erosional levels through vein systems displaying a vertical mineral zoning.

The combined evidence suggests that the Dalsland-Värmskog veins formed by hydrothermal activity in connection with block faulting following Dalslandian folding and thrusting in the area. The hydrothermal activity may either have been connected to late Dalslandian metamorphism or to the intrusion of Bohus-type granites and pegmatites in southwest Sweden.

## INTRODUCTION

Sulphide-bearing quartz veins are found in Dalsland and southwest Värmland in southwest Sweden. Most of these veins are concentrated to two limited areas: (1) the Väner coast of Dalsland between Mellerud and Åmål, and (2) the parish of Värmskog in southwest Värmland (Fig. 1). Mining has occurred intermittently from the 17th to the 19th century in Dalsland, and during the mid-19th century in Värmskog (Tegengren *et al.* 1924). Recently, some of the veins were drilled by the Geological Survey of Sweden (SGU) because of their high silver content.

The veins of the Dalsland district have been described by Tegengren *et al.* (1924), including descriptions of individual deposits, and in an unpublished company report by Tegengren (1944a). The Värmskog veins are described by Nordenström (1881), Tegengren *et al.* (1924), Tegengren (1944b, unpublished company report) and Lundegårdh *et al.* (1983). The copper-bearing veins of Värmskog, as well as the nearby Glava copper deposits, are discussed by Sherbina (1941) and Jongejan & Westerveld (1949). Wickman *et al.* (1963) included some lead isotope samples from Dalsland and Värmskog in their study of ore lead in Sweden, and discussed the age of these veins. Short descriptions of the Dalsland and Värmskog veins are also found in Magnusson (1953, 1973), Frietsch (1975) and Grip (1978).

The present work is focussed on the Pb-Zn-bearing veins in this area. Their geological setting and mineralogy is summarized, and new data on wall-rock geochemistry and alteration, fluid inclusion thermometry, and lead and sulphur isotopes are discussed. Special attention has been paid to two deposits, Slädekärr in Dalsland and Vegerböl in Värmskog. Here new drill core samples were obtained from SGU (samples numbered ÅJ 80:xx). Most other samples (numbered ÅJ 79:xxx) are from mine dumps. The old mine workings are no longer accessible, and in most cases nothing of the veins are seen at the surface. Thus, detailed observations of the veins and internal relations within them have not been possible. The purpose of this study is to combine geological, mineralogical and geochemical data into a model for the formation of the sulphide-bearing veins of Dalsland and Värmskog.

## GEOLOGY AND MINERALOGY OF THE VEINS

### GEOLOGICAL SETTING

The location and geological setting of the investigated deposits are shown in Table 1 and Figs. 1–3. For more complete descriptions of individual veins, the reader is referred to Tegengren *et al.* (1924), where information on deposits not included in this study is also found.

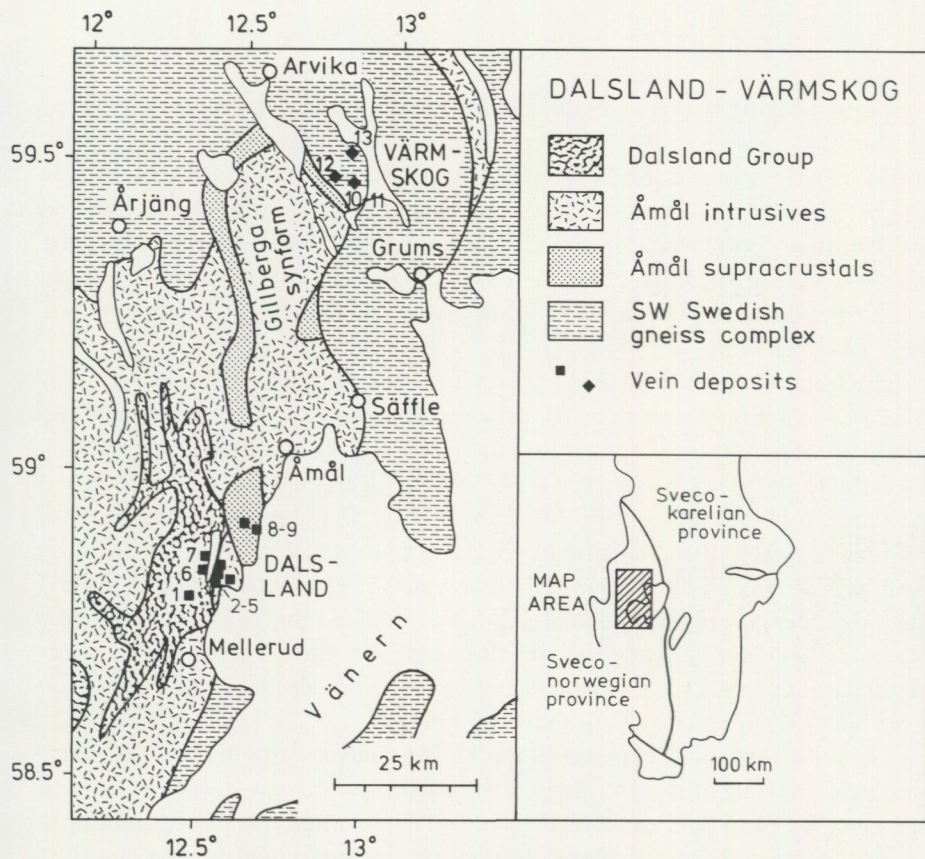


Fig. 1. Map of the Dalsland-Värmskog area, showing location of investigated deposits. Regional geology from Magnusson *et al.* (1957). Numbering of deposits refers to Table 1.

Most of the Dalsland veins (nos. 2-7 in this investigation) are located in a small area around the southern end of lake Ånimmen in Ånimskog parish (Fig. 2B) which has been recently described geologically by Jakobsen *et al.* (1983). The Ingridbyn deposit (No. 1) is located a few kilometres southwest of that area (outside Fig. 2), while Björbyn (No. 8) and Slädekärr (No. 9) are located c. 10 km north of Ånimskog, in Tydje parish (Fig. 2A). Most of the veins are hosted by acid or intermediate gneisses, greenstones or porphyries belonging to the Åmål Complex (Åmål tectonic mega-unit; Åmål supracrustals and intrusives; cf. Gorbatshev 1975, 1977). This includes the Ingridbyn vein, although the map in Fig. 1 shows it within an area otherwise covered with Dalsland Group rocks. The Knollegruvan vein is located in a fault which separates Åmål greenstone from sandstone presumably belonging to the base of the Dalsland Group. The veins at Totten and Stora Kilane are hosted by calcareous phyllite

TABLE 1. Location and geological setting of the investigated deposits.

No.	Name	Map sheet	Coordinates in <sup>1</sup> "Rikets nät"	Latitude / longitude	Strike/dip <sup>2</sup> of vein	Host rock unit	Host rock lithology
D A L S L A N D							
1	Ingribyn	9C 4a	65 22 05 N 13 04 35 E	58 46 35 N 12 25 30 E	N60 W / ?	Åmål Complex	Intermediate to acid gneiss
2	Åskekärr (Edskekärr)	9C 5c	65 26 20 N 13 11 15 E	58 49 00 N 12 32 20 E	N10 W / ?	Åmål Complex	Qz-fsp porphyry
3	Hoppets gruva	9C 5c	65 26 75 N 13 13 05 E	58 49 20 N 12 34 15 E	N30 W/vert.	Åmål Complex	Acid augen gneiss, sericitic fault gouge
4	Vassviken	9C 5c	65 28 70 N 13 11 55 E	58 50 20 N 12 32 35 E	N-S / ?	Åmål Complex	Intermediate gneiss
5	Knollegruvan	9C 5c	65 29 65 N 13 11 25 E	58 50 50 N 12 32 15 E	N20 W/vert.	Åmål Complex, Dalsland Group	Greenstone W of vein, Quartzite E of vein
6	Totten (Snäcke gruva)	9C 5b	65 28 70 N 13 09 30 E	58 50 20 N 12 30 15 E	N-S / ?	Dalsland Group	Calcareous phyllite
7	St. Kilane	9C 6b	65 31 75 N 13 09 15 E	58 52 05 N 12 30 00 E	N55 E/steep	Dalsland Group	Calcareous phyllite
8	Björbyn	9C 7d	65 38 60 N 13 16 15 E	58 55 50 N 12 36 40 E	N-S / ?	Åmål Complex	Greenstone
			65 38 65 N 13 16 25 E	58 55 50 N 12 36 45 E	N25 W / ?	Åmål Complex	Greenstone
9	Slädekärr	9C 7d	65 38 40 N 13 17 65 E	58 55 45 N 12 38 30 E	E-W /steep	Åmål Complex	Qz-fsp porphyry
V Ä R M S K O G							
10	Vegerbol <sup>3</sup>	10C 9h	65 99 20 N 13 35 90 E	59 28 55 N 12 54 45 E	N60 W / 80 NE	SW Swedish gneiss Complex	Intermediate banded gneiss
11	Karlsbol <sup>3</sup>	10C 9h	65 99 05 N 13 36 55 E	59 28 50 N 12 55 25 E	N75 W / vert.	SW Swedish gneiss Complex	Intermediate banded gneiss
12	Näsgruvan	11C 0g	66 01 25 N 13 33 40 E	59 29 55 N 12 51 55 E	ca. E-W / ?	SW Swedish gneiss Complex	Intermediate banded gneiss
13	S. Gärdsjö <sup>3</sup>	11C 0h	66 04 85 N 13 36 20 E	59 31 55 N 12 54 45 E	WNW / steep N	SW Swedish gneiss Complex	Intermediate banded gneiss

1. "Rikets nät" = Swedish national grid.

2. Strikes often determined from shapes of mine workings.

3. Coordinates for center of mine area, in S. Gärdsjö several subparallel veins.

of the Dalsland Group (sometimes also referred to as the Dal Group, the Dal Formation or the Dalslandian supracrustal Group).

The Dalsland veins are not very large; the length rarely exceeds 100 m and they are c. 1–2 m wide. Tegengren *et al.* (1924) report the Vassviken vein to be 10 m wide, but it consists of several narrower veins separated by segments of wall-rock gneiss. The veins have only been mined down to a depth of some tens of metres according to Tegengren (1944a). They dip steeply and are probably bound to faults in most cases. According to Tegengren *et al.* (1924) they should strike N–S in the Åmål rocks and E–W in the Dalsland Group, but this is disputed by Tegengren (1944a), who finds no such regularity in the strikes of the veins. Present field studies support the latter opinion.

The Slädekärr deposit, which has been studied in some more detail, is a steep, E–W trending vein hosted by schistose, rhyolitic porphyry of the Åmål Complex.

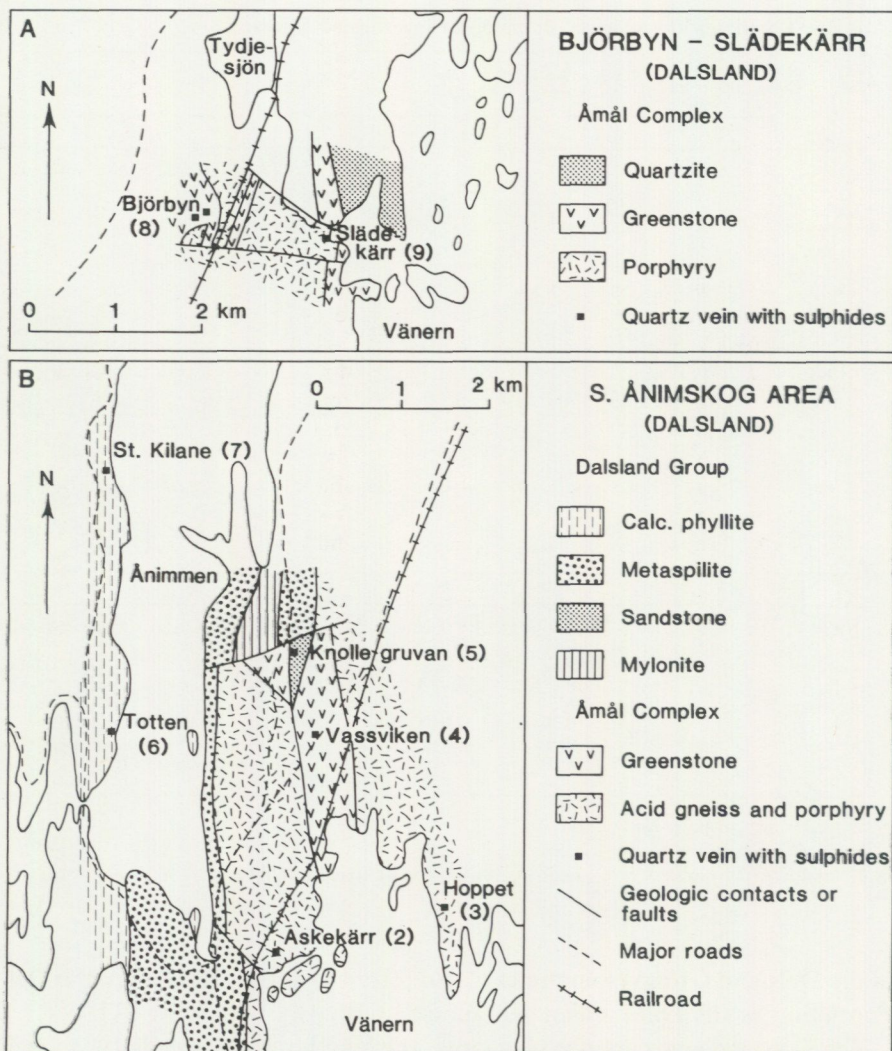


Fig. 2. Maps of the Björbyn-Slädekärr (A) and southern Ånimskog (B) areas in Dalmland, showing local geology and location of investigated deposits. The geology has been compiled from H. E. Johansson (1908; Dalsland Group), unpublished SGU material (Björbyn-Slädekärr area) and own mappings. Numbering of deposits refers to Table 1. The Ingribyn deposit (No. 1) is located outside the map areas.

In addition to the sulphide-bearing quartz veins in Dalmland, two other ore types are present in the same area: Fe-Mn deposits, sometimes containing lenses of Cu sulphides (Tegengren *et al.* 1924; Tegengren 1944a; Geijer 1961), and stratabound copper impregnation in the calcareous phyllite of the Dalsland Group (the copper shale of Stora Strand; H. E. Johansson 1908; Tegengren *et al.* 1924; Tegengren 1944a).

The veins of the Värmskog district (Fig. 3) are hosted by the gneisses east of the Gillberga synform ("southwest-Swedish gneisses" of Lundqvist 1979; "western Pregothian gneiss unit", "iron gneisses", "red and grey gneisses" in older terminology). According to the new geological map of Värmland County by Lundegårdh *et al.* (1983) these gneisses however dominantly consist of gneiss granites of the Åmål type, equivalent to the rocks found within the Gillberga synform/Åmål Complex. The Värmskog veins are divided into Pb-Zn-Ag veins and Cu veins and appear to form four E-W or WNW-running zones (Nordenström 1981; Tegengren *et al.* 1924):

1. The Grindsbol zone, with the small Cu veins at Grindsbol, Borgebol and Hög as well as the more pegmatitic veins of Göksbol, Fjöle and Stömne (studied by Jongejan & Westerveld 1949).
2. The Näs-Vegerbol-Karlsbol zone, about 7 km long, and including the Pb-Zn-Ag veins of Näsgruvan (No. 12), Vegerbol (No. 10) and Karlsbol (No. 11) as well as an apparently barren quartz vein at Degerbynäs (see Fig. 3).
3. The Södra Gärdsjö zone, dominated by the Pb-Zn-Ag deposit of Södra Gärdsjö (No. 13) and with the Cu deposit of Rud as a possible westerly continuation.
4. The Edane zone, with the small Pb-Ag vein of Edane in Brunskog parish north of Värmskog.

These zones probably represent late Dalslandian fault zones crossing the gneisses, although no faulting has been proved. It is improbable that they are continuously mineralized, but the Vegerbol and Karlsbol deposits, separated only by a 400 m wide valley lacking outcrops, may be parts of the same vein structure. (They are often treated together in the literature, either as "Vegerbol", "Karlsbol" or "Vegerbol-Karlsbol". The SGU drill cores are labelled "Karlsbol" although most of them are from the Vegerbol segment. In this paper, Vegerbol refers to the westerly segment of this deposit, Karlsbol to the easterly segment, and Vegerbol-Karlsbol to the deposit as a whole).

The Värmskog veins thus strike E-W or WNW and dip steeply. The Vegerbol vein can be followed for 300 m, and may, as mentioned, be part of an even longer vein structure. It has been mined to a depth of 60 m and has a width of 1-2 m. At Södra Gärdsjö, several parallel veins of similar size are found (Tegengren 1944b).

The Glava copper deposits, on the northern side of the Gillberga synform about 20 km northwest of Värmskog, appear to be similar to the Cu veins of Värmskog and may thus be related. They have been studied in detail by Sherbina (1941).

Thus, the veins of Dalsland and Värmskog are hosted by several different rock units: the southwest Swedish gneisses, the Åmål Complex and the Dalsland Group, representing a total range from perhaps 1 700 Ma to 1 000 Ma in

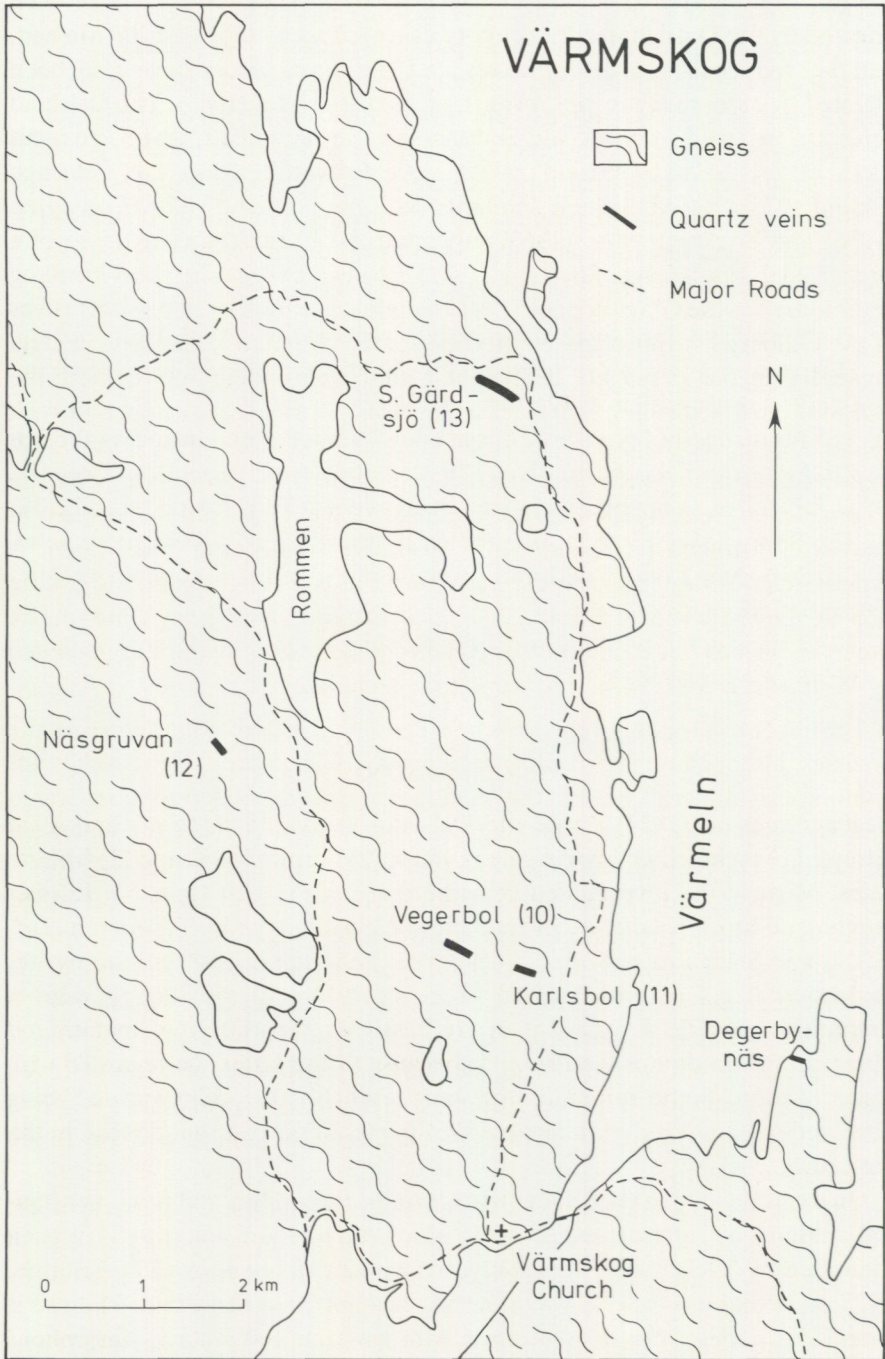


Fig. 3. Map of the Värmskog area, showing location of investigated deposits. Numbering of deposits refers to Table 1.

age (cf. Lundqvist 1979 and Gorbatshev 1980). These rocks have all been affected by the Dalslandian (Sveconorwegian) orogeny around 1 000 Ma ago, but the southwest Swedish gneisses and the Åmål rocks have also been affected by older metamorphic events (cf. Jakobsen *et al.* 1983). The Dalsland veins are believed to be of late Dalslandian age, as some of them cross-cut rocks of the Dalsland Group, which were formed c. 1 100–1 050 Ma ago (Skiöld 1976). Based on their similarity with the Dalsland veins, Tegengren (1956) and Wickman *et al.* (1963) suggested the Värmskog veins to be of a similar, Dalslandian age. Sherbina (1941), however, suggested the Värmskog veins as well as the Glava copper ores to be related to the older Åmål intrusives of the Gillberga synform, based on their spatial closeness. Lead isotope data presented in this paper are consistent with a Dalslandian age for both the Dalsland and Värmskog veins. They probably formed in connection with block faulting during a late stage of the Dalslandian orogeny. The E–W trending Värmskog veins may have been formed in connection with the second, east–westerly deformation phase of the Dalslandian orogeny in southern Värmland (cf. Lundegårdh 1980 and Lundegårdh *et al.* 1983). A genetic relationship between the veins and the late-orogenic Bohus granite (Rb–Sr age  $891 \pm 34$  Ma; Skiöld 1976, recalculated to new decay constants by Welin 1979) which may underlie large parts of southwest Sweden, is discussed by Wickman *et al.* (1963), and cannot be excluded.

#### VEIN MINERALOGY

Tegengren *et al.* (1924) divide the Dalsland veins into three mineralogical groups: (1) pyrite-chalcopyrite-galena veins, (2) bornite veins, and (3) fahlertz veins. Most of the investigated veins here are of the first type, but Knollegruvan and Stora Kilane are included in the bornite type by Tegengren *et al.* (1924) and Slädekärr is of the fahlerz type (although it also contains pyrite, chalcopyrite, galena and bornite). The mineralogy of the studied veins is summarized in Fig. 4. These data are based on literature information and observations on dumps, and should, because of the latter, be regarded with some caution. Some minerals may be present in one vein without being observed on the dump or being specifically mentioned for that deposit in the literature.

Quartz is the dominating mineral in all veins. In the Dalsland veins, substantial amounts of carbonates also often occur. Calcite and ankerite have been identified by XRD during this study, while siderite (mentioned by Frietsch, 1975, in addition to calcite and ankerite) has not been identified. Fluorite is found in Knollegruvan in association with ankerite and a black, amorphous substance, possibly bitumen (reported from Knollegruvan and Slädekärr as well as some Värmskog veins). Barite has been found in small amounts at

		DALSLAND								VÄRMSKOG			
		Ingribyn	Äskekärr	Hoppets gruva	Vassviken	Knollegruvan	Totten	St. Kilane	Björby	Slådekärr	Vegerbol- -Karlsbol	Näsgruvan	S. Gårdsjö
Gangue Minerals	Quartz	●	●	●	●	●	●	●	●	●	●	●	●
	Calcite		0	0	0	●	●	0	●	0	X	0	0
	Ankerite			●		●	●	0					
	Siderite										Lt		Lt
	Fluorite		X			0							Lt
	Barite						Lt			X			Lt
	Sericite	0	X										
	Chlorite				Lt						0		
	Bitumen					Lt				Lt	Lt		Lt
	Ore Minerals	Galena	0	0	X	X	X	0	X	X	●	●	●
Sphalerite				0			X				●	●	0
Chalcopyrite		Lt	X	0	0	0	●	●	X	●	0		0
Bornite			X	X		0	X	●		●			Lt
Chalcocite						Lt			Lt				Lt
Covellite							X	0		X			X
Fahlerz						Lt	X			●	Lt		0
Pyrite		●	Lt	●	●	0	X	0	●	0	●	0	●
Magnetite				0									
Hematite				0				X			Lt		Lt
Native Silver					Lt	Lt							Lt
Argentite													Lt
Proustite - -pyrargyrite										Lt	Lt		Lt

●: For gangue minerals abundant,  
for ore minerals common

0: For gangue minerals common,  
for ore minerals present but not common

X: Present in minor amounts

Lt: Reported in the literature but not found in this  
investigation

Fig. 4. Mineralogy of the investigated veins, based on observations on dumps and older literature data. In the literature, some minerals (e.g. siderite, hematite, barite, and also albite) are sometimes reported to occur without mentioning of specific deposits, making their inclusion in the above tabulation problematic. Sericite and chlorite are only reported above when they occur as primary gangue minerals, not as alteration products in the wall-rocks or fragments thereof. Chalcocite may also include digenite and neodigenite.

Slädekärr, and has been reported from Totten by Tegengren (1944a). Sericite and chlorite are sometimes seen in fragments of altered wall-rock in the veins, more rarely in a form that suggests them to be primary vein minerals.

Pyrite, chalcopyrite and galena occur in all the studied Dalsland veins. Sphalerite, earlier thought to be absent in all Dalsland veins (Tegengren *et al.* 1924; Tegengren 1944a), has been found at Hoppets gruva and Totten. It has a similar light grey or beige colour with opaque zones as the Värmskog sphalerite (see Johansson 1983a). Bornite is common at Stora Kilane and Slädekärr and also occurs elsewhere, fahlerz is common at Slädekärr, and covellite and chalcocite are also found in some veins. Malachite is sometimes seen as a supergene alteration product, but has not been included in Fig. 4. At Hoppets gruva, magnetite occurs in intergrowths with galena (Tegengren *et al.* 1924) and sphalerite (this study), while hematite is found in separate, lath-shaped crystals. Native silver and proustite-pyrargyrite have been reported from some veins (Tegengren *et al.* 1924) and the Slädekärr vein is noted for its high silver content.

The Värmskog veins may be divided into Cu veins and Pb-Zn-Ag veins. The mineralogy of the Cu veins is discussed in detail by Sherbina (1941) and Jongejan & Westerveld (1949), while the mineralogy of the investigated Pb-Zn-Ag veins is shown in Fig. 4. Also in Värmskog quartz dominates, with calcite and primary chlorite occurring as additional gangue minerals, and siderite, fluorite, barite and bitumen having been reported in the literature (Tegengren *et al.* 1924; Frietsch 1975). Galena, sphalerite, pyrite and chalcopyrite are found both at Vegerbol-Karlsbol and at Södra Gärdsjö, the former three also in the smaller Näsgruvan deposit. The sphalerite has a pale grey or beige colour with opaque zones around grain boundaries and fractures in the crystals. Its composition is discussed by Johansson (1983a). Hematite has not been found in this study, although it should be quite common, especially at Karlsbol, according to Nordenström (1881) and Tegengren *et al.* (1924). The Södra Gärdsjö deposit has a more complex mineralogy compared to Vegerbol-Karlsbol, with Ag-rich fahlerz (a rare mineral at Vegerbol-Karlsbol according to Tegengren 1944b) as well as other copper and silver minerals (Nordenström 1881; Tegengren *et al.* 1924; Sherbina 1941; Tegengren 1944b), but the dumps at Södra Gärdsjö are very poor in ore minerals compared to those at Vegerbol-Karlsbol.

The vein quartz in the Dalsland and Värmskog veins generally consists of coarse, anhedral crystals. The other minerals (carbonates, sulphides, etc.) form nodules and aggregates in the quartz, sometimes apparently filling vugs in it. These minerals thus appear to postdate the quartz. Detailed paragenetic sequences are hard to work out, as many of these minerals occur separate from each other and as observations of zonations or other internal structures in the veins are impossible because of the inaccessibility of the mine workings. As

noted by Tegengren *et al.* (1924), the Slädekärr vein with its complex mineralogy has a different structure. It contains more fine-grained quartz with bands of fine-grained sulphide impregnation and layers of more or less dissolved and altered wall-rock. This "crustiform" structure suggests repeated fault movements during deposition. Also in some other veins (e.g. Knollegruvan and Södra Gärdsjö) signs of movements during or after the vein formation is seen.

Some sulphides also occur as impregnations in altered wall-rock. Minor impregnations of pyrite, chalcopyrite and galena occur in strongly silicified greenstone around the Björbyn vein. Impregnations of pyrite as well as of other sulphides occur in the strongly altered gneiss (quartz-sericite rock) around the Vegerbol-Karlsbol and Södra Gärdsjö veins. One of the Södra Gärdsjö veins in fact is reported to consist of fragments of quartz, galena, sphalerite and fahlerz in a chloritic matrix (Nordenström 1881; Tegengren *et al.* 1924), possibly a fault cutting the other quartz veins.

Differences in vein mineralogy and structure may reflect lateral, geographical variations between types of deposits, but may also, at least partly, reflect vertical variations within single vein systems eroded to different levels. Thus, Sherbina (1941) suggests that the Södra Gärdsjö deposit, with its complex mineralogy and several parallel veins, may reflect a deeper level of erosion than the single, simple Vegerbol-Karlsbol vein.

#### WALL-ROCK ALTERATION

The Dalsland-Värmskog veins are often characterized by a distinct alteration of the wall-rocks around the veins. This is best developed in the gneisses around the Värmskog veins, where an outer dark green chlorite zone and an inner, light green quartz-sericite zone often envelopes the veins themselves. The inner zone was called "serpentine" by Nordenström (1881) and "sericite-epidote" by Tegengren *et al.* (1924), but neither serpentine nor epidote has been found in it. The light green colour comes from fine-grained greenish sericite, and "quartz-sericite rock" seems the most appropriate term for this rock. The total thickness of these alteration zones rarely exceeds 1 m.

The alteration has been studied in more detail at Vegerbol. The surrounding rock here consists of banded, intermediate gneiss containing acidic and amphibolitic bands. The gneiss consists of quartz, K-feldspar, plagioclase, biotite (often green), hornblende, epidote, orthite (as grains surrounded by epidote), sphene, minor apatite, and accessory zircon, hematite, magnetite and pyrite. Some sericitization of feldspar and chloritization of biotite exist several tens of metres away from the vein, presumably as part of a regional alteration not related to the vein formation. In the chlorite zone, the biotite and amphibole have been totally altered to chlorite, and there is also more sericitization of the

feldspar, but the rock still retains its gneissic structure. This structure is lost in the quartz-sericite zone, where the feldspar is pervasively altered to sericite, the biotite altered to light mica with opaque inclusions, sphene altered to a dark, non-reflective material (leucoxene?) and hornblende, epidote and orthite also disappear. There seems to be a neo-formation of quartz, pyrite and carbonate in this zone, and apatite is still stable. Chlorite has disappeared, although it occurs as a late primary mineral within the vein itself. The inner alteration zone is thus characterized by quartz and sericite/muscovite with additional pyrite and carbonate and minor apatite, leucoxene (?) and Fe-oxides.

The alteration around the Slädekärr vein in Dalsland has also been studied in some detail. This vein is surrounded by red, schistose, rhyolitic porphyry, consisting of quartz and feldspar phenocrysts in a fine-grained groundmass (probably also of quartz and feldspar). There is a strong, regional sericitization affecting both the groundmass and some of the feldspar phenocrysts (while others remain fresh). Because ferromagnesium minerals are absent, no chloritization occurs, but within a metre of the vein the red porphyry is altered to a green-grey quartz-sericite rock with occasional weak sulphide impregnation.

Seen under the microscope, the difference between "fresh" and altered porphyry mostly lies in the degree of sericitization of the feldspar. In the latter rock, the feldspar pseudomorphs start to dissolve, and the porphyritic texture of the rock is lost. In the vein itself, highly altered wall-rock fragments, partly dissolved in the vein quartz, may be seen, as well as surprisingly fresh porphyry fragments. The latter may have been enclosed by vein quartz before given time to react with the hydrothermal solution, or they may have come in contact with the solution during a stage when it was in equilibrium with the unaltered porphyry.

The vein at Hoppets gruva is partly enclosed by green, sericitic fault gouge, distinctly different from the surrounding red augen gneiss. This alteration may, however, be related to the faulting rather than the vein formation, *sensu stricto*. In the dumps surrounding the Äskekärr and Ingribyn deposits, rocks displaying similar sericitization as at Slädekärr can be found. Altered porphyry from Äskekärr also contains carbonate. At Björbyn, samples of both dark, calcified greenstone and light, strongly silicified greenstone (with weak sulphide impregnation) may be found, and the phyllite around the Stora Kilane vein appears to have undergone a similar two-way alteration: marked silicification or marked calcification. Because observations in the latter cases have been made on the dumps only, the geometrical relationship between the veins and the altered rock samples remains unknown, making conclusions rather uncertain.

## WALL-ROCK GEOCHEMISTRY

In order to study the chemical changes of the wall-rocks during hydrothermal alteration, samples have been taken from altered as well as relatively fresh rocks on both sides of the veins in two drill cores obtained from the Geological Survey of Sweden, one from Slädekärr, Dalsland, and one from Vegerbol, Värmskog (Fig. 5). Additional samples of altered and unaltered wall-rocks were taken from dumps and outcrops around four other veins in Dalsland, one (Stora Kilane) hosted by calcareous phyllite belonging to the Dalsland Group, the others (Ingribyn, Äskekärr and Björbyn) hosted by metamorphosed igneous rocks of the Åmål Complex. Sample descriptions are given in Appendix I A–C. The wall-rock of the Slädekärr vein is a fairly homogeneous rhyolitic porphyry, although the samples below the vein in the drill core have a somewhat less acidic, rhyodacitic composition. At Vegerbol, the surrounding gneiss had a much more variable pre-alteration composition, making interpretations of the results more difficult. Sampling was done on a drill core where the gneiss appeared more homogeneous in composition than usual, and more amphibolitic bands in the sampled core segment were avoided, the sampling being done on the dominant acidic to intermediate gneiss.

Most samples were analysed by Plasma excitation–Optical emission spectrometry (CMP–OES; Govindaraju *et al.* 1976) by the CNRS–CRPG in Nancy, France. The relative precision of the data is estimated to be  $\pm 0.5\%$  for major and minor oxides,  $\pm 10\%$  for trace elements occurring in the 100 ppm range, and  $\pm 50\%$  for trace elements occurring in the 10 ppm range (K. Govindaraju, written communication 1983). A few samples, rich in carbonate or sulphides, were analysed by wet chemical methods by CNRS–CRPG, as indicated in Appendix II A–C where all analytical results are given. Additional XRF analyses of immobile elements ( $\text{TiO}_2$ , Y and Zr) as well as Rb and Sr were carried out at the Department of Geology in Stockholm to see if correction for dilution effects could be made using the immobile elements. Plots of Zr versus Y, Zr versus  $\text{TiO}_2$  and Y versus  $\text{TiO}_2$  for the Slädekärr samples showed limited variation between altered and unaltered samples, while the Vegerbol samples showed a large variation partly related to the alteration but partly also reflecting earlier inhomogeneities. For the remaining localities, the number of samples per locality is too small to make any firm conclusions. In no case, it was considered meaningful to use the immobile elements for any corrections, and the reported and discussed values thus represent relative rather than absolute changes during alteration, although the Slädekärr trends may be considered “semi-absolute”. Because of the limited number of samples from Ingribyn, Äskekärr, Stora Kilane and Björbyn, and the uncertainty in the geometrical relationship between the dump samples and these veins, the results from these deposits must be interpreted with special caution.

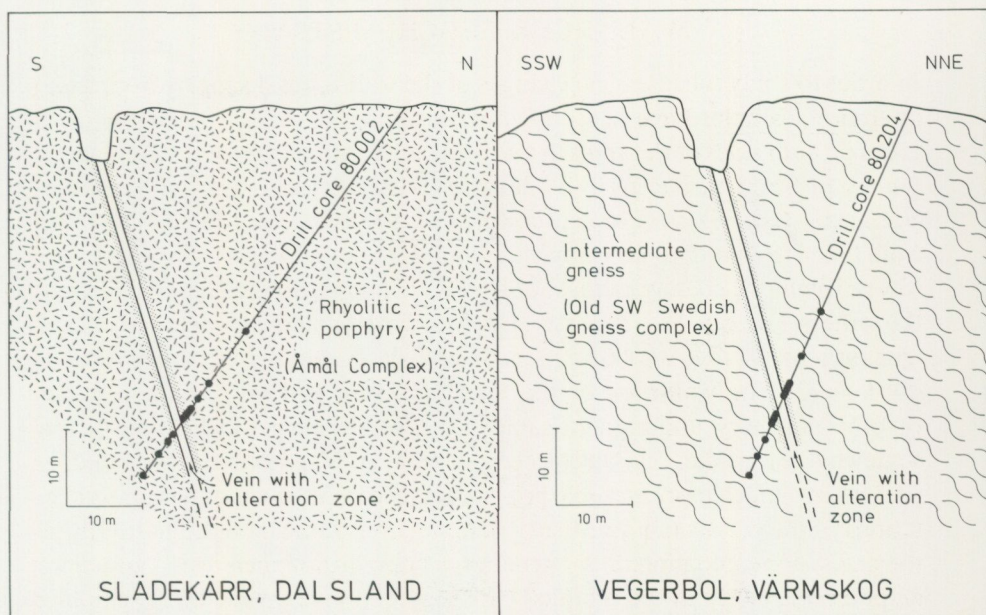


Fig. 5. Highly schematic profiles across the Slådekärr and Vegerbol veins, illustrating the approximate geometric relations between the veins and the sampled drill cores, and the position of the wall-rock samples within each core.

The most important element trends from the Slådekärr and Vegerbol drill cores are illustrated in Figs. 6 and 7. The results may be summarized in terms of two processes: silicification and calcification. Silicification is seen in the Slådekärr data, as well as "below" the vein in the Vegerbol drill core and in two samples each from Stora Kilane and Björbyn. During this alteration, there is an increase in  $\text{SiO}_2$  and often in base metals (sulphide impregnation; in Slådekärr also Ba, probably by barite impregnation), a drastic decrease in  $\text{Na}_2\text{O}$  and often some decrease in  $\text{Al}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{FeO}$  and  $\text{TiO}_2$ , partly by dilution with silica. In the Björbyn samples, the decrease is mostly in  $\text{CaO}$ ,  $\text{MgO}$  and  $\text{FeO}$ , while the alkalis appear rather unaffected. The decrease in  $\text{Na}_2\text{O}$  is most marked in Vegerbol, where sodium is almost entirely absent close to the vein, and in some samples from Slådekärr. The sodium decrease in Vegerbol appears to be complemented by an increase in potassium, probably by local enrichment in new formed K-mica. In Slådekärr, there is a drastic decrease in  $\text{CaO}$  in two samples, although these are not immediately adjacent to the vein. Iron and magnesium appear constant at Slådekärr, while at Vegerbol they are depleted around the vein.

In the hanging wall of the vein in the Vegerbol drill core, and in one altered sample each from Ingridbyn, Åskekärr, Stora Kilane and Björbyn, there is instead a more or less marked decrease in  $\text{SiO}_2$ . At Stora Kilane and Vegerbol,

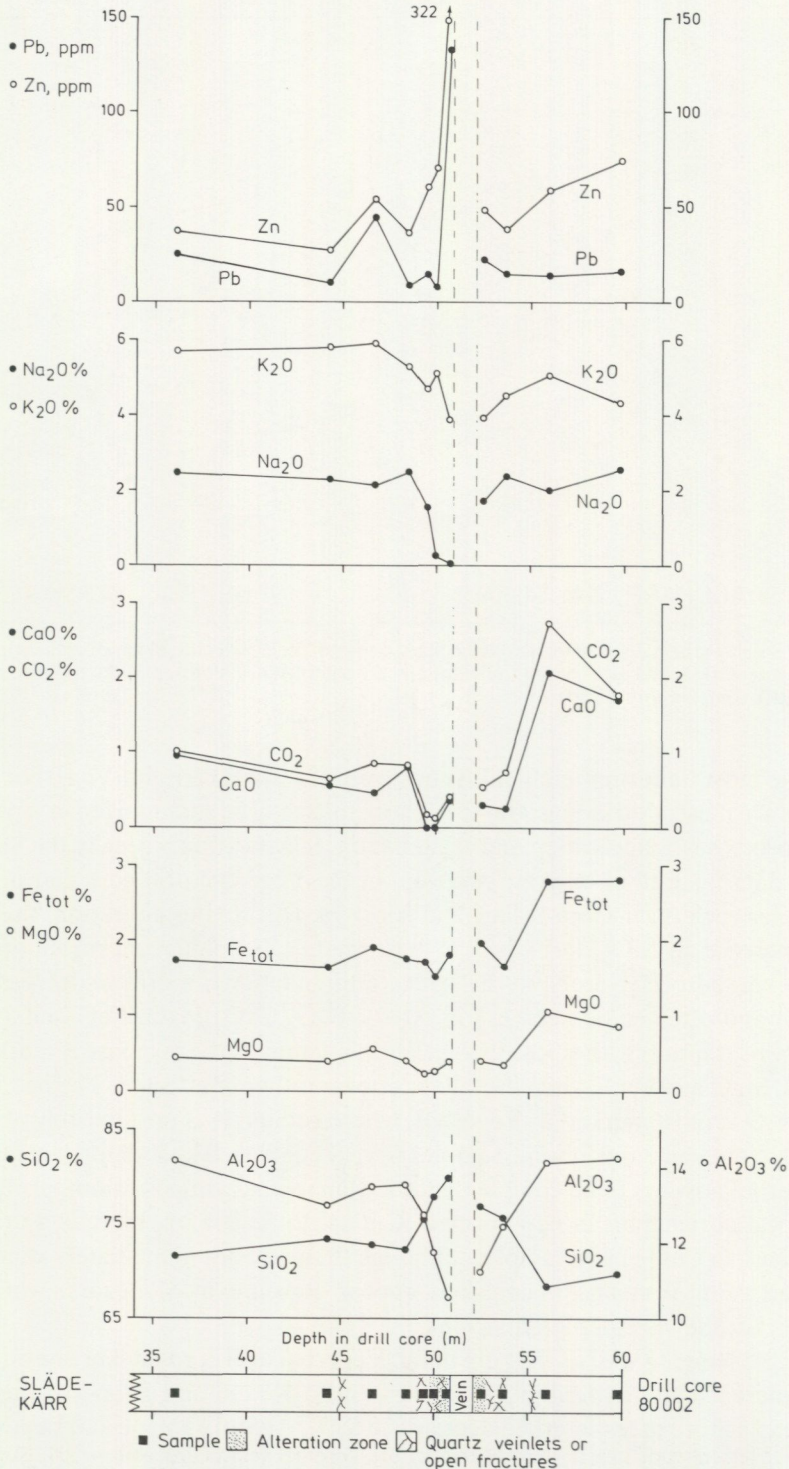


Fig. 6. Element variations in the wall-rock of the Slådekärr vein in drill core 80002. Note the different scales for SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in the lowest plot. Drawing at bottom shows the relation of the rock samples to the alteration zone around the vein.

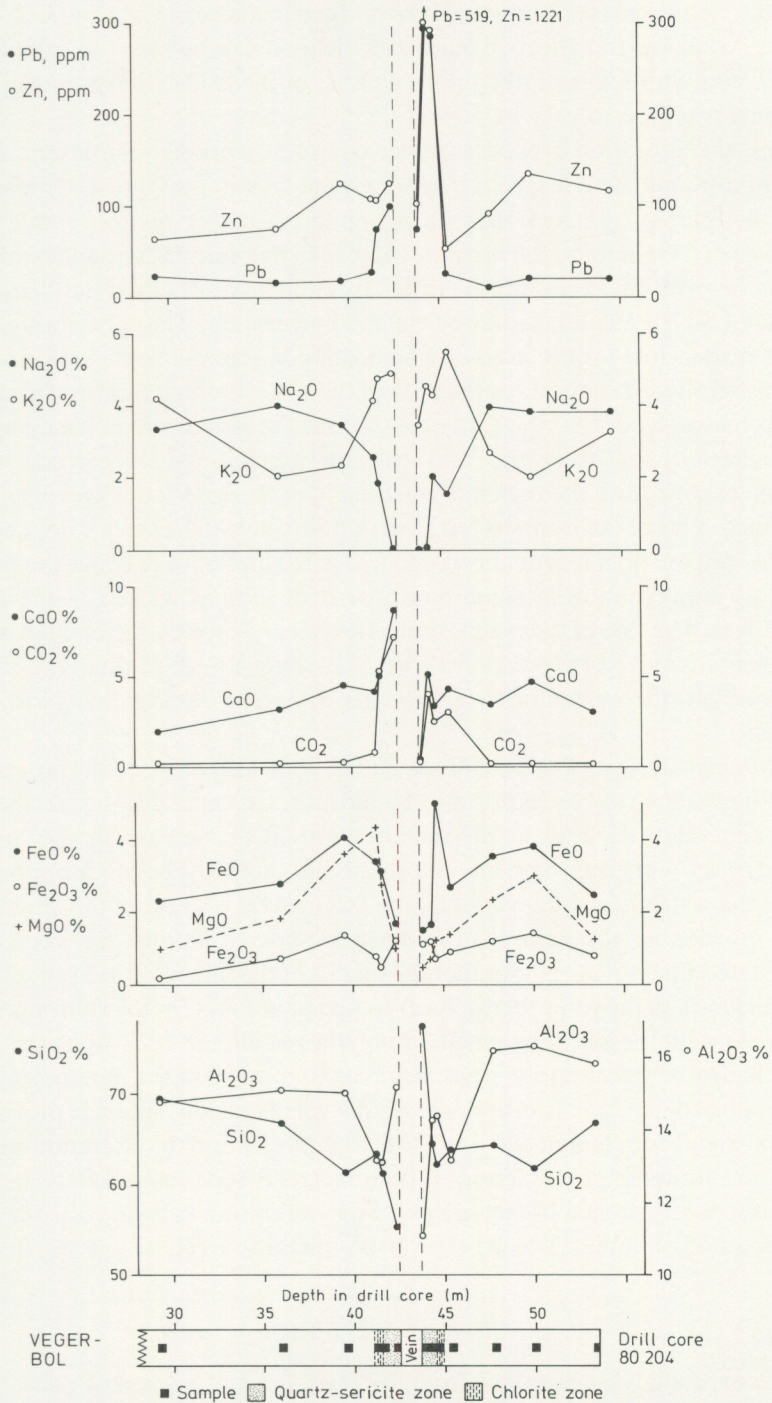


Fig. 7. Element variations in the wall-rock of the Vegerbol vein in drill core 80204. Note the different scales for SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in the lowest plot. Drawing at bottom shows the relation of the rock samples to the alteration zones around the vein.

this  $\text{SiO}_2$  decrease is accompanied by a marked increase in  $\text{CaO}$  and  $\text{CO}_2$ , and also at Äskekärr and Björbyn some calcification can be seen. In sample ÅJ 79:217 from Stora Kilane, the dilution effect of the calcite makes most other elements decrease to very low levels.

Thus, the alteration process is rather complex, working in different directions in different samples even from the same locality.  $\text{SiO}_2$  or  $\text{CaO}$  leached from one part of the rock may be precipitated as free quartz or calcite in another part. Generally, the breakdown of feldspar, hornblende and biotite to sericite involves the consumption of  $\text{H}^+$  from the hydrothermal fluid, and the release of  $\text{SiO}_2$ , calcium, sodium, iron and magnesium. The silica formed the quartz responsible for the marked silicification in some samples, and if larger volumes of altered rocks along the path of the hydrothermal fluid are inferred, this may also account for the vein quartz itself. Potassium was taken up by the muscovite/sericite formation, and calcium precipitated as calcite, while sodium was lost from the rock into the fluid in exchange for the hydrogen ions consumed. Part of the iron was left as dark Fe-oxide patches in biotite pseudomorphs, but much of it probably combined with sulphur to produce the pyrite found as impregnation in some quartz-sericite rock as well as in the veins themselves. The fate of the magnesium is less clear, some being retained in the rock, some involved (together with Fe, Al, Si etc.) in the formation of late primary-hydrothermal chlorite in the veins, and some perhaps being lost with the fluid.

Although it appears likely that base metals were also released during alteration (Pb especially by breakdown of K-feldspar, Cu and Zn by breakdown of mafic minerals), these elements remain constant or increase sharply in the altered rocks. Very high base metal contents are caused by sulphide impregnation of the wall-rocks, but even if all the trace metal content of the alteration zones enveloping the veins had been transported out into the veins and precipitated there, it is obvious that the metals of the thin alteration envelopes (not thicker than the veins themselves) could not account for the vein mineralization. As with the silica, much larger volumes of altered rock along the path of the hydrothermal solution must be invoked to explain the mineralization. At the site of deposition (i.e. at the present level of erosion) sulphide precipitation and metal enrichment occurred both in the veins and the alteration zones. However, although no depletion of base metals is seen immediately around the veins, the existence of strong, pervasive alteration still suggests the surrounding rock complexes to be a probable metal source.

### LEAD ISOTOPES

Lead isotope analyses of galena from the Dalsland and Värmskog veins have been made during a stay at the U.S. Geological Survey in Denver, Colorado,

and at the Swedish Museum of Natural History in Stockholm. Whole rock lead composition of some of the chemically analysed drill core samples from Slådekärr and Vegerbol was analysed at the U.S. Geological Survey. The analytical methods used are summarized in Doe & Delevaux (1980) and Johansson (1981, 1983b). Correction factors, based on NBS standard SRM 981, and estimated analytical uncertainties for the two laboratories are given in Table 2. All reported errors are at the 2 sigma level.

The results of the analyses are found in Tables 3 and 4, and illustrated in Figs. 8 and 9. The isochron calculations are summarized in Table 5. The galenas from Dalsland and Värmskog show a similar, rather restricted range of lead isotope compositions, indicating a similar age of mineralization and source of lead. They fall close to the primary growth curve of Stacey & Kramers (1975; see Fig. 8) and the Orogenic curve of Zartman & Doe (1981; see Fig. 9) with  $^{206}\text{Pb}/^{204}\text{Pb} = 16.8$  to 17.9,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.45$  to 15.60, and  $^{208}\text{Pb}/^{204}\text{Pb} = 36.5$  to 37.5. The samples from Slådekärr and Vegerbol cluster in the middle of that range, while the most radiogenic galena is from Hoppets gruva and the least radiogenic from Näsgruvan and Södra Gärdsjö. In terms of their Stacey-Kramers (1975) model ages, 1080 to 560 Ma, the Dalsland-Värmskog galenas are non-radiogenic to moderately radiogenic compared to their inferred Dalslandian age of 900–1000 Ma. On the  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Figs. 8 and 9) they fall along a linear trend with a slope of  $0.1265 \pm 0.0189$  and a MSWD of 0.26 (Table 5).

From the drill cores at Slådekärr and Vegerbol, three wall-rock samples each were analysed for lead isotope composition, viz. one strongly altered rock adjacent to the vein, one nearby sample of relatively fresh rock, and one sample of fresh rock taken at some distance away. At Vegerbol, the altered rock sample (ÅJ 80:63) contained strong pyrite impregnation and had a lead isotope composition not very different from that of the galena; another fraction of the same powdered sample was leached with  $\text{HNO}_3$  and  $\text{HCl}$  and thereby split into a leach solution containing the non-radiogenic sulphide lead and a residual fraction containing the radiogenic silicate lead (Table 4, Fig. 8). The altered sample from Slådekärr (ÅJ 80:80) is intermediate to the two unaltered samples from that locality in its rock-lead composition.

The rock-lead samples from Slådekärr and Vegerbol (treating the whole rock, leach and residue fractions of sample ÅJ 80:63 as three separate samples) all fall on the same linear trend on the  $^{207}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 8), in spite of them being from different rock types and rock units (porphyry from the Åmål Complex and gneiss from the southwest Swedish gneiss complex, respectively) and being located about 65 km apart. The slope of this line,  $0.0730 \pm 0.0031$  (Table 5), corresponds to an age of  $1010 \pm 90$  Ma. This is clearly not the original age of these rocks (cf. Lundqvist 1979), but an age related to the Dalslandian metamorphism or more specifically to the

TABLE 2. Correction factors and analytical uncertainties of the lead isotope analyses.

	Correction factors			Estimated analytical uncertainty (2 sigma)
	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	
U.S. Geological Survey, Denver	1.002675	1.003966	1.005686	± 0.1 %
Museum of Natural History, Stockholm	1.0010	1.0018	1.0041	± 0.2 %

Based on multiple analyses of NBS standard SRM 981. The Värmskog and Slädekärr galena data of Table 3, and the whole rock lead data of Table 4, have been multiplied with the correction factors for Denver; the remaining galena data of Table 3 with those for Stockholm.

TABLE 3. Lead isotope composition of galena in the Dalsland and Värmskog veins.

Deposit	Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Description of hand specimen
D A L S L A N D					
1. Ingridbyn	AJ 79:132	17.348	15.534	36.799	Galena in quartz
2. Åskekärr	AJ 79:191	17.330	15.518	36.730	Ga in qz vein in porphyry
	AJ 79:192	17.339	15.528	36.738	Ga + cpy in qz vein in altered porphyry
	AJ 79:194	17.306	15.500	36.679	Ga in qz veinlets in altered porphyry
3. Hoppets gr.	AJ 79:161	17.856	15.590	37.408	Qz+ga+carbonate+sericite gouge fragments
4. Vassviken	AJ 79:172	17.327	15.513	36.736	Qz with py and minor cpy and ga
5. Knollegruvan	AJ 79:183	17.277	15.505	36.717	Qz, cpy, minor ga+py in veins in greenstone
6. Totten	AJ 79:211	17.454	15.538	36.728	Qz, cpy, ga, minor bn and py
7. St. Kilane	AJ 79:232	17.558	15.542	36.810	Qz with ga and bn
8. Björby	AJ 79:236	17.388	15.516	36.942	Py and ga as impregnation in silicified
	AJ 79:237	17.279	15.516	36.801	" " greenstone
	AJ 79:239	17.199	15.496	36.696	Galena in vein quartz
9. Slädekärr	AJ 79:252	17.332	15.521	36.911	Qz with cc+ga+fa+cpy+altered wall-rock
	AJ 79:253	17.372	15.525	36.957	Qz with cc+ga+cpy+altered wall-rock
	AJ 79:254	17.350	15.520	36.923	Qz with cc+ga+cpy+py+fa+altered wall-rock
	AJ 79:255	17.412	15.533	37.005	Qz with cc+ga+cpy+altered wall-rock
	AJ 79:259	17.314	15.513	36.879	Qz with ga+fa+cpy+altered wall-rock
V Ä R M S K O G					
10. Vegerbol	AJ 80:50	17.290	15.523	36.903	Quartz with ga and py
	AJ 80:53	17.485	15.543	37.080	Qz with sp and ga, minor py
	AJ 80:56	17.420	15.531	37.039	Quartz with ga and py
	AJ 80:57	17.275	15.515	36.886	Qz with ga and py, minor cpy
11. Karlsbol	AJ 79:316	17.179	15.502	36.806	Qz with sp, ga and py
	AJ 79:320	17.152	15.499	36.778	Quartz with sp and ga
12. Näsgruvan	AJ 79:350	16.883	15.461	36.514	Quartz with galena
	AJ 79:351	16.929	15.467	36.560	Qz with carbonate, ga, sp, minor py
13. S. Gärdsjö	AJ 79:342	17.081	15.497	36.802	Qz veinlets with carbonate, ga, cpy in altered wall-rock gneiss
	AJ 80:86	16.847	15.461	36.515	Ga, sp, py as impregnation in heavily altered wall-rock gneiss

Estimated analytical uncertainty: ± 0.1 % for Värmskog and Slädekärr data, ± 0.2 % for all other Dalsland data.

Mineral abbreviations: qz = quartz, cc = calcite, ga = galena, sp = sphalerite, cpy = chalcopyrite, py = pyrite, bn = bornite, fa = fahlerz.

Correction factors used: see Table 2.

TABLE 4. Present-day lead isotope composition of wall-rock samples from the Slådekärr and Vegerbol veins<sup>1</sup>.

Sample no.	Position in drill core	Distance <sup>2</sup> to vein	Sample description <sup>3</sup>	Type <sup>4</sup>	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>204</sup> Pb	<sup>208</sup> Pb/ <sup>204</sup> Pb
SLÅDEKÄRR (DALSLAND), Drill core 80 002							
AJ 80:75	36.2 m	14.7 m	Rhyolitic porphyry	wr	19.014	15.640	38.709
AJ 80:78	48.5 m	2.4 m	Rhyolitic porphyry	wr	20.561	15.742	39.985
AJ 80:80	50.0 m	0.9 m	Altered porphyry (quartz-sericite rock)	wr	19.516	15.672	40.004
VEGERBOL (VÄRMSKOG), Drill core 80 204							
AJ 80:58	29.3 m	13.2 m	Monzogranitic gneiss	wr	20.936	15.781	38.763
AJ 80:61	41.3 m	1.2 m	Monzonitic gneiss (weakly chloritized)	wr	21.515	15.814	37.126
AJ 80:63	42.4 m	0.1 m	Heavily altered gneiss (qz-sericite rock with pyrite mineralization)	wr	17.681	15.531	37.049
				leach	17.509	15.521	37.001
				res.	23.156	15.932	38.904

1. Multiplied with the correction factors for Denver in Table 2.
2. Measured along the drill core (= maximum true distance).
3. Normative classifications based on chemical analyses in the Appendix, and following the classification scheme of Streckeisen (1976).
4. Type: wr = whole rock sample.  
leach = leach solution from leaching of wr with HNO<sub>3</sub> and HCl.  
res. = residue remaining after that leaching.

TABLE 5. Isochron calculations.

	Slope	Y-intercept	MSWD	T <sub>1</sub> (Ma)	T <sub>2</sub> (Ma)
Rock lead isochron	0.0730 ± 0.0031	14.24 ± 0.06	0.44	0	1010 ± 90
Galena isochron	0.1265 ± 0.0189	13.33 ± 0.32	0.26	1010 ± 90	1410 + 370 - 400

All error limits 2 sigma.

MSWD = Mean square of weighted deviates.

T<sub>1</sub> = Assumed "upper" age (mineralization age for galena).

T<sub>2</sub> = Calculated "lower" age (metamorphic rock-lead age, source rock age for galena isochron).

hydrothermal alteration around the veins (in case the latter affected the macroscopically unaltered rock several metres away from the veins to such a degree as to reset the Pb isotope system completely). The fit to one single isochron of both the Slådekärr and Vegerbol rock lead, rather than two separate parallel ones, implies either that a regional metamorphic homogenization of lead occurred on a large scale 1000 Ma ago, or that a Pre-Dalslandian homogeneity in lead isotope composition existed between these different rocks.

The rock-lead isochron intersects the galena line at a point very close to the composition of Slådekärr and Vegerbol galena (Slådekärr-Vegerbol galena mean: <sup>206</sup>Pb/<sup>204</sup>Pb = 17.36, <sup>207</sup>Pb/<sup>204</sup>Pb = 15.525). This composition may thus

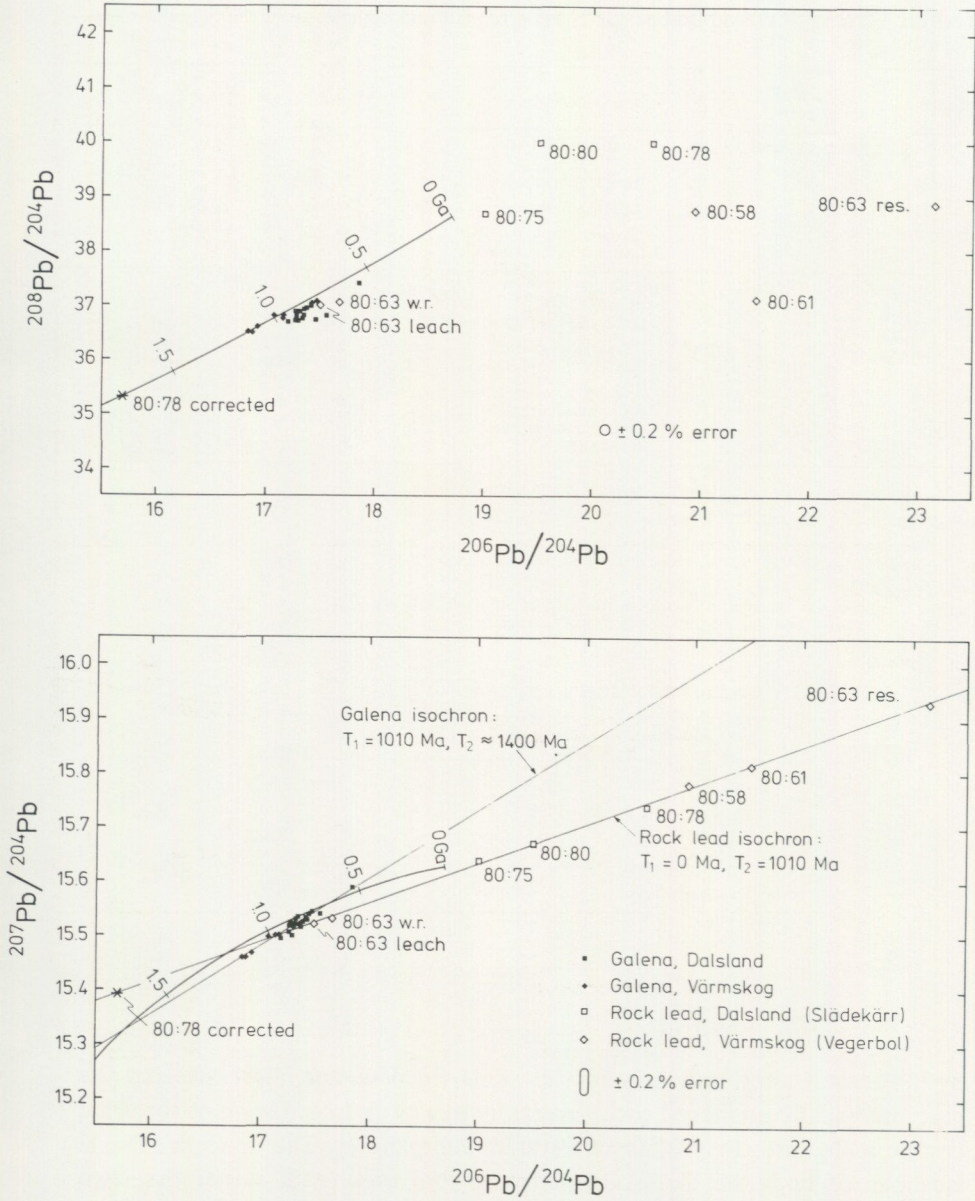


Fig. 8. Lead isotope composition of Dalsland-Värmskog ore and rock lead (Tables 3 and 4) plotted in the conventional  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagrams. The asterisks mark the lead isotope composition of rock-lead sample ÅJ 80:78 corrected for *in situ* decay of U and Th in a closed system during the past 1010 Ma. The isochrons drawn are from Table 5, the primary growth curves from Stacey & Kramers (1975).

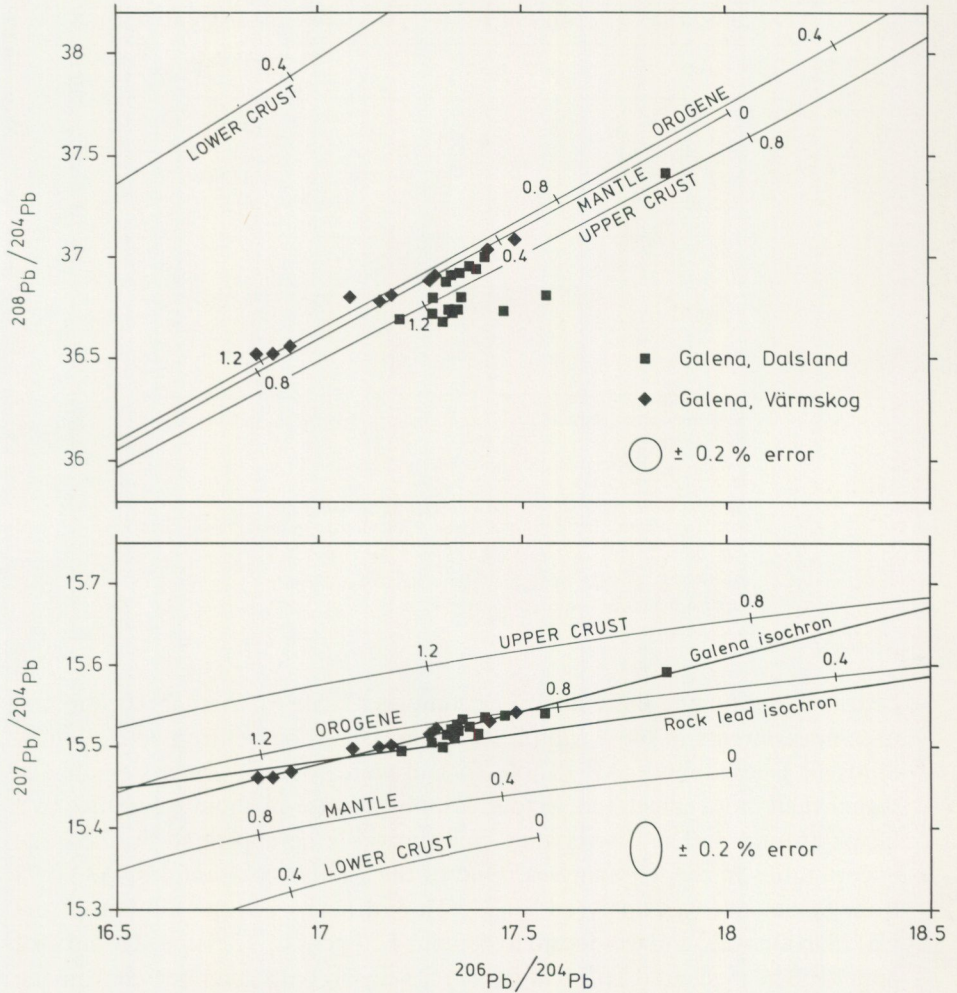


Fig. 9. Enlarged lead isotope diagrams, showing the lead isotope composition of the Dalsland and Värmskog galenas in Table 3 in relation to the curves of the Plumbotectonics model (version II; Zartman & Doe 1981). Both the galena and rock-lead isochrons from Table 5 are shown for reference on the lower plot.

be taken as the starting point of the rock-lead isochron  $1\ 010 \pm 90$  Ma ago, since it appears likely that the galena lead represents the isotope composition of these rock units during leaching and mineralization. This also means that the figure  $1\ 010 \pm 90$  Ma may be taken as the best radiometric estimate of the age of mineralization of the veins.

On the  $^{208}\text{Pb}/^{204}\text{Pb}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  plot in Fig. 8, both galena leads and rock leads show much more scatter. If the galena mean is used as a starting point for the latest stage of rock-lead evolution, Th/U ratios in the range 0.1 to 4.5 may

TABLE 6. Th-U systematics of wall-rocks from Vegerbol and Slädekärr.

	Sample	Analyt. method	Th (ppm)	U (ppm)	Th/U	Factor <sup>1)</sup>	
Vegerbol	ÅJ 80:58	2)	18.8 ± 2.3	7.53 ± 0.16	2.50	1.6	
		3)			1.58		
	ÅJ 80:61	2)	6.5 ± 2.2	10.0 ± 0.20	0.65	6.5	
3)		0.10					
	ÅJ 80:63	2)	13.2 ± 2.0	3.51 ± 0.09	3.76	7.1	
		3)			0.53		
Slädekärr	ÅJ 80:75	2)	24.2 ± 2.0	4.08 ± 0.09	5.93	1.7	
		3)			3.41		
	ÅJ 80:78	2)	23.0 ± 2.0	4.65 ± 0.10	4.95	1.6	
		3)			3.03		
			4)	13.5	4.37	3.09	-
	ÅJ 80:80	2)	21.3 ± 1.8	3.06 ± 0.08	6.96	1.5	
3)		4.53					

- 1) Th/U ratio from neutron activation analysis divided by Th/U ratio calculated from lead isotope data.
- 2) Neutron activation analysis by Studsvik Energiteknik AB; Analytical errors indicated are 1 standard deviation.
- 3) Th/U ratio calculated from lead isotope data using the following starting points, based on ore lead composition in respective deposit:  
 Vegerbol:  $^{206}\text{Pb}/^{204}\text{Pb} = 17.368$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 36.997$   
 Slädekärr:  $^{206}\text{Pb}/^{204}\text{Pb} = 17.356$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 36.935$
- 4) Isotope dilution - mass spectrometer analysis at USGS in Denver.

be calculated for the individual rock samples (Table 6). Actual thorium and uranium contents in these samples were measured by neutron activation by Studsvik Energiteknik AB (Table 6) and were found to be systematically higher than those calculated, in four cases by a factor of about 1.6, in two by a factor around 7. The discrepancy could possibly be explained by the large uncertainties in the Th analyses. One of the whole rock samples, ÅJ 80:78 from Slädekärr, was analysed for U, Th and Pb by isotope dilution at the USGS in Denver, and was found to contain 4.37 ppm U, 13.5 ppm Th and 10.2 ppm Pb. The measured Th/U ratio (3.1) fits closely with that inferred from the  $^{208}\text{Pb}/^{206}\text{Pb}$  plot (3.0). However, if the measured isotope composition for that sample is corrected for *in situ* decay during the past 1 010 Ma using the above concentrations, the obtained figure ( $^{206}\text{Pb}/^{204}\text{Pb} = 15.69$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.39$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 35.29$ , asterisk in Fig. 8) deviates markedly from the galena composition believed to represent the rock lead in Dalslandian time. The most likely cause for this discrepancy is recent loss of lead from the rock, with the Th/U system staying closed.

As stated earlier, the best radiometric estimate of the mineralization age of the veins is  $1\ 010 \pm 90$  Ma, which is in accordance with geological evidence from Dalsland suggesting a Dalslandian age of the veins (veins found in the Dalsland Group). Using this mineralization age, a source rock age for the ore lead of  $1\ 400 \pm 400$  Ma may be computed from the slope of the galena isochron (Table 5). The large uncertainty in this age, in spite of the low MSWD of the

galena line, is caused by the narrow range of galena-lead isotope compositions. This age needs not necessarily be the original age of the source rocks, but may reflect homogenization during an earlier metamorphic event, as southwest Sweden is known to have a complex, polymetamorphic history during the time range 1700 to 1000 Ma (cf. Lundqvist 1979 and Gorbatshev 1980). If the surrounding rock units, viz. the rocks of the Åmål Complex in Dalsland and the southwest Swedish gneiss complex in Värmskog, are considered to be the lead sources, the galena isochron suggests a common history for these rock units, or at least parts of them, back to Mid-Proterozoic time. This would agree with the interpretation by Lundegårdh *et al.* (1983) that the gneisses in Värmskog dominantly are gneiss-granites of similar origin as the granitoids of the Åmål Complex in Dalsland. It is interesting to note that the Dalslandian ore-lead line presented here can be extrapolated back to the composition of ore leads within the Svecokarelian province and the Post-Svecokarelian Belt (Johansson & Rickard 1985), just like the Phanerozoic ore-lead line of Johansson & Rickard (1984). In particular the Älvdalen ore lead ( $^{206}\text{Pb}/^{204}\text{Pb} = 16.04$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.36$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 35.51$ ) fall right on the Dalslandian ore-lead line, but it would be premature to invoke a genetic link between the rocks of southwest Sweden and those of the Älvdalen area based just on this coincidence.

To sum up the lead isotope data, they suggest that the lead evolved in a crustal environment (presumably the southwest Swedish gneisses and the better preserved volcanites and granitoids of the Åmål Complex) from at least Mid-Proterozoic time ( $1400 \pm 400$  Ma) to the time of the Dalslandian orogeny. At  $1010 \pm 90$  Ma, part of this lead was leached to form the galena mineralization in the veins, and thus the fossil, "secondary" galena isochron. At the same time, the remaining lead in the rocks underwent at least local homogenization, and from a composition approximated by the ore lead, it has evolved until present, forming the "tertiary" rock-lead isochron. It is likely that some of the ore lead in the veins hosted by the Dalsland Group meta-sediments was Åmål basement lead redeposited in these clastic sediments. Contributions from other sources, such as the spilitic greenstone of the Dalsland Group, or a direct magmatic contribution from late Dalslandian Bohus-type granite, cannot be substantiated from the present data. The lead isotope compositions of these rock units are, however, unknown. A common, Dalslandian mineralization age for both the Dalsland and Värmskog veins is indicated by the present lead isotope data.

#### FLUID INCLUSION THERMOMETRY ON THE VEGERBOL VEIN

Fluid inclusion temperatures have been measured on quartz and sphalerite from the Vegerbol vein, Värmskog, using a Chaixmeca heating and freezing

stage mounted on a Leitz microscope (cf. Poty *et al.* 1976). The stage was heated electrically and cooled with liquid nitrogen pumped directly through the stage, calibration of the temperature scale being made by measurements of melting points of standard substances (Poty *et al.* 1976). The accuracy of the obtained temperatures depends both on the precision of the thermocouple and the correctness of the calibration curve as well as more variable factors such as the visibility within the individual inclusions and the alertness of the observer. However, the low temperature measurements are probably correct within  $\pm 0.5^\circ\text{C}$ , and the homogenization temperatures within  $\pm 5^\circ\text{C}$ .

Most of the Vergerbol vein quartz contains an abundance of very tiny inclusions (smaller than 2 micrometers) as well as numerous larger, irregular single-phase inclusions of unknown nature, making visibility very poor and observations on "good" two-phase fluid inclusions difficult. Measurements thus were restricted to 6 crystals in 5 double-polished thin sections where the quartz was unusually clear and numerous large (longest dimension in the plane of the thin section some micrometers to some tens of micrometers), clear, two- or three-phase fluid inclusions were found. The measured inclusions mostly occurred scattered or in groups, suggesting a primary origin. One may still question whether these unusually large inclusions in this unusually clear quartz are truly representative. However, nothing in the textural relationship suggests this to be a different generation of quartz, and the results obtained are thus considered at least tentatively representative for the bulk of the vein quartz.

The measured fluid inclusions in the quartz normally contained a liquid phase and a vapour bubble with an estimated volume of between 5 and 20%. Some inclusions (not measured) contained an abnormally large vapour phase (50–100 vol. %); many large dark inclusions presumably contained solely vapour or air (they appear dark because of the large contrast in refraction index between quartz and vapour/air). As leakage of fluid inclusions during heating runs occurred rather frequently, these inclusions probably had leaked earlier, and no boiling is inferred from these vapour-rich inclusions. In some unusually large and clear inclusions in sample ÅJ 80:56, a separate  $\text{CO}_2$  liquid phase was observed between the  $\text{H}_2\text{O}$  liquid phase and the vapour bubble at room temperature. In the other thin sections, the presence of  $\text{CO}_2$  in addition to water was indicated in many inclusions by their freezing behaviour, although the thick meniscus of the vapour bubble made observation of a separate  $\text{CO}_2$  phase impossible (cf. Roedder 1972).

Much of the sphalerite was unsuitable for fluid inclusion work because of wide opaque zones surrounding grain boundaries and fractures (Johansson 1983a). Where transparent, the sphalerite was seen to contain dark (semi-opaque to opaque) inclusions without visible gas bubbles, ranging from highly irregular to almost perfectly cubic in shape. Only rarely fluid inclusions with

visible gas bubbles were observed along what appeared to be healed fractures. The measured fluid inclusions, in 5 sphalerite crystals from 3 samples, are thus probably of secondary origin. They were of the same size as those measured in the quartz, a few micrometers to a few tens of micrometers, with liquid H<sub>2</sub>O and a vapour bubble of a few per cent by volume. Often, the vapour bubble failed to reappear after heating or freezing runs, making it difficult to obtain both heating and freezing data from the same inclusions. In one sample, ÅJ 80:53, inclusions containing CO<sub>2</sub> in addition to water were observed in the sphalerite.

The thermometric results are summarized in Figs. 10–12. During cooling of H<sub>2</sub>O–CO<sub>2</sub> inclusions, three major solid components may form (disregarding minor components such as hydrated salts): ice, CO<sub>2</sub> hydrate (CO<sub>2</sub> clathrate, CO<sub>2</sub>×5.75 H<sub>2</sub>O) and solid CO<sub>2</sub>. Solid CO<sub>2</sub> did not form until cooling to about –100°C, and was observed to melt rapidly within a few tenths of a degree from the triple point of CO<sub>2</sub>, –56.6°C. Most inclusions were, however, never cooled this far. Formation of ice and CO<sub>2</sub> hydrate during cooling occurred in the range –30 to –45°C. Contrary to the observation of Collins (1979), the impression was that the ice formed prior to the hydrate on cooling. Some inclusions nucleated ice only during some freezing runs and both ice and hydrate during others, some inclusions (CO<sub>2</sub>-poor or CO<sub>2</sub>-free) never nucleated anything but ice during freezing.

The observation of the last melting of ice ( $T_m$  ice) was made more difficult by the presence of another solid, CO<sub>2</sub> hydrate. Recorded temperatures are in the range –6 to 0°C (Fig. 10) both in the quartz and in the sphalerite. Two modes may be seen, a major mode around –4°C (weakly saline water) and a minor mode around 0°C (fresh water – heated ground water). The melting of CO<sub>2</sub> hydrate occurred around +8°C in the quartz and around +10°C in the few inclusions in sphalerite where it was recorded (Fig. 10). As discussed by Collins (1979), the melting point depression of hydrate melting (+10°C for pure H<sub>2</sub>O–CO<sub>2</sub> mixtures) gives a more accurate estimate of the salinity of CO<sub>2</sub>-bearing inclusions than does the melting point depression of ice, as part of the water has been used up by the hydrate formed. Using the formula of Bozzo *et al.* (1973), a melting temperature of CO<sub>2</sub> hydrate of +8±1°C corresponds to a salinity of 4±2 equivalent wt % NaCl.

In some inclusions in quartz, a small colourless crystal was found to persist above the melting of the CO<sub>2</sub> hydrate. Its dissolution temperature was recorded in 12 inclusions, mostly in sample ÅJ 80:56, and ranged between +10 and +81°C. It did not nucleate again at room temperature, but only during freezing runs, and was not present initially in the inclusions. Most likely, considering the composition of the inclusions, it is some form of sodium carbonate or bicarbonate (hydrated or not) nucleated during freezing. From its dissolution behaviour, sodium bicarbonate (nahcolite) seems to be the best candidate,

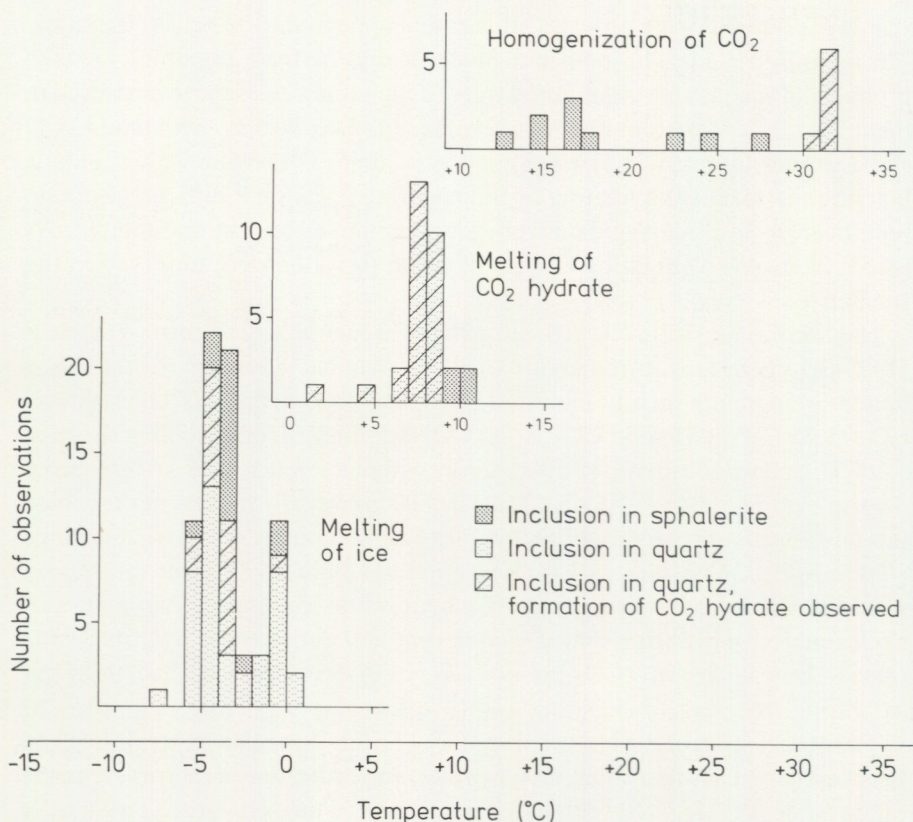


Fig. 10. Histograms showing observed temperatures of melting of ice, melting of CO<sub>2</sub> hydrate, and homogenization of CO<sub>2</sub> liquid and gas, in fluid inclusions in quartz and sphalerite from the Vegerbol vein in Värmskog.

although the crystals do not show the prismatic needles typical for that mineral (cf. Borisenko 1974; Crawford 1981).

Homogenization of CO<sub>2</sub> liquid and gas was recorded in inclusions in sphalerite in sample ÅJ 80:53 and in quartz in ÅJ 80:56, the temperatures being presented in Fig. 10. In the sphalerite, it occurred by shrinking and disappearance of the gas phase between +12 and +28°C, while in the quartz it occurred by critical (fading of meniscus) or near-critical homogenization around +31°C, the critical temperature of CO<sub>2</sub>.

Final homogenization temperatures (homogenization of H<sub>2</sub>O liquid and vapour or H<sub>2</sub>O liquid and CO<sub>2</sub> fluid) are presented in Fig. 11. Most inclusions in quartz homogenized in the liquid phase in the interval +190 to +330°C. A trimodal distribution, possibly caused by different pulses of quartz-precipitating solution, may be discerned within this interval. One case of homogenization to the CO<sub>2</sub> fluid phase at +371°C was recorded in a CO<sub>2</sub>-rich inclusion in

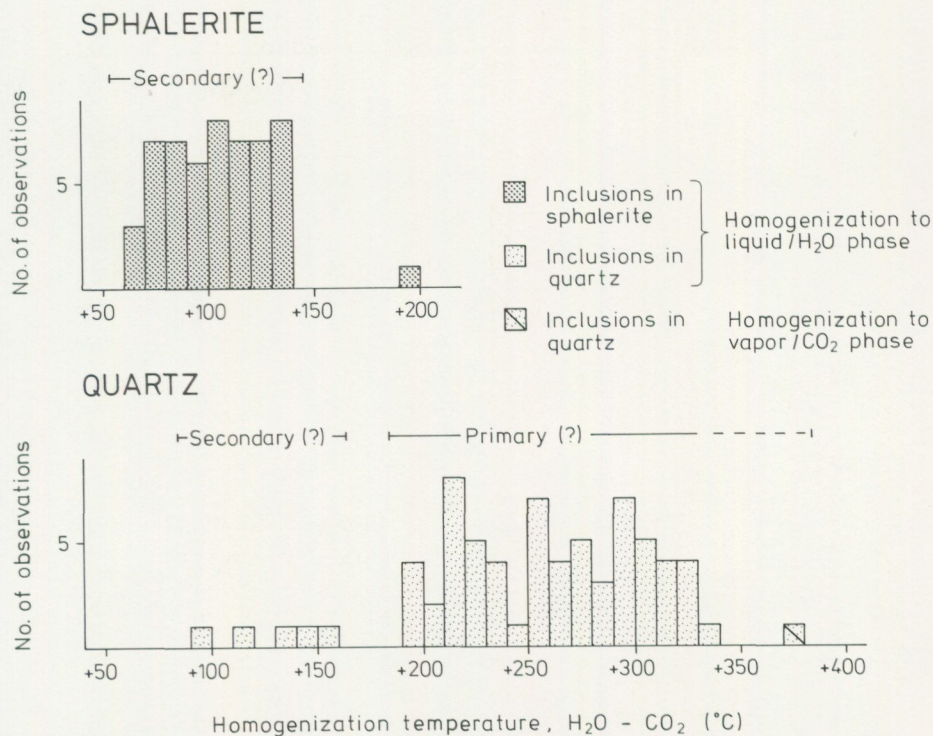


Fig. 11. Histograms of observed temperatures of homogenization of H<sub>2</sub>O liquid and gas, or H<sub>2</sub>O liquid and CO<sub>2</sub> fluid (final and total homogenization), in fluid inclusions in sphalerite and quartz from the Vegerbol vein in Värmskog.

ÅJ 80:56, while several other CO<sub>2</sub>-rich inclusions in that sample leaked before homogenization. The quartz inclusions homogenizing around +100 to +150°C are interpreted as secondary. The inclusions in the sphalerite all homogenized in the range +60 to +140°C, with the exception of one CO<sub>2</sub>-bearing inclusion in sample ÅJ 80:53 which homogenized around +190°C (for the other CO<sub>2</sub>-bearing inclusions in that sample no final homogenization temperature could be recorded because of poor visibility). Although the sphalerite texturally appears later than the quartz (filling vugs etc. in the quartz) and thus may have formed at lower temperatures, and although a formation temperature for sphalerite around +100°C is not unreasonable, the measured fluid inclusions probably were secondary and the formation temperature of the sphalerite higher than the +60 to +140°C range recorded. The inclusions apparently contain cooled ore fluid, and some of them heated ground water (cf. Fig. 12).

No pressure correction has been applied to the homogenization data, as the depth and pressure of formation of the Vegerbol deposit is unknown. The 190–330°C range recorded in the Vegerbol quartz is thus a minimum estimate



of the formation temperature of the Vegerbol deposit, although the range in itself does not appear geologically unreasonable (cf. the 200–330°C range for epithermal Au-Ag-Cu-Pb-Zn vein and replacement deposits considered typical by Spooner 1981). The ore-forming fluid apparently was a CO<sub>2</sub>-bearing hydrothermal solution with about 4 wt % salt. Fig. 12 shows a plot of final homogenization temperature *versus* melting temperature for ice for those inclusions where both were recorded. It indicates the presence of cooler solution of similar salinity in many inclusions in sphalerite as well as quartz, but also the presence of heated non-saline ground water in some inclusions both in quartz and sphalerite. The presence of significant amounts of CO<sub>2</sub> in the ore fluid may suggest a contribution of metamorphic (Dalslandian) or magmatic (Bohus-type granite) fluid, although the carbon dioxide could also be derived from dissolution of carbonates by acid hydrothermal fluid.

### SULPHUR ISOTOPES

The sulphur isotope composition of galena, sphalerite, chalcopyrite and pyrite from the Vegerbol-Karlsbol vein in Värmskog, and of galena from other veins in Dalsland and Värmskog, has been analysed at the Swedish Museum of Natural History using standard methods (Robinson & Kusakabe 1975; Nord & Billström 1982). The absolute analytical error is estimated to be  $\pm 0.3$  per mil (Nord & Billström 1982). The results are presented in Table 7 and Fig. 13.

The Vegerbol-Karlsbol sulphides (24 analyses) have  $\delta^{34}\text{S}$ -values between  $-2.7$  and  $+2.2$  per mil *versus* CDT, with the exception of one sphalerite sample from Karlsbol with  $-9.0$  per mil. Generally, the Vegerbol galena has a lighter sulphur isotope composition (i.e. lower  $\delta^{34}\text{S}$ ) than the other sulphides, but sulphide pairs from the same hand specimen give a wide variety of temperature estimates, indicating that full isotopic equilibrium between sulphides was not reached on that scale. Galena from Näsgruvan and Södra Gärdsjö (Värmskog) is a few per mil lighter than the Vegerbol-Karlsbol galena, while galena in the Dalsland veins is even lighter, between  $-6$  and  $-18$  per mil *versus* CDT.

It is likely that sulphide (H<sub>2</sub>S) rather than sulphate was the dominant sulphur species in the Vegerbol-Karlsbol ore solution. This means that  $\delta^{34}\text{S}$  of the total sulphur in solution probably was within a few per mil of zero (cf. Ohmoto 1972), which would indicate that the sulphur probably was of igneous origin in Vegerbol-Karlsbol (cf. Ohmoto & Rye 1979). This in turn would either mean magmatic sulphur derived directly from fluids emanating from late Dalslandian Bohus-type granite and pegmatite, or, perhaps more likely, sulphur of ultimate igneous origin derived by leaching of the surrounding gneisses. The much lighter sulphur isotope composition of the Dalsland galenas may be explained by a contribution of light sedimentary sulphur to these

TABLE 7. Sulphur isotope composition of Dalsland and Värmskog sulphides.

Deposit	Sample	$\delta^{34}\text{S}$ vs. CDT (per mil)				Description of hand specimen
		ga	cpy	sp	py	
D A L S L A N D						
1. Ingribyn	ÅJ 79:132	-8.5				Galena in quartz
2. Åskekärr	ÅJ 79:191	-8.1				Ga in qz vein in porphyry
	ÅJ 79:192	-6.6				Ga+cpy in qz vein in altered porphyry
	ÅJ 79:194	-6.6				Ga in qz veinlets in altered porphyry
3. Hoppets gruva	ÅJ 79:161	-14.9				Qz+ga+carbonate+sericite gouge fragments
6. Totten	ÅJ 79:211	-9.8				Qz, cpy, ga, minor bn and py
7. St. Kilane	ÅJ 79:232	-11.6				Qz with ga and bn
8. Björbyn	ÅJ 79:239	-6.8				Galena in quartz
9. Slädekärr	ÅJ 79:253	-11.3				Qz with cc+ga+cpy+altered wall-rock fragments
	ÅJ 79:254	-18.1				Qz with cc+ga+cpy+py+fa+altered wall-rock fragments (porphyry)
	ÅJ 79:255	-18.3				Qz with cc+ga+cpy+altered wall-rock fragments
V Ä R M S K O G						
10. Vegerbol	ÅJ 79:285	-2.4		-0.2	+2.2	Qz with ga, sp, py, cpy
	ÅJ 79:291			0.0		Qz with sp, cc and minor ga
	ÅJ 79:292	-2.2			0.0	Qz with ga and py
	ÅJ 79:294			+0.2		Qz with sp, py, ga and minor cpy
	ÅJ 79:295	-1.4			+0.3	Qz with ga and py
	ÅJ 79:296	-1.9	-0.2	+0.3	+0.3	Qz with ga, py, sp, cpy
	ÅJ 79:301	-1.8				Qz with ga and sp, minor py and cpy
	ÅJ 80:50	-1.1				Qz with ga and py
	ÅJ 80:51				+1.1	Py in chloritized wall-rock gneiss
	ÅJ 80:52		+0.9	+1.8		Qz with sp, cpy, ga
ÅJ 80:53	-1.1				Qz with sp and ga, minor py	
ÅJ 80:56	-2.0				Qz with ga and py	
11. Karlsbol	ÅJ 79:319			-2.7	+0.8	Sp, py, ga, minor he, in strongly altered wall-rock gneiss (qz-sericite rock)
	ÅJ 79:320	-1.2				Qz with sp and ga
ÅJ 79:325				-9.0		Qz with sp and py
12. Näsgruvan	ÅJ 79:350	-4.7				Quartz with galena
	ÅJ 79:351	-4.9				Qz with carbonate, ga, sp, minor py
13. S. Gärdsjö	ÅJ 79:342	-6.5				Qz veinlets with carbonate, ga, cpy in altered wall-rock gneiss

Estimated analytical uncertainty:  $\pm 0.3$  per mil (absolute value).

Mineral abbreviations: qz = quartz, cc = calcite, ga = galena, cpy = chalcopyrite, sp = sphalerite, py = pyrite, bn = bornite, fa = fahlerz, he = hematite.

veins from the Åmål or Dalsland Group metasediments, or by more oxidizing conditions during galena precipitation, with the presence of some sulphate in the solution. The latter hypothesis is attractive because of the occurrence of barite in Slädekärr (also reported from Totten in Dalsland and Södra Gärdsjö in Värmskog; cf. Fig. 4) as well as other minerals indicating more oxidizing conditions (magnetite, hematite etc.) in veins showing light sulphur isotope values of galena.

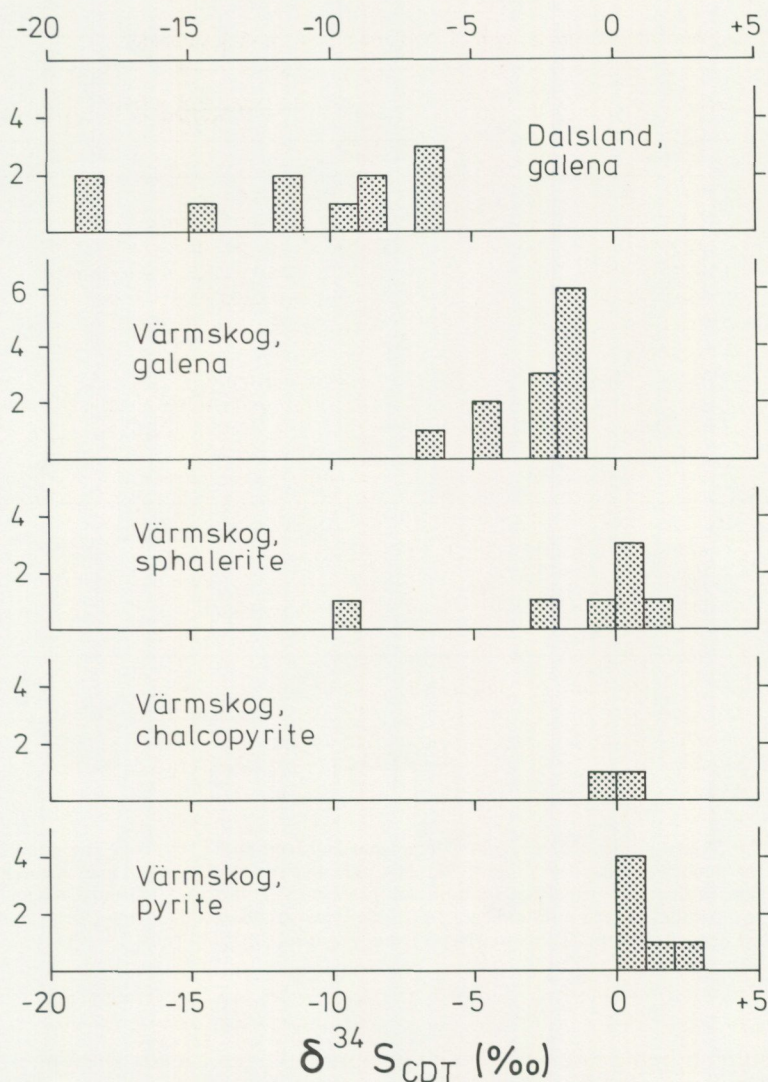


Fig. 13. Histograms of sulphur isotope values from sulphides in the Dalsland and Värmskog veins (Table 7). Except for the three galenas containing the lightest sulphur in Värmskog, all Värmskog sulphides are from the Vegerbol-Karlsbol vein system.

Fig. 14 shows a plot of  $\delta^{34}\text{S}$  vs.  $^{206}\text{Pb}/^{204}\text{Pb}$  for galena samples analysed both for lead and sulphur isotope composition. Only four of the galena samples from Vegerbol-Karlsbol (nos. 10–11 in Fig. 14) were analysed for both isotopes, but the total range of lead and sulphur isotope compositions recorded in galena from there is indicated by the box in Fig. 14. Most lead and sulphur isotope values from Dalsland and some from Värmskog appear to fall along a linear trend, indicated by two parallel dashed lines in the figure, with the

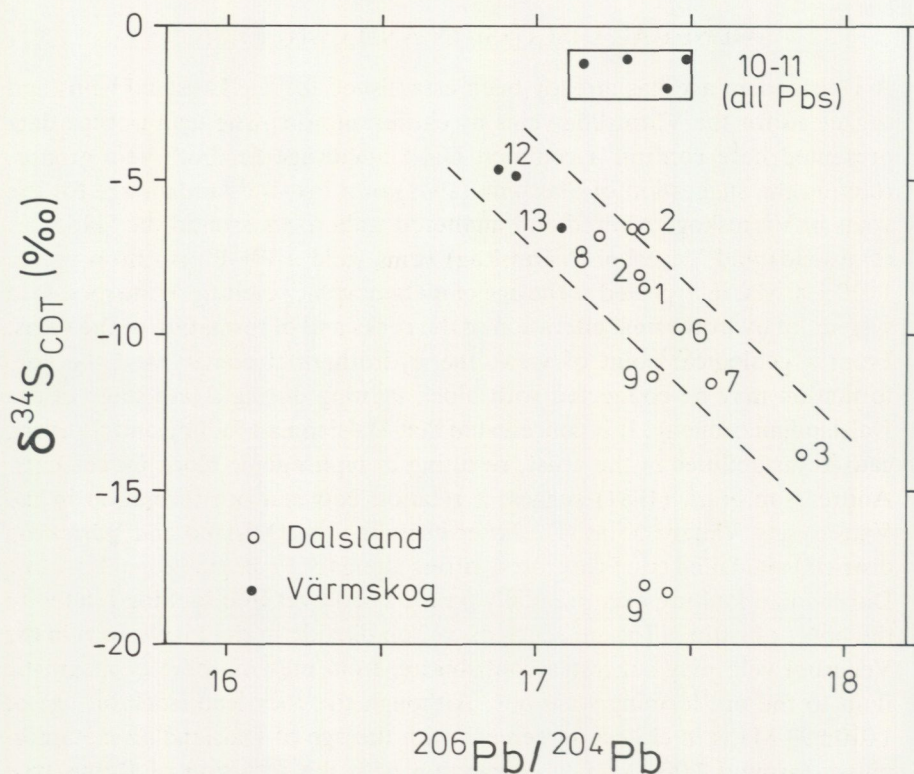


Fig. 14. Plot of  $\delta^{34}\text{S}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  in galena from Dalsland and Värmskog. The numbering refers to the deposit numbers in Table 1. The box indicates the total range of lead and sulphur isotope values in galenas not analysed for both isotopes from Vegerbol (No. 10) and Karlsbol (No. 11). The two parallel dashed lines indicate a possible linear trend encompassing galena from all investigated deposits except Slädekärr (No. 9) and Vegerbol-Karlsbol (nos. 10-11).

lighter sulphur being associated with the more radiogenic lead. The Vegerbol-Karlsbol galenas (nos. 10-11) and two of the Slädekärr galenas (No. 9), however, fall markedly outside the trend on opposite sides. Oxidation of sulphur, leading to lighter sulphide sulphur, should not affect the lead isotopes directly, but a process where the ore solutions gradually leached more radiogenic lead from the source rocks and at the same time gradually became more oxidized, or *vice versa*, may be envisaged to explain the trend. Alternatively, mixing of lead and sulphur from two different sources (rock units), one with light sulphur and more radiogenic lead, the other with heavier sulphur and less radiogenic lead, may be suggested. In either case, the deviation of some deposits from the trend points to the complexities involved in the isotope geochemistry of these veins.

## GENERAL DISCUSSION AND CONCLUSIONS

A Dalslandian age has already been established for the Dalsland veins and suggested for the Värmskog veins by earlier authors. The lead isotope data presented here confirm a common Dalslandian age for both vein groups, refuting the suggestion of Sherbina (1941) of a Pre-Dalslandian age for the veins in Värmskog. Altered and unaltered wall-rocks around the Slädekärr (Dalsland) and Vegerbol (Värmskog) veins yield a Pb–Pb isochron age of  $1010 \pm 90$  Ma, interpreted as the age of metamorphic resetting of the rock-lead system, of hydrothermal alteration of the rocks and of formation of the veins. From a geological point of view, the hydrothermal activity and the vein formation may be connected with block faulting during a late stage of the Dalslandian orogeny. It is conceivable that Dalslandian folding and thrusting caused instabilities in the crust, resulting in taphrogenic block movements. Andreasson *et al.* (1984) suggest a relation between ore formation in the Vättern and Vänern areas (the latter including the Dalsland and Värmskog districts) and failed late Proterozoic rifting along the Protogine zone. If so, late Dalslandian faulting may gradually have passed over into faulting related to the onset of rifting. The presence of carbon dioxide in fluid inclusions in the Vegerbol vein may suggest a contribution from metamorphic or magmatic fluid to the ore-forming solutions. Although the rock-lead isochron age of  $1010 \pm 90$  Ma is in closest agreement with the age of Dalslandian metamorphism (around 1000 Ma), a connection with the intrusion of Bohus-type granite and pegmatites in southwest Sweden around 900 Ma BP, as suggested by Wickman *et al.* (1963), may be as likely. The more pegmatitic character of the Cu veins in Värmskog, as reported by Tegengren *et al.* (1924) and Jongejan & Westerveld (1949), would support such an interpretation.

The lead isotope data point to a crustal source of at least Mid-Proterozoic age for the ore lead. It is likely that the source of metals, and possibly also sulphur, was the rocks of the southwest Swedish gneiss complex and the Åmål Complex hosting most veins. Sulphur isotope compositions of vein sulphides were, however, modified by redox reactions in the ore solution or mixing with lighter, sedimentary sulphur. Data on wall-rock geochemistry mostly show an enrichment of metals and sulphur in the alteration zones adjacent to the veins, suggesting that the source was not the immediate wall-rocks of the veins but rocks further away traversed by the hydrothermal solutions on their way. The marked wall-rock alteration, with breakdown of feldspar and mafic minerals, created a quartz-sericite zone adjacent to the veins and, where mafic minerals were more abundant, also an outer chloritization zone. Chemically, the alteration caused a drastic depletion of sodium, while many other constituents (such as  $\text{SiO}_2$  and CaO) may show either relative enrichment or relative depletion. The sericitization produced free quartz in the alteration zones and in the veins

themselves. It also produced calcium to form calcite, ankerite and fluorite in the veins, and iron to form pyrite and other Fe-bearing sulphides, hematite, magnetite, chlorite, ankerite or siderite. Potassium was taken up by the sericite forming in the wall-rocks, while sodium was lost to the fluid in exchange for  $H^+$ . The increasing pH of the ore solution as wall-rock alteration proceeded promoted sulphide and carbonate precipitation, thereby explaining the general paragenetic sequence, with sulphides and carbonates following quartz in the veins.

Fluid inclusion studies indicate that the ore-forming solution, at least in Vegerbol, was a weakly saline (c. 4 eq. wt% NaCl),  $CO_2$ -bearing hydrothermal fluid. They also indicate the presence of some heated, non-saline ground water. Quartz deposition at Vegerbol occurred at a minimum temperature (no pressure correction added) of +190 to +330°C, while the temperature of sphalerite deposition is more uncertain. In Fig. 15, a  $\log fO_2$  versus pH diagram for +250°C has been compiled from Ohmoto (1972) and Barton *et al.* (1977), and mineralogical and geochemical data have been used to reconstruct the chemical environment of formation of these veins.

The environment of quartz and sulphide deposition at Vegerbol was probably in the lower part of the crosshatched area in Fig. 15 ( $\log fO_2$  around -38 at 250°C, pH between 5 and 6, i.e. approximately neutral at this temperature). The area is limited by the conversion of K-feldspar to muscovite (sericite) in the wall-rock, the presence of less than 3.2 mole per cent FeS in the sphalerite (Johansson 1983a), and the constant sulphur isotope values of the Vegerbol sulphides, suggesting an environment below the sulphide-sulphate transition zone (shaded band in Fig. 15) where sulphide totally dominates the ore solution. The presence of carbon dioxide, rather than methane, also limits the environment to oxygen fugacities above -39 (cf. Ohmoto 1972). The environment in Slådekärr may have been slightly more oxidizing than at Vegerbol, somewhere in the upper part of the crosshatched area crossing the sulphide-sulphate boundary. This is suggested by the presence of bornite in addition to chalcopyrite in Slådekärr, the occurrence of barite, and the lower and apparently more variable sulphur isotope ratios of the Slådekärr galena.

Wall-rock reactions would tend to increase the pH of the ore solution, moving it towards and into the K-feldspar stability field, thereby promoting sulphide and carbonate precipitation. Mixing with ground water could lead to a more oxidized environment. These effects are indicated by the two arrows in Fig. 15. Thus, during the final stages of mineral precipitation, the chemical environment may have moved towards the upper right in Fig. 15, causing the precipitation of hematite, magnetite, chlorite or Fe-bearing carbonates (ankerite or siderite). According to Barton *et al.* (1977), chlorite may form instead of magnetite under certain conditions, and siderite may overtake the magnetite field at high  $CO_2$  fugacities and lower temperatures according to Holland

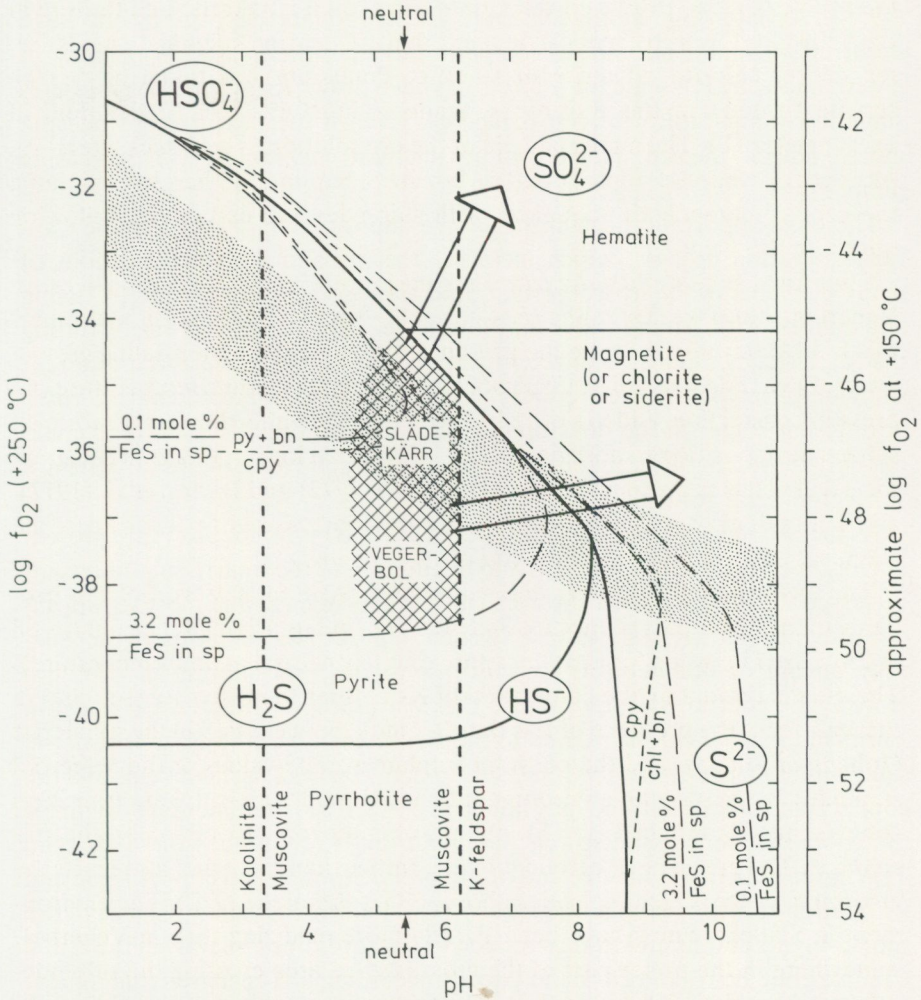


Fig. 15. Log  $f_{O_2}$  versus pH-diagram for  $+250^\circ\text{C}$ , compiled from the diagrams of Ohmoto (1972) and Barton *et al.* (1977). The shaded band marks the transition zone from reduced to oxidized sulphur in solution, and the encircled symbols show the dominant sulphur species in solution. Solid lines indicate Fe mineral stability boundaries at  $S_{\text{tot}} = 0.02$  molal (from Barton *et al.* 1977). At certain conditions, Fe chlorite (Barton *et al.* 1977) or siderite (Holland 1959) may overtake the magnetite field. Kaolinite - muscovite - K-feldspar boundaries from Ohmoto (1972), chalcopyrite stability field (cpy = chalcopyrite, py = pyrite, bn = bornite, chl = chlorite) from Barton *et al.* (1977). Barite is stable above the sulphide-sulphate transition zone. Long dashed lines show 0.1 and 3.2 mole per cent FeS in sphalerite at 50 bars (Barton *et al.* 1977). The lower part of the cross-hatched area is the inferred environment of quartz and sulphide deposition in Vegerbol, and the upper part that in Slädekärr. The two arrows suggest a late-stage development with increase in pH and/or mixing with oxidized ground water. At the right-hand side, a scale of approximate  $\log f_{O_2}$  values at  $+150^\circ\text{C}$  (presumed late low-temperature stage) has been drawn.

(1959). As late-stage sulphide, oxide and carbonate deposition may have occurred at significantly lower temperatures than the quartz deposition, an approximate log  $fO_2$  scale for +150°C has been drawn to indicate possible late-stage low-temperature oxygen fugacities. Even if the environment became more oxidized, the actual log  $fO_2$  values decrease very rapidly with decreasing temperature.

The most important mechanism for ore deposition appears to be the wall-rock alteration process, which increases the pH and the concentrations of many elements in the hydrothermal fluid and produces free quartz. Cooling and dilution with ground water may also have played a role, especially during the later stages. Veins of different mineralogy, such as the three different sulphide vein types of Tegengren *et al.* (1924) in Dalsland, could have formed at different stages in the development of a hydrothermal system, and could possibly represent different erosional levels through vein systems displaying a vertical mineral zoning.

As mentioned earlier, different types of Cu and Fe-Mn deposits are present in Dalsland and southwest Värmland in addition to the quartz-sulphide veins discussed here. This makes the area west of lake Vänern the most significant ore province known in southwest Sweden, a part of Sweden otherwise generally devoid of ore deposits, in contrast to the Precambrian of southern Norway or central Sweden. While the Värmskog and Glava Cu veins in Värmland may be closely related to the Värmskog Pb-Zn veins as part of the same mineralizing event, the relationship between the Dalsland veins and the copper shale of Stora Strand may not be as close, if a synsedimentary origin for the copper shale is assumed (cf. discussion by H. E. Johansson, 1908, and Tegengren, 1944a, on the age and origin of the Stora Strand copper shale and its relation to the vein mineralization). The Fe-Mn deposits in Dalsland are replacements and fissure fillings related to fracture zones, mainly in the Åmål Complex but also in the Dalsland Group, according to Tegengren *et al.* (1924) and Geijer (1961). The occurrence of Cu sulphide mineralization inside some of the Fe-Mn ores (Kesebol, Spethult; Tegengren *et al.* 1924, Geijer 1961) may indicate a connection between the Fe-Mn mineralization and the formation of the quartz-sulphide veins. In any case, at least in a broader sense the sulphide-bearing quartz veins of Dalsland and Värmskog can be considered part of a Dalslandian metallogenic province and epoch encompassing several other types of ore as well.

## ACKNOWLEDGEMENTS

This study had not been possible without the assistance of many persons both at the Department of Geology of the University of Stockholm and elsewhere. Boliden Mineral AB and the Geological Survey of Sweden (SGU) contributed with unpublished maps and reports, and drill core samples were obtained from SGU through the permission of Göran Petersson (now at Studsvik Analytica AB, Stockholm) and Paul Hammergren (now at Sveriges Geologiska AB, Uppsala). Chemical rock analyses were made by the CNRS-CRPG in Nancy, France. The access to the isotope laboratories of the USGS in Denver and the Museum of Natural History in Stockholm and the assistance given by people there, especially Maryse Delevaux in Denver and Kjell Billström in Stockholm, is gratefully acknowledged. At the Department of Geology, Britta Hedengran carried out XRD identifications of minerals and Ragnheidur Olafsdottir assisted with XRF analyses. Polished thin sections were made by Gösta Fastrup, Conny Jonsson, Allan Stråhle and Fernando Miranda. Fernando Miranda also made the double polished "thick" thin sections necessary for the fluid inclusion work. Discussions of fluid inclusion results with Sten Lindblom, Curt Broman and Lennart Sjöberg and of sulphur isotopes with Peter Torssander and Kjell Billström were of great value. The drawings were made by Solveig Jevall and Inger Arnström, and Kristina Edström typed the manuscript.

An earlier version of this paper formed a part of my Ph. D.-thesis on lead-zinc veins in Sweden and was critically discussed by Eric Welin during my doctoral disputation. The manuscript was also read and discussed by David Rickard, Per-Gunnar Andreasson and Bengt Lindqvist. The study was financed by the Swedish Board for Technical Development (STU) and the University of Stockholm and was supervised by David Rickard (now at University College, Cardiff), whose support and critical discussions were indispensable to the final result. Publication in SGU series C was supported economically by the Swedish Natural Science Research Council (NFR) and the Swedish Board for Technical Development (STU). All this support is gratefully acknowledged.

## REFERENCES

GFF = Geologiska Föreningens i Stockholm Förhandlingar  
 SGU = Sveriges geologiska undersökning

- ANDREASSON, P.-G., SOLYOM, Z. & JOHANSSON, I., 1984: Geodynamic significance of Mn-Fe-Ba and Pb-Zn-Cu-Ag mineralizations along the Protogine Zone and parallel lineaments, southern Sweden. – Manuscript, Department of Mineralogy and Petrology, University of Lund, 24 pp.
- BARTON, P. B., BETHKE, P. M. & ROEDDER, E., 1977: Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado: Part III. Progress toward interpretation of the chemistry of the ore-forming fluid for the OH vein. – *Econ. Geol.* 72, pp. 1–24.
- BORISENKO, A. S., 1974: Determination of sodium carbonates and bicarbonates in solutions of gas-liquid inclusions in minerals. – *Doklady Akad. Nauk SSSR* 214, pp. 208–211.
- BOZZO, A. T., CHEN, H.-S., KASS, J. R. & BARDUHN, A. J., 1973: The properties of the hydrates of chlorine and carbon dioxide. – *In* A. DELYANNIS and E. DELYANNIS (Eds.): 4th International Symposium on Fresh Water from the Sea 3, pp. 437–451. Athens.
- COLLINS, P. L. F., 1979: Gas hydrates in CO<sub>2</sub>-bearing fluid inclusions and the use of freezing data for estimation of salinity. – *Econ. Geol.* 74, pp. 1435–1444.
- CRAWFORD, M. L., 1981: Phase equilibria in aqueous fluid inclusions. – *In* L. S. HOLLISTER & M. L. CRAWFORD (Eds.): Short course in fluid inclusions: Applications to petrology, pp. 75–100. Mineralogical Association of Canada.
- DOE, B. R. & DELEVAUX, M., 1980: Lead isotope investigations in the Minnesota River Valley – late-tectonic and post-tectonic granites. – *Geol. Soc. America Spec. Paper* 182, pp. 105–112.
- FRIETSCH, R., 1975: Brief outline of the metallic mineral resources of Sweden. – SGU C 718, 64 pp.
- GEIJER, P., 1961: The manganese, iron and copper mineralization at Kasebol in Dalsland, southwestern Sweden. – *Bull. Geol. Inst. Univ. Uppsala* 40, pp. 37–49.
- GORBATSCHEV, R., 1975: Fundamental subdivisions of Precambrian granitoids in the Åmål Mega-unit and the evolution of the south-western Baltic Shield, Sweden. – GFF 97, pp. 107–114.
- GORBATSCHEV, R., 1977: Correlation of Precambrian supracrustal complexes in south-western Sweden and the sequence of regional deformation events in the Åmål tectonic Mega-unit. – GFF 99, pp. 336–346.
- GORBATSCHEV, R., 1980: The Precambrian development of southern Sweden. – GFF 102, pp. 129–136.
- GOVINDARAJU, K., MEVELLE, G. & CHOUARD, C., 1976: Automated optical emission spectrochemical bulk analysis of silicate rocks with microwave plasma excitation. – *Analytical Chemistry* 48, p. 1325–1331.
- GRIP, E., 1978: Sweden. – *In* S. H. U. BOWIE, A. KVALHEIM & H. W. HASLAM (Eds.): Mineral deposits of Europe, volume I, Northwest Europe, pp. 93–198. The Institution of Mining and Metallurgy and The Mineralogical Society, London.
- HOLLAND, H. D., 1959: Some applications of thermochemical data to problems of ore deposits. I. Stability relations among the oxides, sulfides, sulfates and carbonates of ore and gangue metals. – *Econ. Geol.* 54, pp. 184–233.
- JAKOBSEN, H., MUNKSGAARD, N. C. & ZECK, H. P., 1983: Pre-Dalslandian deformation and recrystallization in the basement of the Dalslandian supracrustals, Grenvillian (Sveconorwegian) Belt, south-west Sweden. – GFF 105, pp. 205–212.
- JOHANSSON, H. E., 1908: Om kopparmalmsförekomsterna vid Stora Strand i Dalsland. – SGU C 214, 35 pp.
- JOHANSSON, Å., 1981: Isotopic composition of lead from the Boda and Sollerön deposits, Siljan Ring area, central Sweden. – *In* D. T. RICKARD (Ed.): ORG 81 – Annual Report of the Ore Research Group, Stockholm University, 1981, pp. 199–218.
- JOHANSSON, Å., 1983a: Composition of sphalerite in some Swedish Pb-Zn-bearing veins. – *In* S. LINDBLOM (Ed.): ORG 83 – Annual Report of the Ore Research Group, Stockholm University, 1983, pp. 117–150.
- JOHANSSON, Å., 1983b: Lead isotope composition of Caledonian sulfide-bearing veins in Sweden. – *Econ. Geol.* 78, pp. 1674–1688.
- JOHANSSON, Å. & RICKARD, D. T., 1984: Isotopic composition of Phanerozoic ore leads from the Swedish segment of the Fennoscandian Shield. – *Mineralium Deposita* 19, pp. 249–255.
- JOHANSSON, Å. & RICKARD, D. T., 1985: Some new lead isotope determinations from the Proterozoic sulfide ores of central Sweden. – *Mineralium Deposita* 20, pp. 1–7.
- JONGEJAN, A. & WESTERVELD, J., 1949: A few data on the copper ore deposits near Värmskog in Värmland, Sweden. – GFF 71, pp. 577–594.

- LUNDEGÅRDH, P. H., 1980: The gneissic granites and allied rocks in central and northwestern Värmland, western Sweden. – SGU C 777, pp. 3–23.
- LUNDEGÅRDH, P. H., GORBATSHEV, R. & LINDH, A., 1983: Beskrivning till översiktlig berggrunds-karta. *In* Berg och malm i Värmlands län. – SIND PM 1983:8, Statens Industriverk, Stockholm, pp. 1–31.
- LUNDQVIST, TH., 1979: The Precambrian of Sweden. – SGU C 768, 87 pp.
- MAGNUSSON, N. H., 1953: Malmgeologi. – Jernkontoret, Stockholm, 439 pp.
- MAGNUSSON, N. H., 1973: Malm i Sverige 1, Mellersta och södra Sverige. – Almqvist & Wiksell, Stockholm, 320 pp.
- MAGNUSSON, N. H., *et al.*, 1957: Karta över Sveriges berggrund / Map of the pre-Quaternary rocks of Sweden. – SGU Ba 16.
- NORD, A. G. & BILLSTRÖM, K., 1982: A system for stable isotope analyses of geological samples. – GFF 104, pp. 113–120.
- NORDENSTRÖM, G., 1881: Om Värmskogs och angränsande socknars silfver- och kopparmalms-gångar i västra Vermland. – GFF 5, pp. 455–469.
- OHMOTO, H., 1972: Systematics of sulfur and carbon isotopes in hydrothermal ore deposits. – Econ. Geol. 67, p. 551–579.
- OHMOTO, H. & RYE, R. O., 1979: Isotopes of sulfur and carbon. – *In* H. L. BARNES (Ed.): Geochemistry of hydrothermal ore deposits, 2nd edition, p. 509–567. John Wiley & Sons, New York.
- POY, B., LEROY, J. & JACHIMOWICZ, L., 1976: Un nouvel appareil pour la mesure des températures sous le microscope: l'installation de microthermometrie Chaixmeca. – Bull. Soc. fr. Mineral. Cristallogr. 99, pp. 182–186.
- ROBINSON, B. W. & KUSAKABE, M., 1975: Quantitative preparation of sulfur dioxide for  $^{34}\text{S}/^{32}\text{S}$  analyses from sulfides by combustion with cuprous oxide. – Analytical Chemistry 47, pp. 1179–1181.
- ROEDDER, E., 1972: Composition of fluid inclusions. – *In* M. FLEISCHER (Ed.): Data of geochemistry, 6th edition, U.S. Geol. Survey Prof. Paper 440-JJ, 164 pp.
- SHERBINA, A. S., 1941: Die Goldreiche Kupferglanz-Bornit-Lagerstätte von Glava in Vermland, Schweden, und ihre geologische Stellung. – Neues Jahrb. Mineral. Geol. Paläont., Abt. A, 76, pp. 377–458.
- SKIÖLD, T., 1976: The interpretation of the Rb-Sr and K-Ar ages of Late Precambrian rocks in south-western Sweden. – GFF 98, pp. 3–29.
- SPOONER, E. T. C., 1981: Fluid inclusion studies of hydrothermal ore deposits. – *In* L. S. HOLLISTER & M. L. CRAWFORD (Eds.): Short course in fluid inclusions: Applications to petrology, pp. 209–240. Mineralogical Association of Canada.
- STACEY, J. S. & KRAMERS, J. D., 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. – Earth Planet. Sci. Letters 26, pp. 207–221.
- STRECKEISEN, A., 1976: Classification of the common igneous rocks by means of their chemical composition: A provisional attempt. – Neues Jahrb. Mineral., Monatshefte 1976 no. 1, pp. 1–15.
- TEGENGREN, F. R., 1944a: Rapport rörande sulfidmalmsförekomsterna i Dalsland. – Unpublished report, Boliden Mineral AB, Boliden, 13 pp.
- TEGENGREN, F. R., 1944b: Rapport rörande Värmskogs och Glava sulfidmalmsgångar i västra Värmland. – Unpublished report, Boliden Mineral AB, 10 pp.
- TEGENGREN, F. R., 1956: Fennoskandias postkarelska bly-zink-malmsförekomster. – Unpublished report, Boliden Mineral AB.
- TEGENGREN, F. R., *et al.*, 1924: Sveriges ädlare malmer och bergverk. – SGU Ca 17, 406 pp.
- WELIN, E., 1979: Tabulation of recalculated radiometric ages published 1960–1979 for rocks and minerals in Sweden. – GFF 101, pp. 309–320.
- WICKMAN, F. E., BLOMQUIST, N. G., GEJER, P., PARWEL, A., VON UBISCH, H. & WELIN, E., 1963: Isotopic constitution of ore lead in Sweden. – Arkiv för Mineralogi och Geologi (KVA) 3–11, pp. 193–257.
- ZARTMAN, R. E. & DOE, B. R., 1981: Plumbotectonics – the model. – Tectonophysics 75, pp. 135–162.

## Appendix I-A: Description of rock samples for chemical analysis; Ingribyn, Äskekärr, St. Kilane and Björbyn.

Deposit	Sample no.	Location	Rock description	Normative classification <sup>1</sup> (based on Streckeisen, 1976)
1. Ingribyn	AJ 79:136	Dump at mine	Green sericitized gneiss	-
	AJ 79:137	Dump at mine	Green and red gneiss	(Syeno-)granite
	AJ 79:139	Outcrop 300 m south mine	Green and red gneiss	(Monzo-)granite
2. Äskekärr	AJ 79:190	Dump at mine	Greenish, sericitized porphyry	Rhyodacite
	AJ 79:191	Dump at mine	Red qz-fsp porphyry	Rhyolite
	AJ 79:199	Outcrop 100 m NW of mine	Red qz-fsp porphyry	Rhyodacite or rhyolite
7. St. Kilane	AJ 79:215	Dump at mine	Normal phyllite (quartz-muscovite-carbonate schist)	-
	AJ 79:216	Dump at mine	Calcified and silicified phyllite (quartz-carbonate rock)	-
	AJ 79:217	Dump at mine	Strongly calcified phyllite (quartz-carbonate rock)	-
	AJ 79:221	Dump at mine	Strongly silicified phyllite (quartz-muscovite rock)	-
8. Björbyn	AJ 79:236	Dump at W mine	Silicified greenstone with sulphide impregnation	-
	AJ 79:237	Dump at W mine	Silicified greenstone with sulphide impregnation	-
	AJ 79:244	Outcrop 80 m S of western mine	Greenstone (relatively fresh)	Monzodiorite
	AJ 79:247	Dump at E mine	Calcified greenstone	-

1. No normative classification for metasediments and heavily altered rocks.

## Appendix I-B: Description of rock samples for chemical analysis; Slädekärr, drill core 80002.

Sample no.	Position in drill core <sup>1</sup>	Distance to vein <sup>1</sup>	Rock description	Normative classification <sup>2</sup> (based on Streckeisen, 1976)
AJ 80:75	36.2 m	14.7 m	Red qz-fsp porphyry	Rhyolite
AJ 80:76	44.3 m	6.6 m	Red qz-fsp porphyry	Rhyolite
AJ 80:77	46.8 m	4.1 m	Red qz-fsp porphyry	Rhyolite
AJ 80:78	48.5 m	2.4 m	Red qz-fsp porphyry	Rhyolite
AJ 80:79	49.5 m	1.4 m	Red qz-fsp porphyry with narrow qz veinlets	Rhyolite (altered)
AJ 80:80	50.0 m	0.9 m	Altered porphyry (green quartz-sericite rock)	-
AJ 80:81	50.8 m	0.1 m	Altered porphyry (green quartz-sericite rock)	-
Vein: 50.9 - 52.1 m				
AJ 80:82	52.5 m	0.4 m	Partly altered porphyry	Rhyolite (altered)
AJ 80:83	53.7 m	1.6 m	Red qz-fsp porphyry with narrow qz veinlets	Rhyolite (altered)
AJ 80:84	56.0 m	3.9 m	Reddish grey qz-fsp porphyry	Rhyodacite or dacite
AJ 80:85	59.8 m	7.7 m	Reddish grey qz-fsp porphyry	Rhyodacite

1.  $\pm$  0.1 to 0.2 m. Distance to vein measured along drill core (= maximum true distance).

2. No normative classification for heavily altered samples.

Appendix I-C: Description of rock samples for chemical analysis; Vegerbol, drill core 80204<sup>1</sup>.

Sample no.	Position in drill core <sup>2</sup>	Distance to vein <sup>2</sup>	Rock description	Normative classification <sup>3</sup> (based on Streckeisen, 1976)
AJ 80:58	29.3 m	13.2 m	Light, acidic gneiss	(Monzo-)granite
AJ 80:59	36.0 m	6.5 m	Intermediate gneiss	Granodiorite
AJ 80:60	39.6 m	2.9 m	Intermediate gneiss	Monzodiorite
AJ 80:61	41.3 m	1.2 m	Slightly chloritized intermediate gneiss	Monzonite
AJ 80:62	41.6 m	0.9 m	Strongly altered gneiss (quartz-sericite rock)	-
AJ 80:63	42.4 m	0.1 m	Strongly altered, mineralized quartz-sericite rock	-
Vein:	42.5 - 43.7 m			
AJ 80:64	43.8 m	0.1 m	Strongly altered, mineralized quartz-sericite rock	-
AJ 80:65	44.3 m	0.6 m	Strongly altered, mineralized quartz-sericite rock	-
AJ 80:66	44.6 m	0.9 m	Chloritized, pegmatitic gneiss	-
AJ 80:67	45.4 m	1.7 m	Pegmatitic gneiss	(Monzo-)granite, granodiorite or tonalite
AJ 80:68	47.8 m	4.1 m	Intermediate gneiss	Granodiorite
AJ 80:69	50.0 m	6.3 m	Intermediate gneiss	Diorite or monzodiorite
AJ 80:70	53.4 m	9.7 m	Intermediate gneiss	Granodiorite

1. Drill core named "Karlsbol 80 204" by Geol. Survey of Sweden, although being from the Vegerbol segment of the Vegerbol-Karlsbol vein.

2.  $\pm$  0.1 to 0.2 m. Distance to vein measured along drill core (= maximum true distance).

3. No normative classification for heavily altered samples.

## Appendix II-A: Chemical composition of altered and unaltered wall-rock samples; Ingribyn, Åskekärr, St. Kilane and Björbyn.

Deposit	Ingribyn				Åskekärr			St. Kilane				Björbyn			
	Sample no. 1)	79:136	79:137	79:139	79:190	79:191	79:199	79:215	79:216	79:217	79:221	79:236	79:237	79:244	79:247
Anal. method	2)	2)	2)	2)	2)	2)	2)	3)	3)	3)	2)	2)	2)	2)	
SiO <sub>2</sub>	wt. %	52.29	65.00	64.58	64.28	75.01	70.91	57.81	62.63	39.23	72.69	67.98	66.40	56.36	50.25
Al <sub>2</sub> O <sub>3</sub>	wt. %	21.32	14.73	14.48	15.64	13.04	14.80	13.38	9.62	0.75	5.28	14.72	14.53	16.19	16.98
Fe <sub>tot</sub>	wt. % 7)	6.38	3.93	3.96	3.62	1.11	2.03	6.36	-	-	-	4.04	3.51	6.70	9.81
FeO	wt. % 5)	(1.41)	(1.24)	(1.41)	(1.23)	(0.63)	(0.90)	(1.48)	0.86	0.58	1.08	(0.80)	(1.21)	(2.95)	(6.37)
Fe <sub>2</sub> O <sub>3</sub>	wt. % 5)	(4.81)	(2.55)	(2.39)	(2.25)	(0.41)	(1.03)	(4.72)	0.72	0.10	2.63	(3.15)	(2.17)	(3.42)	(2.73)
MnO	wt. %	0.09	0.08	0.08	0.10	0.03	0.07	0.05	0.05	0.11	0.05	0.07	0.06	0.15	0.23
MgO	wt. %	1.84	0.83	1.64	1.24	0.17	0.60	2.57	0.71	1.59	0.60	0.82	1.04	4.07	6.22
CaO	wt. %	1.83	2.65	1.86	2.88	0.09	2.04	4.41	9.88	30.30	7.75	1.92	1.18	5.39	2.90
Na <sub>2</sub> O	wt. %	0.08	3.05	3.66	2.45	2.58	3.40	3.23	4.38	0.38	0.16	2.96	2.92	3.42	3.58
K <sub>2</sub> O	wt. %	8.92	4.83	4.39	5.19	6.20	4.31	3.54	0.95	0.05	1.84	3.84	4.75	3.18	5.36
TiO <sub>2</sub>	wt. %	0.97	0.61	0.68	0.52	0.08	0.38	0.66	0.30	0.02	0.12	0.30	0.39	0.71	1.16
P <sub>2</sub> O <sub>5</sub>	wt. %	0.27	0.22	0.18	0.11	traces	0.07	0.22	0.08	0.11	0.40	0.11	0.13	0.30	0.34
loss on ign.		5.35	3.78	3.34	4.27	0.99	1.03	7.14	-	-	-	2.74	3.69	2.10	3.40
H <sub>2</sub> O	wt. %	-	-	-	-	-	-	-	0.91	0.43	1.38	-	-	-	-
CO <sub>2</sub>	wt. % 5)	(1.97)	(2.42)	(2.12)	(2.32)	(0.27)	(0.19)	(5.55)	8.70	26.11	5.97	(1.32)	(0.71)	(0.38)	(1.41)
S <sub>tot</sub>	wt. % 5)	(0.04)	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	0.01	0.08	0.01	(1.26)	(0.93)	(0.14)	(0.03)
Total 5)		99.34	99.71	98.85	100.30	99.30	99.64	99.37	99.80	99.84	99.96	99.50	98.60	98.57	100.23
Pb	ppm	11	25	13	38	2	23	7	154	155	43	387	1383	51	194
Zn	ppm	162	70	60	72	26	46	82	23	15	39	97	279	233	487
Cu	ppm 6)	(172)	(10)	(10)	30	(10)	(10)	(10)	28	10	32	(266)	(668)	54	22
Ba	ppm	1132	899	1139	1022	438	663	(10)	-	-	-	866	802	656	21
Rb	ppm	538	215	164	328	222	161	146	-	-	-	157	193	126	238
Sr	ppm	51	98	111	79	45	167	112	-	-	-	130	163	617	208
TiO <sub>2</sub>	wt. % 4)	0.79	0.57	0.62	0.51	0.12	0.30	0.79	0.42	0.00	0.14	0.36	0.36	0.80	1.21
Y	ppm 4)	91	40	40	22	16	28	34	24	15	28	25	44	18	22
Zr	ppm 4)	450	310	322	174	85	172	186	200	18	52	170	189	127	102
Rb	ppm 4)	550	204	158	318	197	154	144	29	0	77	154	177	135	243
Sr	ppm 4)	40	104	106	78	40	182	111	123	638	66	136	174	685	224

1) See Appendix I-A for sample descriptions.

2) Standard plasma excitation - optical emission spectrometry (Govindaraju et al., 1976) by CNRS-CRPG of major elements and Cu, Ba, Rb and Sr; special analysis by CNRS-CRPG of FeO, CO<sub>2</sub>, S<sub>tot</sub>, Pb and Zn; Fe<sub>2</sub>O<sub>3</sub> calculated from Fe<sub>tot</sub> and FeO.

3) Wet chemical analysis by CNRS-CRPG of major and trace elements (including FeO, Fe<sub>2</sub>O<sub>3</sub>, H<sub>2</sub>O, CO<sub>2</sub> and S<sub>tot</sub>).

4) XRF analysis of TiO<sub>2</sub>, Y, Zr, Rb and Sr at the Department of Geology, Stockholm.

5) Values in brackets not included in total.

6) Cu values in brackets (above 150 ppm) only approximate ("valeur indicative").

7) Fe<sub>tot</sub> = all Fe given as Fe<sub>2</sub>O<sub>3</sub>.

## Appendix II-B: Chemical composition of rock samples from drill core 80002, Slädekärr.

Sample no. <sup>1)</sup>	80:75	80:76	80:77	80:78	80:79	80:80	80:81	Vein	80:82	80:83	80:84	80:85
Distance to vein <sup>2)</sup>	14.7 m	6.6 m	4.1 m	2.4 m	1.4 m	0.9 m	0.1 m		0.4 m	1.6 m	3.9 m	7.7 m
SiO <sub>2</sub> wt. %	71.67	73.43	72.91	72.23	75.43	77.75	79.78		76.93	75.63	68.40	69.54
Al <sub>2</sub> O <sub>3</sub> wt. %	14.20	13.00	13.52	13.55	12.67	11.73	10.56		11.26	12.44	14.10	14.26
Fe <sub>tot</sub> wt. % <sup>3)</sup>	1.73	1.64	1.88	1.76	1.72	1.53	1.79		1.97	1.66	2.81	2.82
FeO wt. % <sup>3)</sup>	(0.59)	(0.61)	(0.79)	(0.59)	(0.66)	(0.43)	(0.91)		(0.92)	(1.09)	(1.43)	(1.39)
Fe <sub>2</sub> O <sub>3</sub> wt. % <sup>3)</sup>	(1.07)	(0.96)	(1.30)	(1.10)	(0.99)	(1.05)	(0.78)		(0.95)	(0.45)	(1.22)	(1.28)
MnO wt. %	0.06	0.04	0.05	0.04	0.02	0.02	0.03		0.03	0.03	0.08	0.06
MgO wt. %	0.44	0.39	0.54	0.41	0.22	0.27	0.41		0.40	0.34	1.06	0.86
CaO wt. %	0.94	0.53	0.47	0.79	0.01	traces	0.33		0.30	0.26	2.06	1.70
Na <sub>2</sub> O wt. %	2.68	2.30	2.13	2.47	1.54	0.24	0.06		1.70	2.37	2.01	2.55
K <sub>2</sub> O wt. %	5.73	5.79	5.89	5.29	4.72	5.09	3.91		3.96	4.51	5.06	4.31
TiO <sub>2</sub> wt. %	0.36	0.36	0.37	0.42	0.35	0.25	0.25		0.34	0.31	0.35	0.46
P <sub>2</sub> O <sub>5</sub> wt. %	traces	traces	traces	traces	traces	traces	traces		traces	0.02	traces	0.03
loss on ign. wt. % <sup>3)</sup>	1.97	1.64	2.00	2.07	2.30	2.13	2.39		1.89	1.76	4.26	3.44
CO <sub>2</sub> wt. % <sup>3)</sup>	(0.93)	(0.63)	(0.86)	(0.80)	(0.18)	(0.13)	(0.42)		(0.52)	(0.73)	(2.73)	(1.74)
S <sub>tot</sub> wt. % <sup>3)</sup>	(0.02)	(0.02)	(0.02)	(0.07)	(0.48)	(0.28)	(0.26)		(0.02)	(0.02)	(0.02)	(0.02)
Total <sup>3)</sup>	99.78	99.12	99.76	99.03	98.98	99.01	99.51		98.78	99.33	100.19	100.03
Pb ppm	25	10	44	9	15	8	132		22	15	14	16
Zn ppm	37	27	53	36	60	70	322		48	38	58	74
Cu ppm <sup>4)</sup>	( 10	( 10	( 10	( 10	( 10	( 10	(4504)		( 10	( 10	( 10	( 10
Ba ppm <sup>4)</sup>	777	728	798	1697	(2166)	(4743)	759		524	549	599	617
Rb ppm	239	249	250	234	197	200	163		162	160	222	182
Sr ppm	73	53	42	68	521	177	46		31	46	61	66
TiO <sub>2</sub> wt. % <sup>5)</sup>	0.28	0.28	0.30	0.33	0.67	0.45	0.22		0.25	0.27	0.35	0.40
Y ppm <sup>5)</sup>	26	24	36	31	26	22	22		23	23	28	28
Zr ppm <sup>5)</sup>	139	137	145	154	146	141	116		118	143	159	147
Rb ppm <sup>5)</sup>	208	212	184	198	196	189	162		147	148	198	174
Sr ppm <sup>5)</sup>	54	43	20	40	519	164	42		26	40	69	74

Plasma excitation - optical emission spectrometry (Govindaraju et al., 1976) of all samples by CNRS-CRPG (major elements and Cu, Ba, Rb and Sr; Fe<sub>tot</sub> = all Fe given as Fe<sub>2</sub>O<sub>3</sub>); special analysis by CNRS-CRPG of FeO, CO<sub>2</sub>, S<sub>tot</sub>, Pb and Zn; Fe<sub>2</sub>O<sub>3</sub> calculated from Fe<sub>tot</sub> and FeO.

1) See Appendix I-B for sample descriptions.

2) ± 0.1 to 0.2 m; distance measured along drill core = maximum possible distance.

3) Values in brackets not included in total.

4) Cu and Ba values in brackets (Cu above 150 ppm, Ba above 2000 ppm) are only approximate ("valeur indicative")

5) XRF analysis of TiO<sub>2</sub>, Y, Zr, Rb and Sr done at the Department of Geology, Stockholm.

## Appendix II-C: Chemical composition of rock samples from drill core 80204, Vegerbol.

Sample no. <sup>1)</sup>	80:58	80:59	80:60	80:61	80:62	80:63	Vein	80:64	80:65	80:66	80:67	80:68	80:69	80:70
Distance to vein <sup>2)</sup>	13.2 m	6.5 m	2.9 m	1.2 m	0.9 m	0.1 m		0.1 m	0.6 m	0.9 m	1.7 m	4.1 m	6.3 m	9.7 m
Anal. method	3)	3)	3)	3)	3)	4)		4)	4)	3)	3)	3)	3)	3)
SiO <sub>2</sub> wt.%	69.65	66.77	61.55	63.67	61.27	55.50		77.54	64.39	62.29	63.94	64.40	61.90	66.77
Al <sub>2</sub> O <sub>3</sub> wt.%	14.83	15.12	15.03	13.23	13.16	15.18		11.08	14.31	14.43	13.18	16.13	16.28	15.85
Fe <sub>tot</sub> wt.%	2.78	3.79	5.87	4.55	3.97	-		-	-	6.28	3.89	5.11	5.69	3.59
FeO wt.% <sup>6)</sup>	(2.33)	(2.79)	(4.05)	(3.38)	(3.13)	1.72		1.53	1.71	(5.01)	(2.70)	(3.54)	(3.83)	(2.50)
Fe <sub>2</sub> O <sub>3</sub> wt.% <sup>6)</sup>	(0.19)	(0.69)	(1.37)	(0.79)	(0.49)	1.22		1.13	1.18	(0.71)	(0.89)	(1.18)	(1.43)	(0.81)
MnO wt.%	0.07	0.07	0.12	0.12	0.10	0.12		0.02	0.07	0.10	0.10	0.11	0.11	0.08
MgO wt.%	1.01	1.83	3.60	4.37	2.76	0.98		0.48	0.70	1.26	1.37	2.31	2.99	1.28
CaO wt.%	2.00	3.18	4.47	4.12	5.07	8.70		0.32	5.09	3.38	4.35	3.52	4.70	3.06
Na <sub>2</sub> O wt.%	3.34	3.97	3.46	2.56	1.80	0.06		0.06	0.10	2.06	1.53	3.93	3.82	3.86
K <sub>2</sub> O wt.%	4.18	2.04	2.33	4.10	4.66	4.89		3.46	4.56	4.32	5.50	2.67	2.00	3.25
TiO <sub>2</sub> wt.%	0.30	0.52	0.50	0.29	0.42	0.48		0.39	0.51	0.58	0.59	0.59	0.79	0.60
P <sub>2</sub> O <sub>5</sub> wt.%	0.04	0.14	0.07	0.02	0.06	0.16		0.04	0.15	0.07	0.05	0.11	0.16	0.13
loss on ign.	0.86	1.09	1.89	2.31	6.75	-		-	-	4.34	4.80	1.13	1.30	0.94
H <sub>2</sub> O wt.%	-	-	-	-	-	3.16		2.24	2.81	-	-	-	-	-
CO <sub>2</sub> wt.% <sup>6)</sup>	(0.10)	(0.11)	(0.31)	(0.85)	(5.21)	7.21		0.27	3.98	(2.45)	(3.03)	(0.15)	(0.11)	(0.09)
S <sub>tot</sub> wt.% <sup>6)</sup>	((0.02)	((0.02)	((0.02)	((0.02)	(0.04)	0.06		0.35	0.32	(0.09)	(0.04)	((0.02)	((0.02)	((0.02)
Total <sup>6)</sup>	99.06	98.52	98.89	99.34	100.02	99.44		98.91	99.88	99.11	99.30	100.01	99.74	99.41
Pb ppm	24	16	18	27	76	102		75	519	285	26	13	21	20
Zn ppm	63	76	124	108	106	124		104	1221	294	55	92	137	118
Cu ppm	( 10	( 10	( 10	( 10	13	10		188	18	( 10	143	( 10	( 10	( 10
Ba ppm	750	318	679	1066	993	-		-	-	928	1300	722	473	813
Rb ppm	153	89	88	134	195	-		-	-	155	246	101	78	104
Sr ppm	263	331	332	246	253	-		-	-	164	198	316	356	333
TiO <sub>2</sub> wt.% <sup>5)</sup>	0.42	0.57	0.55	0.29	0.40	0.49		0.41	0.60	0.57	0.54	0.61	0.73	0.53
Y ppm <sup>5)</sup>	21	26	13	19	19	18		13	37	41	42	22	26	28
Zr ppm <sup>5)</sup>	158	224	82	75	89	122		82	203	222	288	167	164	227
Rb ppm <sup>5)</sup>	120	93	80	124	185	264		180	214	150	211	112	78	96
Sr ppm <sup>5)</sup>	212	322	307	240	256	38		7	22	162	182	340	370	304

1) See Appendix I-C for sample descriptions.

2) ± 0.1 to 0.2 m; distance measured along drill core = maximum possible distance.

3) Standard plasma excitation - optical emission spectrometry (Govindaraju et al., 1976) by CNRS-CRFG of major elements and Cu, Ba, Rb and Sr (Fe<sub>tot</sub> = all Fe given as Fe<sub>2</sub>O<sub>3</sub>); special analysis by CNRS-CRFG of FeO, CO<sub>2</sub>, S<sub>tot</sub>, Pb and Zn; Fe<sub>2</sub>O<sub>3</sub> calculated from Fe<sub>tot</sub> and FeO.

4) Wet chemical analysis by CNRS-CRFG of major and trace elements (including FeO, Fe<sub>2</sub>O<sub>3</sub>, H<sub>2</sub>O, CO<sub>2</sub> and S<sub>tot</sub>).

5) XRF analysis of TiO<sub>2</sub>, Y, Zr, Rb and Sr at the Department of Geology, Stockholm.

6) Values in brackets not included in total.

PRISKLASS B

Liber Distribution  
162 89 STOCKHOLM  
Tel. 08-739 91 30

Fotosats: ORD & FORM AB  
Tryck: Offsetcenter ab, Uppsala 1985

ISBN 91-7158-333-5  
ISSN 0082-0024