

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 795 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 76 NR 8

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RUDYARD FRIETSCH

A MODEL FOR  
THE FORMATION OF  
THE NON-APATITIC IRON ORES  
MANGANESE ORES AND SULPHIDE  
ORES OF CENTRAL SWEDEN



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## CONTENTS

Abstract .....	3
Introduction .....	4
Geological setting .....	4
Iron and manganese ores .....	8
The distribution of the iron and manganese ores in the volcanic sequence .....	11
Depositional environment of the iron and manganese ores and their relationship to basin bathymetry .....	13
Sulphide ores .....	17
On the nature of the Mg-rich alteration rocks .....	18
The relationship between iron ores and sulphide ores .....	20
A model for the formation of the ores of Central Sweden .....	25
Practical implications of the model proposed .....	31
The Falun and Ämmeberg sulphide deposits .....	32
Comparison of the sulphide ores of Central Sweden with some Precambrian and Phanerozoic sulphide ores .....	33
Summary .....	36
Acknowledgements .....	39
References .....	39

## ABSTRACT

Frietsch, Rudyard, 1982-05-04: A model for the formation of the non-apatitic iron ores, manganese ores and sulphide ores of Central Sweden. Sveriges geologiska undersökning, Ser. C, No. 795, pp. 1-43. Uppsala 1982.

The (non-apatitic) iron ores, manganese ores and sulphide ores of Central Sweden, which occur in a volcanic-sedimentary complex of Early Proterozoic age ( $> 1\ 900$  Ma), have a common volcanogenic origin. The close association between specific types of ores and metavolcanics suggests a stratigraphic control of the ores on a regional scale. Deposited in basins, the iron ores formed with increasing water depth (decreasing Eh and increasing pH) in the following order: quartz-banded iron ores (oxide facies); non-manganiferous (Ca-Mg silicate) skarn iron ores (carbonate facies); manganiferous (Ca-Mg-Fe-Mn silicate) skarn iron ores (carbonate-silicate facies); eulysites with Fe-Mn silicates (silicate-sulphide facies). The latter two types of ore formed under reducing conditions adjacent to argillite and greywacke sediments which were deposited under euxinic and more deep water conditions. The Långban type of ore, characterized by iron-manganese oxides and Ca-Mg-Fe-Mn silicates, is intermediate between the quartz-banded ores and the manganiferous skarn ores and was formed under conditions varying from oxidizing to reducing. There is an affinity between the iron ores and sulphides. The manganiferous skarn iron ores mostly contain Zn-Pb sulphides whereas Cu-Fe sulphides are found associated with the other types, mainly represented by the non-manganiferous skarn iron ores. The Cu-Fe sulphide assemblage is believed to have formed nearer to the volcanic vents and at higher temperatures than the Zn-Pb sulphide assemblage. The main structural pattern of the ore-bearing region is controlled by NE, or less commonly NNW, isoclinal folds in which the non-manganiferous skarn iron ores are contained within the antiforms and the quartz-banded iron ores, manganiferous skarn iron ores, ores of the Långban type and the eulysites tend to be associated with the synforms which can be up to 100 km in length. The sulphide ores and associated Mg-rich alterations, which are syngenetic with the volcanism, commonly follow the iron ore-bearing horizons.

## INTRODUCTION

The Zn-Pb-Cu sulphide ores and the non-apatitic iron ores of Central Sweden (Bergslagen region) are numerous and formerly played an important role in the mining activity of the country, although their economic importance is now diminishing. The sulphide ores account for about 10% of the total amount of sulphide ore mined in Sweden, and in terms of the country's base metal production they represent about 40% zinc, 30% lead and 5% copper (all as metals). The iron ores account for a very small percentage of Sweden's production, and their share is steadily decreasing. In addition, there are some quite small uneconomic deposits of manganese ore (of the Långban type).

The purpose with the present paper is to review the genesis of the different ore types of Central Sweden. In many cases the close spatial connection between the iron ores and the sulphide ores indicates that they have a common origin and the different varying positions within the volcanic sequence of the different ore types points to a regional stratigraphic control. Mg-rich alteration rocks associated with the sulphide ores and partly the iron ores have a stratabound appearance. There is therefore an intimate relationship between the chemistry of the ores and the host rock volcanics which favours a volcanogenic origin, the ores being deposited in sedimentary basins under different physico-chemical conditions. The apatite-bearing iron ores of the Kiruna type will not be considered as they represent another mode of formation, namely by intrusive processes. The present work is essentially based on published data with the present author's contribution amounting to a few impressions gained during some short and superficial studies in the field. It must be emphasized that the proposed model for the ore formation is strongly hypothetical, seeking to present the general processes that have been in action which may not always be valid in detail when related to single deposits. A short presentation of the model outlined has previously been given by Frietsch (1982a).

## GEOLOGICAL SETTING

The ores of Central Sweden are mainly restricted to a region about 150 km WNW of Stockholm (Fig. 1). Scattered occurrences are found to the east near the Baltic Sea and in addition there are some deposits about 50 km to the north and the south of the area shown in Fig. 1. The ores are hosted by felsic metavolcanics and associated limestones and dolomites belonging to an Early Proterozoic metamorphic volcano-sedimentary complex. The metamorphism is characterized by a low pressure amphibolite facies; only in the westernmost part of the region do rocks of the greenschist facies exist. Similar low metamorphic conditions occur also further east in the archipelago adjacent to the Baltic coast.

The volcanics, which are calc-alkaline, are predominantly felsic quartz-feldspar

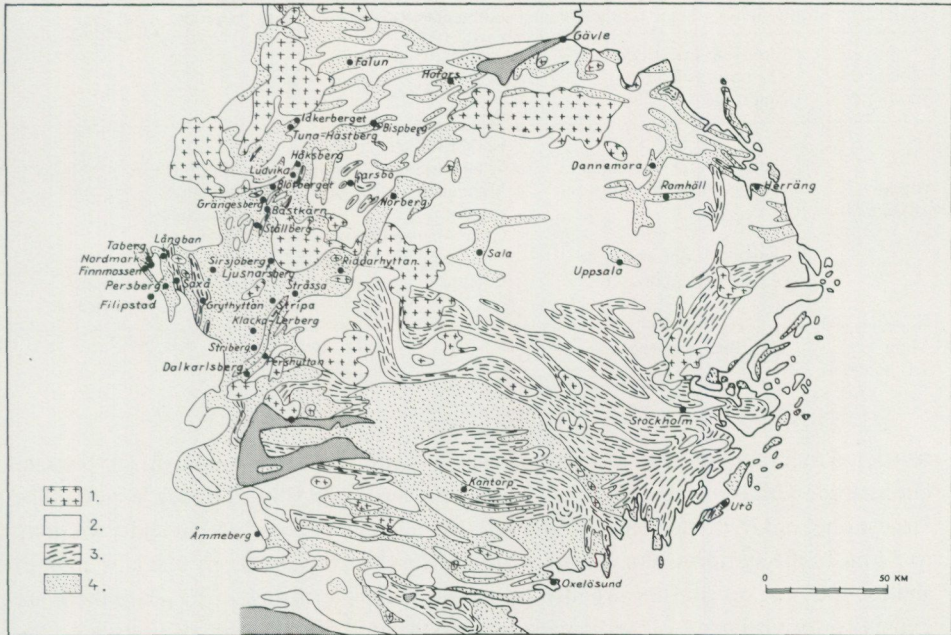


Fig. 1. Map showing the location of some iron ore and sulphide ore deposits in Central Sweden. From Magnusson (1966). 1. Late Svecofennian granites. 2. Early Svecofennian gabbros-granodiorites-granites. 3. Argillites, greywackes and (minor) quartzites. 4. Volcanics, mainly felsic. Grey = Jotnian and Cambro-Silurian sediments.

rocks of rhyolitic composition. They are divided into Na- and K-rich members with alkali-intermediate rocks being relatively rare. Intercalations of limestone and dolomite with a thickness usually less than some hundred metres and a length not exceeding 4–5 kilometres, occur locally, especially in the K-rich volcanics. The volcanics, particularly the K-rich ones, often show layering in which single layers range from some millimetres to some decimetres in width. The volcanics are mainly volcanoclastics in which small amounts of epiclastic sediments are interspersed. The deposition of the rocks occurred in a shallow sub-aqueous (submarine) environment with only a minor part having been lava; coarse pyroclastic material is generally missing. Associated with the felsic volcanics are some scattered occurrences of mafic volcanics, mostly of restricted extension. They are mainly feldspar porphyritic dacites and andesites with occasional basalts.

The sediments in the volcano-sedimentary complex are mostly argillites and greywackes which have become partly metamorphosed to mica schists and mica gneisses. Typical metamorphic phases for the argillitic sediments include andalusite, sillimanite and cordierite. Metaarenites, now metamorphosed into quartz-feldspar gneisses, occur in subordinate amounts.

The relative proportions of volcanics and sediments vary in different parts of Central Sweden. The volcanics dominate to the west where the occurrence of sediments is

TABLE 1. Stratigraphic scheme for the volcano-sedimentary complex of Central Sweden.

Meta-sediments	Argillite-greywacke ± mafic volcanite, quartzite		
Meta-volcanics	Felsic K-rich volcanite ± limestone-dolomite	Fe-Mn silicate (eulysite) Manganiferous skarn iron ore Manganese oxide ore (Lång- ban type) Quartz-banded iron ore Non-manganiferous skarn iron ore	Zn-Pb-(Fe-As) sulphides in limestone- dolomite  Cu-Fe sulphides in volcanite
Meta-sediments	Argillite-greywacke		

restricted to a small number of long and narrow synforms, namely at Saxå, Grythyttan, Grangårde, Guldsmedshyttan, Ställdalen, and Stollberg (Fig. 2, back cover). The largest one, at Grythyttan east of Filipstad, has a length of about 35 km and a width up to 5 km. In the synforms the volcanics are overlain by grey and partly black (graphitic) shales, greywackes and locally also basic volcanics. Northwest of Fagersta there are extensive occurrences of sediments of somewhat different composition; *e.g.* the Larsbo formation which consists of quartzites, mica schists, greywackes and conglomerates with intercalations of basic volcanics (Hjelmqvist 1938). In the southeastern part of Central Sweden, adjacent to the Baltic Sea, sediments characterize the volcano-sedimentary complex. The sediments here comprise metamorphosed argillites and greywackes which occur as almandite-cordierite-sillimanite-bearing gneisses.

Although the stratigraphy of the volcano-sedimentary complex is not yet clearly established, some main features can be outlined (Table 1). In the western part of Central Sweden the volcanics can be divided into a lower Na-rich unit and an upper K-rich unit (Sundius 1923, Magnusson 1925, Hjelmqvist 1937, Magnusson 1940b). This stratigraphic division, although limited, can be generally applied to most volcanic terrains. The Na-rich and K-rich volcanics are often interlayered with sharp variations in composition occurring down to the decimetre scale. Sometimes K-rich volcanics occur in the lower part of the sequence. In addition the Na- and K-rich volcanics have a different regional distribution. The Na-rich volcanites dominate in most of Central Sweden except for the eastern part along the coast, where the K-rich dominate. The latter are almost the sole representatives prevailing in the Nyköping area (Lundström 1976) and the Nynäshamn area (Stålhös 1979). The division into Na- and K-extremes is not of primary magmatic origin, being instead due to large-scale metasomatic alterations during the late stage of the volcanic activity (Frietsch 1982c). The chemical changes are most pronounced in the volcanics which are ore-bearing, indicating a genetic connection between the post-volcanic alterations of the volcanics and the ore-forming processes.

The limestones and dolomites occur at different stratigraphic levels within the

volcanics. In the western part of Central Sweden there seems, however, to be a tendency that the limestones and dolomites lie relatively high in the sequence often in the K-rich volcanics near to overlying metasediments (Fig. 2). Similar conditions prevail further south in the Örebro region where a 500 m thick formation rich in limestones and dolomites occurs between K-rich volcanites and overlying sediments (Lundegårdh *et al.* 1972).

The stratigraphic relationship between the volcanites and the sediments within the volcano-sedimentary complex is still controversial, although according to present knowledge it seems probable that the complex can be divided into three major units, with the volcanites lying between a lower and an upper sedimentary unit. Sediments overlying the volcanites are found in the above-mentioned synforms at Saxå, Grythytan etc. and in addition in the Örebro region (Lundegårdh *et al.* 1972). Possibly also the Larsbo sedimentary formation overlies the volcanites. However, in the eastern and southeastern part of Central Sweden, sediments and associated basic volcanics underlie the acid volcanics (Lundqvist 1962, Stålhös 1975, Gavelin *et al.* 1976, Stålhös 1979). According to Stålhös (1979, 1981, 1982) the stratigraphy of the southeastern region is clearly trisected with sediments both above and below the volcanites. Further to the east in south-western Finland where the volcano-sedimentary complex forms a continuation, a sequence with sediments in a similar stratigraphic position has been described by Edelman (1960). Here forming the base is the lower gneiss formation overlain by a leptite formation which in turn is overlain by a basic horizon until finally the sequence is capped by the upper mica gneiss formation. According to Härme (1980) basalts and andesites with minor dacites, latites, rhyolites and pelites occur stratigraphically highest in the volcano-sedimentary complex, overlying the quartzfeldspar gneisses (volcanics), mica gneisses (sediments) and limestones.

In accordance with what previously has been outlined by Gavelin *et al.* (1976), the evolution of the volcano-sedimentary complex initiated with the deposition of the argillites and greywackes. These sediments reached important thickness in south-eastern Central Sweden and in south-western Finland, particularly in the area comprising the Bothnian schists (Simonen 1980). Simultaneously, or at a somewhat later stage, volcanics with intercalations of limestones and dolomites were formed in the western part of Central Sweden. This volcanic activity was superseded by a younger argillite–greywacke deposition. In the Larsbo formation arenites form an integral part of the sedimentation.

The absolute age of the volcano-sedimentary complex is uncertain. The few radiometric determinations yield ages between 1 830 and 1 898 Ma (Welin *et al.* 1980a, 1980b). In part they reflect the recrystallization of the volcanics and the intrusion of plutonites, rather than extrusion of lavas. In connection with the Svecokarelian orogeny the volcano-sedimentary complex was affected by regional metamorphic processes. At an early stage in the Svecokarelian evolution, intrusive rocks varying from gabbro to granite and dated by Rb/Sr to around 1 900 Ma old (Åberg 1978, Welin *et al.* 1980a) were intruded. Previously they were considered as synkinematic,

but according to Stålhös (1979) and Wikström (1979b) the plutonites are pre-tectonic, being emplaced before the folding and the peak of the Svecokarelian deformation.

After the early intrusions there followed a period of relative quiescence characterized by epeirogenic fracturing and intrusions of dykes of basic composition. These "intra-orogenic dykes" are pyroxene and pyroxene-olivine rocks which have later been metamorphosed to amphibolites with hornblende and biotite. After the intrusion of the dykes, the late and main phase of the Svecokarelian orogeny took place. This phase was previously considered as separate from the initial early phase, but Stålhös (1979) considered both phases taking place over a short period of time. To the late phase belongs the culmination of the regional metamorphism with the formation of veined gneisses and late-kinematic granites and associated pegmatites. The age of the pegmatites is determined to about 1 712–1 826 Ma (Welin and Blomqvist 1964, Welin *et al.* 1980a).

During the Svecokarelian orogeny the volcano-sedimentary complex of Central Sweden was folded and deformed. The original, presumably horizontal sequence, is now characterized by steeply dipping planar structures and lineations. Two phases of tangential forces of different age and perpendicular to each other have resulted in a complicated folding pattern (Koark 1973, Lundegårdh 1974, Lundegårdh and Nisca 1978, Stålhös 1976, 1979). The older folding phase is considered to have taken place before the intrusion of the Early Svecokarelian plutonites and the younger phase subsequently later (Lundegårdh and Nisca 1978). However, Stålhös (1979) suggested that both phases are closely connected in time and formed in close association with the veined gneisses, *i.e.* at the culmination of the regional metamorphism. The older folding phase, with a directed pressure from east to west, caused isoclinal folds to form along flat N-S oriented axes resulting in axial planes dipping to the east, in most cases steeply. The younger folding phase has caused cross-folding along steeply dipping axes with a compression from north and south and E-W oriented steep axial planes were developed. At the intersection between the older and younger folded axial planes, easterly dipping fold axes and lineations appear and as a consequence the ores of Central Sweden are often elongated along these axes. According to Koark (1973) this is due to differences in competency between ore and wall rock during the folding and metamorphism.

## IRON AND MANGANESE ORES

The non-apatitic iron ores of Central Sweden are represented by the quartz-banded iron ores and skarn iron ores (Table 2). The quartz-banded iron ores are composed of hematite, magnetite, quartz and small amounts of Ca-Mg and Ca-Fe<sup>3+</sup> silicates such as andradite, diopside and tremolite. The skarn iron ores, which consist of magnetite and skarn silicates, are divided into a non-manganiferous type (with less than 1% Mn) and a manganiferous type (with more than 1% Mn). The manganiferous ores occur in

TABLE 2. Some mineralogical and chemical features of the (non-apatitic) iron and manganese ores of Central Sweden.

Ore type	Ore mineral	Gangue	% S	% P	% Mn
Quartz-banded iron ore	Hematite-magnetite	Quartz, (Ca-Fe-Mg silicate)	0.001-0.1	0.007-0.03	<0.2
Non-manganiferous skarn iron ore	Magnetite	Ca-Mg and Mg silicate	0.001-0.1	0.004-0.08	<1
Manganiferous skarn iron ore	Magnetite	Fe-Mn silicate	<0.2	<0.1	1-8
Långban	Hematite-magnetite Braunite-hausmannite	Quartz, Ca-Mg-silicate Fe-Mn silicate	0.005-0.1 0.007-0.7	0.01-0.02 0.01-0.03	0.1-1.4 25-45
Eulysite		Fe-Mn silicate	0.05-0.1	0.1	0.5-8

limestone and dolomite layers within the K-rich stratigraphically upper volcanics, whereas the non-manganiferous ores mainly appear in the Na-rich stratigraphically lower volcanics although subordinate amounts are found in the K-rich volcanics. In the non-manganiferous ores, where the carbonate component is of little importance, the skarn is made up by Ca-Fe<sup>3+</sup> and Ca-Mg silicates such as andradite, diopside-hedenbergite, and actinolite. A small number of deposits contain a Mg-rich skarn with anthophyllite-gedrite, cummingtonite, talc, forsterite and serpentine. The skarn silicates in the manganiferous ores are rich in ferrous iron and manganese; common are spessartite, dannemorite, knebelite, fayalite, and rhodonite. The manganese content, present up to a maximum of 7-8%, is bound to the silicates and the carbonate although in some deposits the magnetite also contains small amounts (2-4%) of manganese (Frietsch 1982b).

The quartz-banded iron ores and the skarn iron ores are most likely volcanogene and thus syngenetic with the enclosing volcanics, limestones and dolomites (Frietsch 1977). An exhalative-sedimentary origin is supported by a distinct layering in many of the ores including the skarn ores, particularly the manganiferous ones, and by the fact that the ores form long, narrow, more or less continuous stratabound horizons. The skarn silicates in the quartz-banded ores and the skarn ores have been formed by internal reactions between iron oxides (and hydroxides?), Ca-Mg-Mn-Fe-bearing carbonates and silica (chert). A part of the non-manganiferous skarn ores are quartz-rich, indicating an excess of silica superfluous to the metamorphic reactions. There are transitions in both space and chemistry between the quartz-banded ores and skarn ores; in some cases remnants of the quartz-banded ores are found in the skarn ores.

In the limestone and dolomite intercalations within the K-rich volcanics, some deposits of the Långban ore-type occur (Långban, Pajsberg, Harstigen, Sjögruvan,

Jakobsberg, and Slöjdartorp) which contain manganese oxide-silicate ore associated with jaspilitic hematite-magnetite ore (Sundius 1923, Magnusson 1930, 1970, Koark 1970). Although part of the Nordmark deposit belongs to the same ore type, it is mainly a non-manganiferous skarn iron ore. The Långban type of ore shows affinities both to the quartz-banded iron ores and the manganiferous skarn iron ores. A typical feature is that manganese ore and iron ore occur side by side. The manganese ore is comprised of oxides, mainly braunite and hausmannite, and silicates, mainly spessartite, rhodonite, richterite, schefferite, and tephroite. The iron ore consists of jaspilitic hematite and magnetite, the latter accompanied by skarn silicates such as andradite, diopside and tremolite. The original material for the iron is considered to have been hematite and for the manganese braunite and rhodocrosite; possibly both elements have been precipitated as hydrates. In the Långban deposit, hausmannite is formed from rhodocrosite or in part manganosite. Locally there are in the Långban and Slöjdartorp deposits subordinate amounts of sulphides (pyrite, chalcopyrite, galena, and sphalerite) as a late phase in the ore formation. Barite is a common mineral which occurs with calcite in vugs and fissures and also as an impregnation. The ores of the Långban type are of volcanogene origin (Koark 1970). According to Magnusson (1930, 1970, 1973) the ore material was deposited by volcanic processes, but a metasomatic provenance was also recognized. Boström *et al.* (1979) and Boström (1980) considered the Långban deposit as exhalative-sedimentary formed at a spreading centre or at a subduction zone.

Intermediate in composition between the quartz-banded iron ores and the manganiferous skarn iron ores are some quite unimportant manganese silicate-banded hematite ores e.g. Glatjärn north-west of Guldsmedhyttan, Bastnäs and Högfors at Riddarhyttan, Nya Jakobsgruvan (Andersbenning), Bälsjöberg and Assessorskan, all at Norberg, and Klintgruvan east of Avesta. The dominant ore mineral is hematite, rarely magnetite, and in Nya Jakobsgruvan and in Klintgruvan braunite constitutes part of the ore (Geijer and Magnusson 1944). Free quartz is not present, the silica is bound to rhodonite, schefferite and spessartite, occasionally also manganophyll, barium-bearing feldspar and the lead-manganese silicate kentrolite. The host rocks are mostly potassic volcanics and the deposits consequently occur in the same stratigraphic position as the manganiferous skarn iron ores and the ores of the Långban type. The Bälsjöberg deposit is a manganese-bearing dolomite containing manganese silicates. All the deposits in question have on the map in Fig. 2 (back cover) been designated as belonging to the manganiferous skarn iron ores.

In the K-rich volcanics and limestones and dolomites in the Nyköping area, there are some occurrences of eulysites which are iron-manganese silicate rocks without any substantial amounts of iron or manganese oxides. The most common minerals are fayalite, ferrosilite, garnet, and grunerite which are all manganese-bearing (Palmgren 1917, Geijer and Magnusson 1944, Lundström 1974, 1976). The paragenesis thus resembles that of the manganiferous skarn iron ores and of the Långban type of ore. The eulysites have a stratabound appearance mostly close to adjacent sedimentary

gneisses of argillite to greywacke composition, possibly high up in the stratigraphy.

Within the upper sedimentary unit of the volcano-sedimentary complex a very restricted precipitation of manganese is also found. At Sundshyttan near Grythyttan (Lindroth 1917), at Björnviken near Långban (Magnusson 1925) and at Mårshyttan near Guldsmedshyttan (Geijer and Magnusson 1944) there are iron-manganese silicate layered greywacke sediments close to the underlying volcanics. These layered rocks are rich in amphibole (anthophyllite and grunerite), hedenbergite and garnet. At Björnviken some magnetite is present. The origin of the layered rocks is without doubt sedimentary. Magnusson (1925) considered the sediment at Björnviken as similar to the eulysites.

### THE DISTRIBUTION OF THE IRON AND MANGANESE ORES IN THE VOLCANIC SEQUENCE

It is generally accepted that there is a close relationship between the different types of non-apatitic iron ores in Central Sweden and 1, their stratigraphic position and, 2, the alkali composition of the felsic host rock volcanics (Sjögren 1874-75, Törnebohm 1874-75, Gumaelius 1875, Johansson 1906-07, Sjögren *et al.* 1914, Johansson 1924, Geijer and Magnusson 1944). There is thus a connection between the chemical composition of the ores, their specific stratigraphic position and the specific alkali composition of the host rock volcanics, all of which favour a syngenetic volcanogene origin for the ores.

As a general rule the manganiferous skarn iron ores are found in the upper potassic volcanics; the only known exception is the Ramhäll deposit which occurs in sodic volcanics (Lindroth 1916). In contrast the non-manganiferous skarn iron ores lie almost exclusively in sodic volcanics. An important exception includes the skarn ores at Norberg which mostly occur in potassic volcanics (Geijer 1936). The Vattholma skarn ores likewise appear in potassic volcanics; some of the deposits are, however, manganese-bearing and quartz-banded (Magnusson 1973, Åhman 1973). The wall rock composition of the quartz-banded ores of Central Sweden is ambiguous. Many of the quartz-banded ores, such as Norberg, Stråssa, Riddarhyttan, and Fanthyttan, occur in potassic, locally banded volcanics. On the other hand there are many deposits of quartz-banded ore in which sodic volcanics dominate or make up an integral part of the wall rock. In these deposits, however, there is a common tendency for potassic volcanics to occur adjacent to the sodic ones, in some cases making up the main part of the bedground. For example, in the Norberg area where potassic volcanics dominate, some single ore bodies (Långgruvan and part of the Kallmora mine) occur in sodic volcanics (Johansson 1924, Geijer 1936). Clearly associated with sodic volcanics is the Bispberg ore even though potassic and alkali-intermediate volcanics occur in the near vicinity (Hjelmqvist 1941, Geijer and Magnusson 1944). At Striberg the ore occurs in potassic volcanics which form narrow intercalations in sodic volcanics which

dominate (Hjelmqvist 1942). The Stripa deposit is mainly characterized by sodic volcanics although alkali-intermediate and potassic volcanics are also present (Geijer 1938, Geijer and Magnusson 1944). The jaspilitic hematite ores at Saxå occur in sodic volcanics which form relatively large areas within the potassic volcanics (Sundius 1923). It is thus evident that the quartz-banded ores do not show any preference for either the sodic or the potassic volcanics. There is, however, a tendency that the ores occur close to the potassic volcanics, which means in the terms of the Na-K stratigraphic division that the quartz-banded ores occur relatively high up in the volcanic sequence.

The preference of manganese for the K-rich volcanics is not only restricted to the manganiferous skarn iron ores, it is also valid for the manganese oxide ores of the Långban type and the eulysites. The ores of the Långban type occur in K-rich volcanics although at Jakobsberg and Nordmark the regionally most important host rock is a Na-rich volcanite. The Nordmark ore is, however, as already pointed out, mainly of the non-manganiferous skarn iron ore-type. The eulysites lie in the potassic volcanics close to the overlying argillite to greywacke sediments. As described previously local iron-manganese silicate occurrences are present in the argillite to greywacke metasediments close to the underlying volcanics.

There is thus a clear division between the non-apatitic iron ores and manganese ores of Central Sweden in terms of stratigraphic position and host rock lithology. The lower sodic volcanics contain non-manganiferous skarn iron ores and the upper potassic volcanics contain manganiferous skarn iron ores, manganese oxide ores and eulysites (Table 1). The quartz-banded iron ores seem to occur in both types although mostly near to the potassic volcanics, *i.e.* relatively high up in the stratigraphic sequence. In the metasediments overlying the K-rich volcanics there are present local iron-manganese silicate occurrences similar to the eulysites.

The distribution of the different types of iron and manganese ore in the western part of Central Sweden is shown in Fig. 2 (back cover) which is mainly based on data taken from Geijer and Magnusson (1944), Magnusson (1973) and available geological map sheets. In principle the map is the same as given by Magnusson (1961, 1970), but covers a larger area and includes also occurrences of limestones and dolomites, K-rich volcanics, argillite to greywacke sediments, Mg-rich alteration rocks, and sulphide mineralizations, even those of subeconomic importance.

Allowing for the generalizations illustrated in Fig. 2, it is evident that the different types of iron and manganese ores appear in a specific order. Laterally outwards from the synforms with the argillite to greywacke sediments, one encounters: 1, manganiferous skarn ores, 2, quartz-banded ores and non-manganiferous, quartzitic skarn ores and 3, non-manganiferous, quartz-free skarn ores. The order outlined is from the stratigraphically higher parts to the stratigraphically lower parts in the volcanic sequence. The manganese ores of the Långban type occur in the same stratigraphic position as the manganiferous skarn ores, *i.e.* high up in the sequence.

Taking into consideration the stratigraphic position of the different iron and

manganese ore types together with the known tectonic structures, it is possible to show that the main structural pattern in the western part of Central Sweden is that of a north-easterly trending alternating sequence of synforms and antiforms (cf. Fig. 2). In the westernmost area the structures, however, trend NNW. The non-manganiferous skarn ores occur in the antiforms and the manganiferous skarn ores, the manganese oxide ores and the quartz-banded ores in the synforms. The present appearance of narrow, elongate ore-bearing structures mostly exceeding tens of kilometres in length, is due to isoclinal folding. One of the most persistent is the north-easterly trending synform between Nora and Norberg and its eastward extension. Even if the structure is not totally continuous, there are good reasons based, in part, on aeromagnetic measurements in believing it to be one single structure with a length of more than 100 km.

A conspicuous feature of many of the synforms is the common occurrence of K-rich volcanics. This is a natural consequence of the stratigraphically higher parts of the volcanic sequence being preserved in the down-folded parts. More extensive occurrences are found between Riddarhyttan and Fagersta in the Nora-Norberg synform and east of Filipstad in the Grythyttan synform. In addition potassic volcanics of areal importance occur in the synform WNW of Hedemora.

It should be emphasized that the tectonic pattern shown in Fig. 2 must be considered as rather speculative and should only be considered in a regional context. It should also be stressed that the form of single deposits of iron, manganese and sulphide ores in Central Sweden is essentially controlled by steeply dipping structures (folds and columnar structures), the ores often being elongated along these (Koark 1973). This pattern is governed by the intersection of two folding phases: an older E-W compression and a younger N-S cross-folding (cf. p. 8).

#### DEPOSITIONAL ENVIRONMENT OF THE IRON AND MANGANESE ORES AND THEIR RELATIONSHIP TO BASIN BATHYMETRY

As stated previously the non-apatitic iron ores and manganese ores of Central Sweden are of volcanogene origin. It is here postulated that the ores were concentrated and transported by hydrothermal fluids in connection with the volcanic activity and deposited in submarine basins. The ore material was precipitated at the sea-bottom/water interface and the different ore types reflect different conditions of deposition. The water depth in the basins, which in the main were relatively shallow, has fluctuated resulting in different iron ores facies which often overlap each other. Generally with increasing distance from the source and increasing depth of water, iron formations are formed in the order of oxide – carbonate – sulphide facies (James 1954, Goodwin 1973a, 1973b). The silicate facies represents roughly the same environment as the carbonate and oxide facies. The main factor in the physico-chemical conditions of deposition is the redox potential, being highest in the oxide facies and lowest in the sulphide facies. The changes of the pH value are also important, being lowest in the

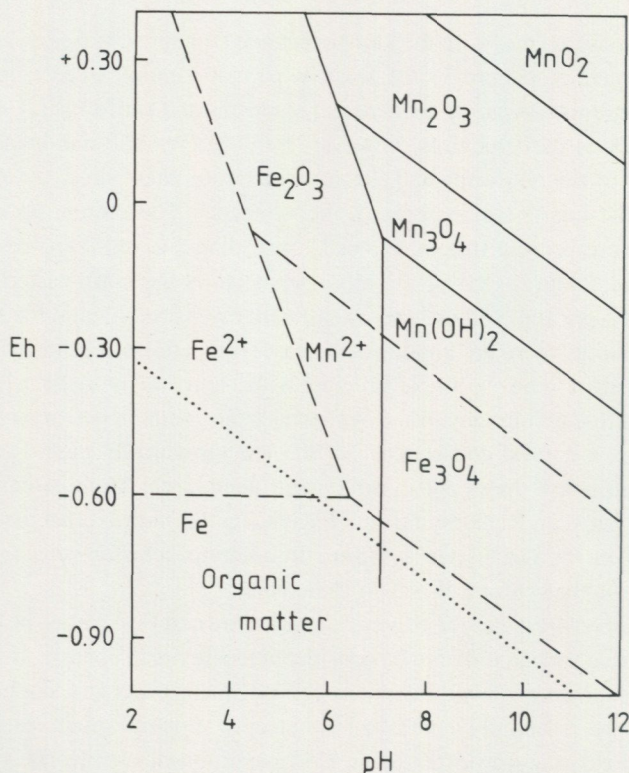


Fig. 3. The stability of iron and manganese compounds at 100°C and 600 bar after Boström (1967). Activity of Fe and Mn about  $10^{-2}$  M. Iron compounds are delineated by dashed lines, organic matter by a dotted line.

oxide facies, increasing in the carbonate facies and possibly being the same in the sulphide facies.

One of the main genetic problems connected with the non-apatitic iron ores of Central Sweden, as in many other metamorphic sedimentary iron ores, is that the original state in which the iron was precipitated is unknown. There are no relict mineral assemblages preserved, but it is generally believed (cf. for example Geijer and Magnusson 1944) that the original mineral in the quartz-banded iron ores was hematite, or in part limonite. In the other ore types it has presumably been magnetite. The designation of the different ore types to different facies is therefore controlled by physico-chemical constraints; the quartz-banded ores belong to the oxide facies, and as will be shown below the other ore types belong to the carbonate and in part sulphide facies.

The physico-chemical conditions under which the different types of non-apatitic iron ores, manganese ores and the sulphide ores in Central Sweden were deposited, can be interpolated using data concerning the stability of the various mineral assem-

blages (Figs. 3 and 5). The deposition of the quartz-banded iron ores with hematite as the main pre-metamorphic component indicates oxidizing conditions (oxide facies). As seen from Fig. 3 the stability of hematite, compared to the stability of magnetite, indicates a relatively high redox potential, largely independent of the pH value. However, if alkaline conditions with a pH greater than 6 prevailed, which is less likely due to, among other reasons, the restricted presence of carbonates, the redox potential must have been lower than zero. Most possibly the quartz-banded iron ores were deposited under conditions with an  $Eh = 0$  to  $+0.30$  and a pH below 6.

In contrast the skarn iron ores have been deposited under more reducing and more alkalic conditions. The skarn ores are carbonaceous sediments in which iron, manganese (possibly as carbonate or hydroxide), silica, and Ca-Mg-carbonate gave rise to the present skarn silicate assemblages by internal reactions during the regional metamorphism. The non-manganiferous skarn iron ores (carbonate facies) were probably formed at a redox potential somewhat below zero (0 to  $-0.30$ ), the pH value being around 6. This assumption is based mainly on the stability fields of siderite and rhodocrosite given by Krauskopf (1957), Garrels and Christ (1965) and Boström (1967). The deposition of the manganiferous skarn iron ores (carbonate to silicate facies) occurred under still more reducing conditions. Valuable information concerning the conditions under which the different skarn ore types have been deposited can be obtained from the mineralogical-chemical composition of the silicates in the ores. Of special interest is the relationship between iron and magnesium in the skarn minerals; the lower the oxygen fugacity of the environment the lower is the  $Mg/(Mg + Fe)$  ratio in the silicates (Frietsch 1980b).

In the manganiferous skarn ores and the non-manganiferous skarn ores there commonly occur similar silicates (in part hedenbergitic diopside and hornblende) but in the manganiferous ores the magnesium-iron ratio is lower than in non-manganiferous ores indicating that the manganiferous ores have been formed in a more reducing environment. In addition the silicates of the manganiferous ores are rich in ferrous iron and often also rich in divalent manganese. High manganese contents (3–30% MnO) are found in knebelite, spessartite-almandite, grunerite, and hedenbergite, whereas manganese has not entered diopside, hornblende and actinolite. A similar mineral assemblage comprising minerals rich in divalent iron and manganese is encountered in the eulysites (silicate-sulphide facies).

In the manganiferous skarn iron ores and the eulysites, iron and manganese have co-precipitated which is contrary to what usually occurs in nature, *i.e.* a separation of these two elements. Even if these elements are similar to each other geochemically, there are some significant differences. Manganese enters into solution more easily but tends to remain longer in solution than iron. In addition, iron is precipitated at a lower redox potential and lower pH value than manganese. These differences generally result in a separation of the metals during sedimentary and volcanogeno-sedimentary processes and iron is deposited closer to the source than manganese which tends to be transported further away.

The manganiferous skarn iron ores and eulysites of Central Sweden have thus been deposited under conditions which were not conducive to form manganese oxides. As pointed out by Frietsch (1980b) the manganiferous skarn iron ores and the eulysites were formed in a reducing environment. As seen from Fig. 3 the co-precipitation of divalent iron and manganese can only be achieved under conditions of relatively high acidity (pH less than 7) and low redox potential (Eh lower than zero), otherwise manganese oxides would have formed. However, a co-precipitation of iron and manganese is also feasible if the ore-bearing solutions were highly oxidized and/or were made basic so rapidly that the elements were not separated. In the first instance with a high oxygen fugacity, manganese must, however, have formed hydroxide or oxide compounds. In the second case which would involve a rapid increase in pH, most of the iron would have precipitated as magnetite, and not as ferrous iron silicates.

Field geological data also favour a reducing milieu for the formation of the manganiferous skarn iron ores and the eulysites. Both occur adjacent to argillite and greywacke sediments which characterize the deeper parts of the depositional basins where the environment was reducing. Evidence for this is supported by the presence of iron sulphides and graphite in the manganese-bearing deposits. The eulysites contain pyrrhotite and pyrite. The manganiferous skarn iron ores are mostly sulphide-bearing, a feature that is discussed further below. In addition graphite is present in small amounts with contents of 0.5–1.5% C being quite common (Geijer and Magnusson 1944). This feature is well developed in the manganiferous skarn iron ores of Kolningsberg and Klackberg in the Norberg district (Geijer 1936, Hjelmqvist 1946, Landergren 1961) and in the ores of Västerby and Garpa near Askersund (Geijer and Magnusson 1944). It should also be emphasized that all known occurrences of graphite in the volcanics of the volcano-sedimentary complex are associated with potassic volcanics which occupy a high stratigraphic position close to the overlying meta-sediments. Graphite in K-rich volcanics is found in the Grythyttan area (Sundius 1923) and at Utö (Geijer and Magnusson 1944). The grey Mg-Mn-Fe-bearing limestone present at the Dannemora manganiferous skarn iron ore and intercalated within potassic volcanics, contains finely dispersed graphite (Geijer and Magnusson 1944).

In summary a reducing environment for the formation of the manganiferous skarn ores and eulysites is favoured by the geological and geochemical data presented. The presence of graphite indicates an euxinic environment in which organic compounds were stable, reflecting an Eh value below  $-0.6$ . Most likely the co-precipitation of manganese and iron in the manganiferous skarn iron ores and the eulysites is due to a direct debouchement of the ore solutions into a reducing sea-bottom environment containing carbonates, some sulphur and organic material. The carbonate component has only to a restricted degree taken part in the later metamorphic reactions. It is remarkable that the amount of Ca silicates is very subordinate or totally absent, especially in the manganiferous skarn ores which essentially occur in carbonate rocks. The small amounts of manganese present have possibly, at a lower grade, stabilized the formation of Fe-Mn silicates in preference to the formation of Ca silicates.

In the Långban ore type the deposition of manganese and iron occurred under quite different conditions. The ore mineral formation initiated under relatively oxidizing conditions with the formation of trivalent oxides (braunite and hematite) together with precipitation of silica. The conditions then changed to become more reducing with the formation of divalent-trivalent oxides (hausmannite and magnetite); associated with the manganese oxides are silicates with divalent iron and manganese. According to Magnusson (1970, 1973) hausmannite is formed from braunite, and magnetite from jaspilitic hematite by later metamorphic processes, but in the opinion of the present author these differences are primary features already established during the very early stages of precipitation.

The amount of manganese in the Långban ore type seems to be quite inferior to that found in the manganiferous skarn iron ores. There is no estimate of the amount of manganese oxide ore in Central Sweden where all the deposits are described as small; possibly some hundred thousand tons of manganese is bound to the Långban ore type. The reserves of the manganiferous skarn iron ores are estimated to about 250 million tons of ore (Frietsch 1980b). The average manganese content of these is not known, but if 2 per cent is postulated, this means that the manganese metal content in the skarn ores is about 5 million tons. These rough estimates show that the main deposition of manganese was in the manganiferous skarn ores, and that the amount manganese deposited in the Långban ore type is relatively small.

### SULPHIDE ORES

The sulphide ores in Central Sweden occur in the felsic volcanics and their limestone and dolomite intercalations. In addition, sulphides are found in many iron ore deposits, particularly in the skarn-bearing ones. The sulphides occur in concentrations which vary from weak impregnations to massive ore bodies and the present configuration of the mineralizations is controlled by tectonic structures such as fold axes, fissures, faults and zones of schistosity. The base metals comprising the mineralization consist of varying amounts of zinc, lead and copper and containing on average 4.5% Zn, 2.5% Pb and 0.5% Cu; the content of precious metals is 10–100 ppm Ag and 0.2–1 ppm Au (Magnusson 1970b, Frietsch 1980a). The main ore minerals are pyrite, pyrrhotite, sphalerite, galena, and chalcopyrite; magnetite is usually present. In the limestones and dolomites the ore minerals are mostly sphalerite and galena; the carbonates are usually metasomatically altered to Mg-rich skarns containing tremolite, diopside, garnet, anthophyllite, cummingtonite, humite minerals, forsterite, serpentine, and talc. In the volcanics the ore minerals are mainly chalcopyrite although pyrite, sphalerite and galena are often in association. The volcanics are metasomatically altered to Mg-rich compositions, either to mica schists with quartz, mica, cordierite, and more rarely sillimanite, or to quartzites with cordierite, gedrite, anthophyllite, cummingtonite, partly also almandite and andalusite. The main changes in chemical

composition brought about by the alteration is the addition of magnesium and removal of sodium and calcium (Frietsch 1982c). Potassium and iron show less marked variations although potassium is often retained in mica, therefore increasing. The spatial relationship between the Mg-rich rocks and sulphide ores is unambiguous in so far that the sulphides are always accompanied by Mg-rich rocks; but the latter do not necessarily always contain sulphides. For example, large areas of sulphide-free Mg-rich rocks occur at Riddarhyttan (Geijer 1923).

According to Geijer (1917, 1962, 1964) and Magnusson (1936, 1948, 1960) the sulphides were formed in association with the metasomatic processes which gave rise to the Mg-rich alteration rocks. The ore-bearing fluids emanated in connection with the folding of the volcano-sedimentary complex and the intrusion of the Early Svecokarelian plutonic rocks. Koark (1962, 1973) suggested that the iron and sulphide ores and the Mg-rich rocks were pre-metamorphic (syngenetic), formed during a single event by exhalative-sedimentary processes. Based on comparison with massive sulphide ores elsewhere in the world, Vrána (1975), Schermerhorn (1978) and Berge (1978) considered the Mg-rich rocks of Central Sweden as metamorphic equivalents to chloritization and silicification products brought about in connection with the volcanism and the formation of the sulphides. Levi and Malmqvist (1979) and Levi *et al.* (1980) postulated the ore formation to be a complex process with several stages of regional alteration and metamorphism. Most important is the first stage with leaching of magnesium and copper, lead, silver and sulphur from the volcanites, and the subsequent deposition of these elements in limestone (dolomitization) and surrounding volcanites (Mg-metasomatism). Hedström (1980), Selkman (1980) and Zakrzewski (1982) have also forwarded the opinion of a volcanogene, exhalative-sedimentary origin to the sulphide ores of Central Sweden.

#### ON THE NATURE OF THE Mg-RICH ALTERATION ROCKS

The regional distribution of the Mg-rich alterations in the volcanics and limestones and dolomites is shown in Fig. 2 (back cover). The Mg-rich rocks occur high up in the stratigraphic sequence in connection with the synformal structures. The alteration rocks form zones of considerable length occurring more or less continuously along the synforms, for example in the Nora-Norberg structure. Thus in a regional context the Mg-rich rocks have a stratabound appearance in the volcanics, this also being illustrated in the region north-east of Ludvika where the volcanics contain horizons of cordierite-bearing mica schist and gedrite quartzite (Fig. 4). It is possible that the alteration has at least partly followed specific beds in the volcanics which were more permeable. On a small scale the Korphytte field in the Riddarhyttan region illustrates a sequence in which decimetre-wide, argillitic, biotite-rich and quartzitic layers alternate. Abundant cordierite porphyroblasts occur in the argillitic layers but are absent from the quartzitic layers thus indicating a selective alteration; the argillitic layers with

abundant aluminium have a chemical composition and porosity more susceptible to change. A selective Mg-metasomatic alteration of the volcanites, in which sedimentary intercalations have been more susceptible, has been outlined for the Lindesberg area by Hjelmqvist (1942) and Lundström (1981).

However, seen on a local scale the Mg-rich rocks are cross-cutting the structures, in some cases following fractures and forming networks. Examples are found at Getön (Magnusson 1925), Finnmosse (Magnusson 1929), and at Önsbacken and Korsarvet, west of Falun (Geijer and Magnusson 1944). At Riddarhyttan and at Kallmorberg, in the Norberg area, the alteration is extending outwards from steeply-dipping schistosity planes (Geijer and Magnusson 1944).

In the volcanics the Mg-rich minerals may also appear as post-tectonic. Lundström (1974) described post-tectonic sheaves of anthophyllite in metabasites, probably of volcanic provenance, in the Nyköping area. In the layered rock of the Korphytte field described above, cordierite often grows on the schistosity surfaces. In amphibolites of possibly volcanic origin in the Katrineholm area, Wikström (1979a) found anthophyllite and cummingtonite, the former occurring as radiating aggregates on the schistosity surfaces.

The age of the Mg-metasomatic alteration cannot be established with certitude. Due to the inferred stratabound nature of the alteration it is probable that it occurred para-contemporaneously with the volcanism, or as a final phase during diagenesis and compaction. A somewhat later occurrence after crystallization of the volcanics can be envisaged in those cases when the alteration is controlled by fractures and fissures in the volcanics. The only clear proof of an alteration coeval with the volcanism is given by Koark (1962) in the Falun area where the Mg-rich rocks were present prior to the intrusion of certain quartz-porphry dykes belonging to a late stage of the volcanism. Indirectly a pre-deformative alteration can be indicated when it is found to be prior to the intrusion of the Early Svecokarelian plutonites. However, only at three localities they have been observed to intersect the Mg-rich rocks. For example, in the Riddarhyttan area a granite intrudes a cordierite-bearing mica schist (Geijer 1923); in the Intrånget skarn iron ore the granite is younger than the Mg-alteration and the sulphides found in the iron ore (Magnusson 1973); the granite cuts the folded sequence and, according to Lundström (1981) there is at Munkhyttan, on the Lindesberg SV map sheet, a sericite altered volcanite which is veined by an Early Svecokarelian granite.

On the other hand there are many examples where the Mg-rich rocks and associated sulphides are later than the early plutonites and the still younger "intra-orogenic" metabasites. Mg-rich mineral assemblages and sulphides younger than the plutonites are found in Dannemora (Baekström 1923), Mårtanberg (Tegengren 1924, Magnusson 1973) and Herräng (Magnusson 1940a). Mg-alteration of the metabasite dykes is described from Falun (Geijer 1917) and Ljusterö-Rödlöga (Lundqvist 1962). It should be emphasized that the above-mentioned acid porphyry dykes in Falun, which according to Koark (1962) occur late in the volcanism and are later than the Mg-rich alterations, have also undergone Mg-rich alterations, albeit only locally and less

intensely compared to the basic dykes (Koark 1962, Geijer 1964). Sulphides in the metabasite dykes occur at Dannemora (Baeckström 1923), Ryllshyttan (Tegengren 1924, Magnusson 1973) and Lövåsen (Magnusson 1960). In Ryllshyttan the sulphides are accompanied by Mg-metasomatic alterations.

In the "intra-orogenic" basic dykes at Ljusterö-Rödlöga, the Mg-alteration is at least in part related to faults and joints; the new-formed minerals lack preferred orientation related to existing planes of schistosity and lineation (Lundqvist 1962). Similar phenomena have been described by Lundegårdh (1956) from the area north of Gävle. According to Koark (1960) there are in the Falun mine "sköls" partly containing sulphide ore, in which are to be found post-deformative crystallizations of minerals such as cordierite and anthophyllite.

The argillites and greywackes are locally rich in Mg-bearing mineral assemblages, these being due to internal reactions caused by the regional metamorphism of a sediment originally rich in magnesium, iron and aluminium. Sediments with a layering of anthophyllite, cordierite, hornblende, cummingtonite, and garnet have been found in the Nyköping area (Lundström 1974, Stålhös 1975, Lundström 1976), in the Uppsala area (Stålhös 1972) and the Nynäshamn area (Stålhös 1979). Of special interest is the post-tectonic appearance of the Mg-rich minerals known from several localities in the sediments. Post-tectonic anthophyllite forming radial crystal aggregates occurs in the areas of Nyköping (Lundström 1974), Uppsala (Stålhös 1972) and Örebro (Lundegårdh *et al.* 1973). Post-tectonic cordierite and cummingtonite are described from the Uppsala area (Stålhös 1972). In the sediments of the Nynäshamn area garnet occurs as long and narrow aggregates oriented parallel with the older schistosity (Stålhös 1979).

In summary, it can be stated that within the volcano-sedimentary complex there are Mg-rich rocks present both in the volcanics and in the sediments. The formation of the Mg-rich mineral assemblages in the volcanics took place during different events. It seems plausible that the main alteration phase was during the volcanism. The metasomatic processes must, however, have been active for a long period of time as shown by the occurrence, in part post-deformational, of Mg-rich silicates in the volcanites and in the "intra-orogenic" metabasite dykes. The post-tectonic appearance of these minerals is possibly the result of late recrystallization. The same applies to the Mg-rich minerals in the sediments which, although syngenetic in origin, have undergone subsequent mobilization giving the impression of a postgenetic mode of occurrence.

#### THE RELATIONSHIP BETWEEN IRON ORES AND SULPHIDE ORES

A great number of the non-apatitic iron ores in Central Sweden are accompanied by varying amounts of sulphides (pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena). The occurrence of the sulphides is restricted to the magnetite ores; the hematitic ores, mainly the quartz-banded varieties, do not contain sulphides. As already described, the

TABLE 3. Sulphides in the manganiferous skarn iron ores of Central Sweden.

The data are taken from Geijer (1923), Hjelmqvist (1937, 1948), Geijer and Magnusson (1944), Koark (1962), and Magnusson (1970).

	Sulphide-bearing					
	ZnS	PbS	CuFeS <sub>2</sub>	FeS <sub>2</sub>	FeS	Other
Rödgruvefältet				+		
Dannemora	+	+	(+)	+	+	
Holmgruvan (Garpenberg)	+	+	+			
Stigsbo (Hofors)	+	+				
Sjöströmsgruvan (Hofors)	+	+	(+)	(+)		
Siggeboda	+	+	+			
Mårdshyttan	+	+	+			
Fanthyttan	+	+	+			
Håkansboda	+	+		+	+	(CoFe)AsS
Hilläng	+	+	(+)	(+)	(+)	FeAsS
Stollberg	+	+				
Dammberg	+	+				
Svartberg	+	+				
Grängsgruvan	+	+				
Gyllingen	+	+				
Ämme	+	+				
Garpa	+	+				
Västerby	+				+	
Fromma	+					
Hällefors	+	+	+	+	+	FeAsS
Guldsmedshyttan	+	+		+	+	FeAsS
Ingagruvan	+	+				
Klackberg (partly)		+	+	+	+	FeAsS
Tallbottengruvan	+				+	
Fäbäcksgruvan (Basttjärn)	+	+				

## Sulphide-free

Klackberg (partly), Kolningsberg, Vikersfältet, Ställberg, Limgruvan (Gåsborn), Basttjärn, Svartviksfältet, Hästhagsgruvan, Långvik (Garpenberg), Ramhäll, Tuna-Hästberg, Stav, Skinnaräng, and Kråknäs.

sulphide mineralizations in the limestones and dolomites are made up of sphalerite and galena, whereas the mineralizations in the volcanics consist of chalcopyrite, pyrite and pyrrhotite. Even if exceptions exist there is thus a fractionation into a sphalerite-galena assemblage and a chalcopyrite-iron sulphide assemblage. This division can also be applied to the sulphide content of the iron ores.

The manganiferous skarn iron ores, which are mostly rich in carbonates, contain sphalerite and galena whereas the other types of iron ores (quartz-banded ores and non-manganiferous skarn ores) contain pyrite, pyrrhotite and chalcopyrite (Table 1). Although there are naturally many exceptions, it is evident that most of the manganiferous skarn iron ores contain sphalerite and galena and in many deposits there is also arsenopyrite and chalcopyrite, whereas pyrite and pyrrhotite are less common (Table 3). In the Håkansboda ore there is in addition cobaltite and glaucodote. Many of the deposits have been mined for their Zn and Pb. Manganiferous skarn iron ores which do

not contain substantial amounts of sulphides are relatively few; among them are several important iron ore deposits such as Bastjörn, Tuna-Hästberg, Ställberg, and Ramhäll.

Quartz-banded iron ores and non-manganiferous skarn iron ores containing sulphides in economic amounts are found in a number of deposits. In Bäckegruvan at Riddarhyttan there is a quartzitic magnetite ore with pyrite, pyrrhotite, chalcopyrite, and some cobaltite (Geijer 1923). In the Norberg iron ore field several sulphide mineralizations are known including the Kallmorberg skarn iron ore (chalcopyrite, bornite and covellite), the Kallmora Silver Mine quartz-banded iron ore (galena, pyrite and sphalerite) and the Bondgruvan quartz-banded iron ore (chalcopyrite, covellite and molybdenite; Geijer 1936, Magnusson 1973). In the Stråssa deposit the homogeneous quartz-magnetite-hematite ore and diopside-hornblende-bearing magnetite ore contains pyrite, chalcopyrite and pyrrhotite (Magnusson 1973). With the exception of the Kallmora Silver Mine, all the mineralizations described here are Cu-Fe sulphide-dominated.

In the opinion of Geijer (1964) and Magnusson (1973) the formation of the iron ores and the sulphide ores is definitively separated in time, the sulphides always being later. The time interval is considerable; the deposition of the iron ore belongs to the "older" volcanogenic event whereas the sulphides are related to solutions which emanated coeval with the intrusions of the Early Svecokarelian plutonics (Magnusson 1953). In some of the skarn iron ores the solutions gave rise to magnetite in connection with the formation of the sulphides. In the opinion of these authors, there are transitions between the sulphide-impregnated older iron ores and the contact-metasomatic sulphide ores with magnetite. The addition of contact metasomatic iron is mainly represented by skarn iron ores rich in Mg-bearing minerals.

However, in accordance with what has been stated by Koark (1962), there seems to be clear evidence of a primary coeval formation of the sulphide and the iron ores of Central Sweden. There is scarcely any sulphide ore without magnetite, and the iron ores mostly contain sulphides in greater or smaller amounts. The time interval between the iron and the sulphides is, if seen in a larger context, only relative. On a minor scale (in hand specimens, thin sections etc.) the sulphides always appear later than the iron oxides; the magnetite has often an idiomorphic habit whereas the sulphides are anhedral, occurring as veins and replacing the magnetite. The present textures are, however, due to recrystallization phenomena and the later appearance of the sulphides is due to their greater mobility under metamorphic conditions.

Magnetite in the different types of iron ore and in the sulphide ores of Central Sweden has a similar chemical composition (Frietsch 1982b). This concerns also the magnetite in the iron ores which have been affected by Mg-metasomatic alterations. This compositional homogeneity presents positive evidence for a single phase of iron ore formation because, if formed by two different processes, volcanogenic and contact metasomatic as postulated by Geijer and Magnusson, variations in the magnetite composition should be expected.

An important feature when discussing the relationship between the iron ores and sulphide ores is that in a regional context, there is an intimate spatial connection between the two types of mineralization. This is supported partly by the stratabound appearance of the sulphides which follow the same horizons as the iron ores. As already outlined above there is a chemical relationship between specific types of iron ore and sulphide ore. Examples of the stratabound nature of the sulphides and their chemical affinity to iron ores is presented below.

Stratabound sulphides adjacent to iron oxides occur in the Svarthäll mine WSW of Kungsör (Lundegårdh 1974). Here occurs a dolomite containing three layers of magnetite ore, of which the middle one is manganiferous. Near to the iron ore, which contains quantities of sphalerite, there is a sphalerite impregnated skarn layer.

In the Ludvika area iron and sulphide ores occur on both sides of the Stollberg synform, the central part of which is made up of argillitic schists and greywackes (Fig. 4). On the eastern side of the synform there is a limestone-dolomite which is absent to the west resulting in an asymmetrical structure. Mg-rich alterations occur on both sides of the synform and form persistent layers along the strike. In the opinion of Hjelmqvist (1937) these formations cut obliquely over the schistosity, but recent mapping by Luossavaara-Kiirunavaara Prospecting Company (L.G. Ohlsson, oral comm.) shows that these occurrences are stratiform.

In the Stollberg synform manganiferous skarn iron ores appear on both sides of the central core relatively close to the sediments. Further outwards non-manganiferous skarn iron ores occur; in addition quartz-banded iron ores appear to the west. Associated with, and adjacent to the manganiferous skarn iron ores at Västra Silvberg (Svartberg, Dammsberg and Stollberg), Hilläng and the somewhat more northerly Knipgruvan, sulphide ores with sphalerite and galena are found (Hjelmqvist 1937, Geijer and Magnusson 1944). Further north-west and adjacent to non-manganiferous skarn iron ores, the Brunnsvik, Sörvik and Bastberg deposits contain sulphides mostly consisting of pyrrhotite, pyrite and chalcopyrite.

In the Stollberg synform there is thus a clear "zonation" of different ore types. Outwards from the metasediments to the stratigraphically lower parts in the volcanic sequence, there occur manganiferous skarn ores and Zn-Pb sulphides/quartz-banded iron ore/non-manganiferous skarn iron ore and Cu-Fe sulphides.

Seen in a regional context the following features concerning the distribution of the iron and sulphide ores of Central Sweden are considered relevant. Starting from the Stollberg synform and turning to the south, the same close relationship between the argillites and greywackes, manganiferous skarn iron ores and Zn-Pb-sulphides is found (Fig. 2, back cover). The sedimentary synforms at Hällsjö, east of Grängesberg, and further south at Ställdalen, are on both sides bordered by manganiferous skarn iron ores with sulphide ores also occurring close to the sediments. Turning further west to the synforms at Grythyttan and Saxå, the central part with the sediments is surrounded by potassic volcanites, manganiferous skarn iron ores and also manganese oxide-iron oxide deposits (Långban, Harstigen, Pajsberg, and Sjögruvan). Sulphide mineraliza-

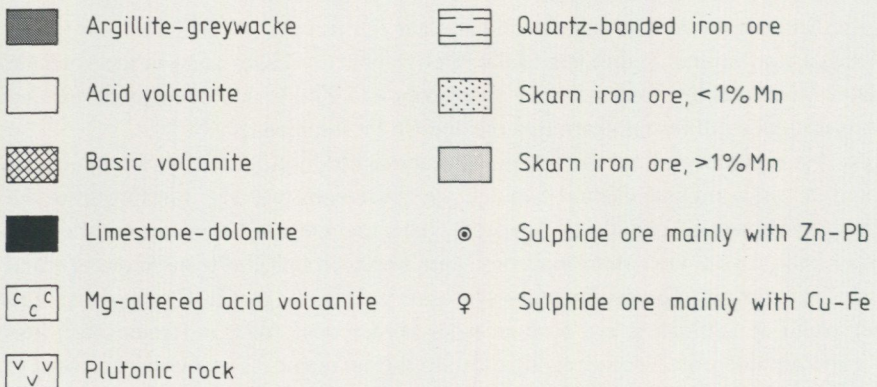
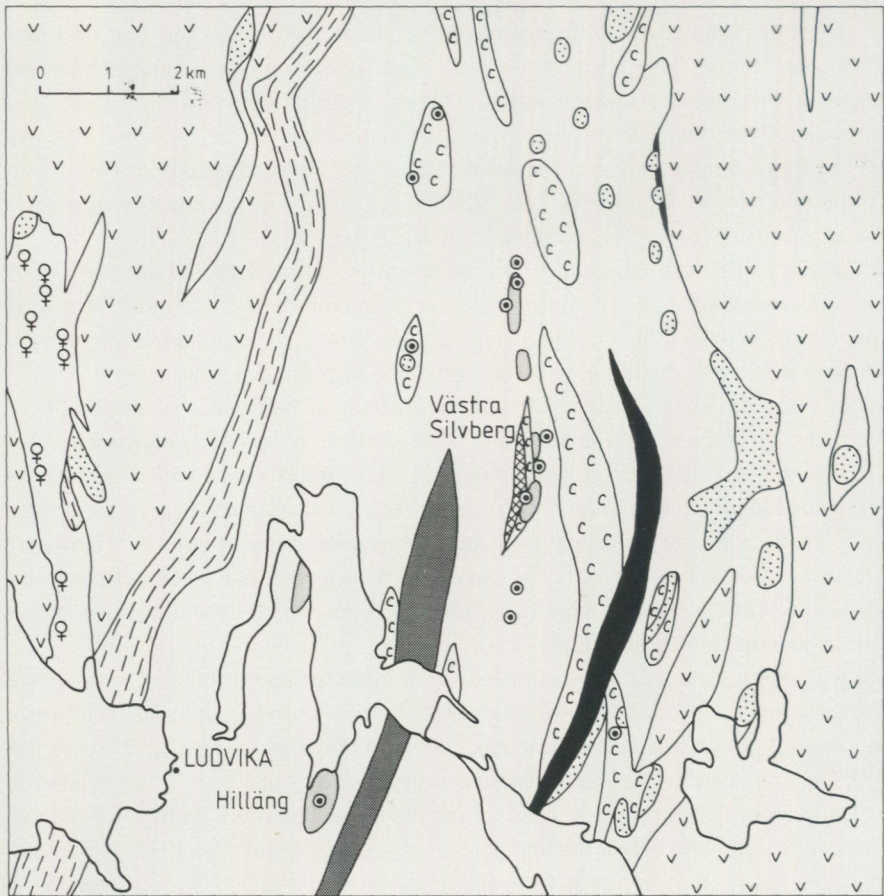


Fig. 4. Schematic map showing iron ores and sulphide ores of the Stollberg synform, north-east of Ludvika. Simplified after Geijer and Magnusson (1944).

tions occur close to the sediments, partly near the manganese-bearing ores, partly within them.

The Nora-Lindesberg-Riddarhyttan-Fagersta-Norberg synformal structure contains a number of sulphide occurrences many of which occur in the vicinity of the manganese-bearing skarn ores. Mg-rich alteration rocks are scattered more or less continuously along the whole synform.

At Garpenberg and Hofors there are abundant sulphide occurrences mainly in the non-manganese-bearing skarn iron ores, but partly also in the manganese-bearing skarn iron ores. Many of the sulphide ores in the Garpenberg area and some of the sulphide ores in the Hofors area are sphalerite-galena-dominated, containing smaller amounts of chalcopyrite and pyrite.

It would thus appear that there is in Central Sweden an affinity between sulphide mineralization and skarn iron ores, especially the manganese-bearing. In the quartz-banded iron ores the occurrence of sulphides is rare which is in common with the manganese oxide ores of the Långban type; small amounts of sulphides are only encountered in the Långban and Slöjdartorp deposits. Therefore it seems plausible that the sulphide ores and associated Mg-rich alterations have a stratabound appearance and that their deposition is connected with the volcanism, in the main coeval with the deposition of the iron ores. The stratabound appearance of these formations renders the previous hypotheses of a magmatic affiliation bound to the Early Svecokarelian plutonics untenable. An indirect indication that the sulphides, iron ores and Mg-rich rocks are not related to magmatism but to the volcanism, is that the ores and Mg-alterations do not occur in the sediments adjacent to the volcanites.

The occurrence of the sulphides and the Mg-rich alterations in the Early Svecokarelian plutonites and the still younger metabasite dykes in the Dannemora, Mårtanberg, Herräng, and Lövåsen deposits (cf. p. 19) cannot be explained by the postulated volcanogenic mode of formation. The late appearance of the sulphides, at least in some cases, is possibly due to mobilization in association with metamorphic processes. An indication of the ductile behaviour of the sulphides when subjected to stress is found in the Saxberget deposit where directed pressure and a temperature of about 600°C during regional metamorphism has resulted in the total mobility of the (syngenetic) sulphides, now present as interstitial fillings in a brecciated skarn (Selkman 1980). However, the textural implications of the sulphides and the Mg-rich alterations cannot as yet be considered conclusive.

#### A MODEL FOR THE FORMATION OF THE ORES OF CENTRAL SWEDEN

On the basis of the evidence cited above, a model for the formation of the different types of iron ores and sulphide ores in Central Sweden is proposed. The ores are volcanogenic, exhalative-sedimentary in origin, resulting from the precipitation of submarine volcanic emanations into basins, each ore type formed under specific

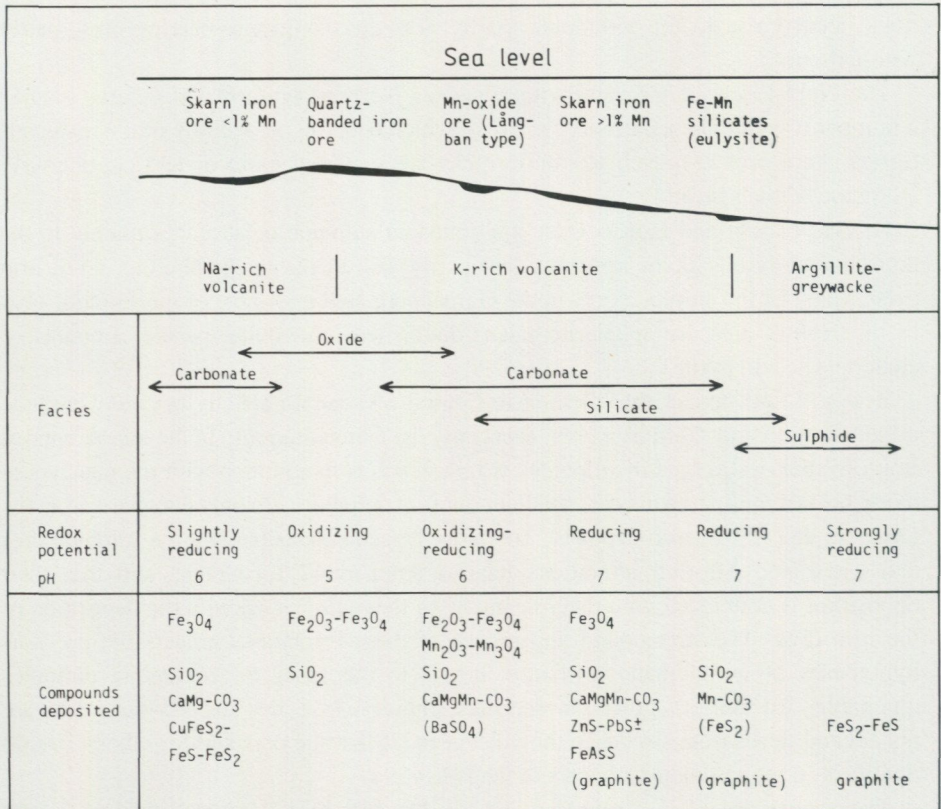


Fig. 5. The environment of deposition for the different types of iron, manganese and sulphide ores in Central Sweden.

conditions. Schematically the evolution is shown in Fig. 5. The different ore types are interrelated both spatially and in time.

During the early stages of the volcanism there occurred the deposition of limestones and dolomites together with iron and silica, now represented by the non-manganiferous skarn iron ores. Where excess silica in relation to the carbonate was precipitated, quartzitic skarn ores occurred under conditions which were slightly reducing and slightly acid. Copper was precipitated as chalcopyrite together with pyrite and pyrrhotite. In the more surface-near parts of the basins there was a deposition of iron and silica and an absence of carbonates; these formations are represented by the quartz-banded iron ores. The redox potential was too high for any formation of sulphides. With ongoing volcanism, increasing carbonate deposition occurred in the deeper parts of the basins where conditions were relatively reducing, this being indicated by small amounts of graphite. In association with the carbonates, iron, manganese and silica were precipitated forming the manganiferous skarn ores with iron-manganese silicates.

At this stage of the basin evolution, with a high activity of reduced sulphur, zinc and lead were precipitated as sphalerite and galena. However, adjacent to the quartz-banded iron ores, where the conditions changed from oxidizing to reducing, manganese was precipitated as oxide and hydroxide in the ores of the Långban type. Late veins containing barite, native lead, pyrochroite, and arsenates were formed by redox reactions between the manganese oxides and introduced sulphides (Magnusson 1930, Boström *et al.* 1979). In the deepest part of the basins, greywackes and argillites formed with associated graphite-pyrite-pyrrhotite which strongly suggests reducing (euxinic) conditions. The occurrence of the iron-manganese-rich silicates (eulysites) in the stratigraphically highest part of the volcanics and in the bottom part of the overlying metasediments, indicates that the precipitation of iron and manganese continued until the final stage of volcanism.

The ore-forming hydrothermal solutions caused alterations of the host volcanics to Mg-rich assemblages. These alterations have a relatively restricted extension confined to the sulphide ores and occasionally also to the iron ores. The main chemical changes affecting the volcanics is, however, the large-scale metasomatic alteration that formed the Na- and K-extreme and silica-enriched (rhyolitic) rocks in which the ores occur (Frietsch 1982c). This secondary, internal re-arrangement of the chemistry is most intense in the ore-bearing areas, in contrast to the barren areas where the volcanics have a more mafic, alkali-intermediate character represented by dacites and andesites; possibly the primary pre-alteration volcanism had such a composition. The mechanism causing this Na-K division is obscure, but may be due to varying degrees of hydration; a more intense one forming the K-rich rocks. The alkali division is accompanied by specific chemical associations. There seems to be a relationship between the Na-rich rocks and Cu-Fe sulphides, and between the K-rich rocks and Mn oxides-silicates and Zn-Pb sulphides. The affinity between K, Mn, Zn, and Pb is very pronounced.

In the above-proposed model the formation of the different ore types is assigned to variations in the depositional environment. The compositional differences of the ores can be ascribed mainly to variations of temperature, redox potential, alkalinity and sulphur activity. For the deposition of the different iron ore types, considered to represent different iron formation facies, Eh and pH are decisive. The iron ores are chemical sediments resulting from direct precipitation onto the sea-floor of the basins, the water depth being of great importance. These sediments are thus sensitive indicators of the depositional environment in terms of the Eh and pH (Gross 1965, Goodwin 1973a, 1973b). Opposed to this is the formation of the volcanogene sulphide ores which is dependent on a multitude of variables which have an influence on the composition and also the appearance of the ores. The metals and the sulphur emanate from hydrothermal fluids discharged just below the sea-floor or onto it. There is a mixing of the ore-bearing fluids with sea-water or connate water and, due to changes in temperature, oxygen fugacity, alkalinity, sulphur activity and dilution, different kinds of sulphide assemblages are deposited (Lusk 1972, Rye and Ohmoto 1974, Large 1977). Below the massive ores there is a feeder channel or pipe with "stringer ore"

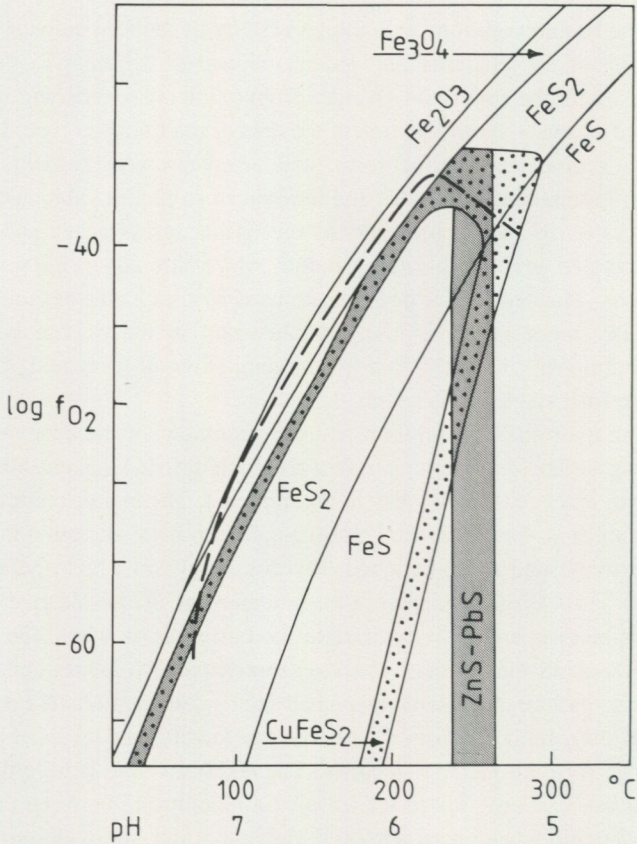


Fig. 6. Mineral stabilities of the system Fe-S-O and chalcopyrite, sphalerite and galena as a function of oxygen fugacity, pH and temperature with constant  $\Sigma S = 10^{-2}$  M and 1 M NaCl. After Large (1977).

comprising veins and impregnations. In this foot-wall part the volcanics are also chloritized, sericitized and silicified with quartz-sericite and Mg-rich assemblages being the most common alterations. The hydrothermal ore-bearing solutions may emanate from magmatic sources; being discharged from submarine volcanic vents (fumaroles). However, a geothermal model with convective circulation of surface water, most probably sea-water, is mainly favoured (Ellis 1967, Corliss 1971, Sangster and Scott 1976, Solomon 1976, Chapman and Spooner 1977). By this convective cell there is a leaching of metals from local volcanic and sedimentary rocks. The volcanics had a great influence on the process as a heat source. By the interaction between volcanics and sea-water, alteration minerals are formed. These reactions are highly exothermic and may release energy in significant amounts to contribute to the heat flow on the sea-floor (Hart 1973, Fyfe *et al.* 1978). The hydrothermal fluids are

released from fractures or other zones of weakness at the sea-bottom (Spooner and Fyfe 1973, Sangster and Scott 1976).

The conditions under which the sulphides in the ores of Central Sweden were formed can be elucidated by some physico-chemical data. According to Anderson (1973) the transport and deposition of galena and sphalerite in ore quantities can be brought about by slightly acid, chlorine-rich brines in which the sulphur content is low and predominantly exists as sulphate. The solubility of these sulphides is decreased by increased pH, decreased temperature and increased dilutions of the ore solutions. A co-precipitation of chalcopyrite necessitates a high activity of reduced sulphur. The ore solutions must be slightly acid with an oxygen fugacity of around  $10^{-50}$  atm. Large (1977) when studying the mineral-solution equilibria in massive sulphide ores, suggested that they are deposited from high temperature, mildly acid and reduced chloride-rich solutions. An increase in pH and sulphur activity accompanied by a drop in the temperature leads to the precipitation of the chalcopyrite-iron sulphide association followed by the sphalerite-galena assemblage. The pyrite-pyrrhotite-chalcopyrite assemblage, in Central Sweden associated with non-manganiferous skarn iron ores, is according to the diagrams by Large (1977) precipitated at 200–300°C with a pH of about 5 and an oxygen fugacity of about  $10^{-36}$  atm (Fig. 6). The sphalerite-galena assemblage, which is mainly bound to the manganiferous iron ores, is precipitated at lower temperatures (about 100°C), at higher pH values (around 7) and at a lower oxygen fugacity (around  $10^{-60}$  atm). The deposition of zinc and lead under these conditions, however, necessitates that during the deposition of the pyrite-pyrrhotite-chalcopyrite assemblage, sulphur in the oxidized state ( $S_o$ ) was quite dominating over reduced sulphur ( $S_r$ ), that is the  $S_o/S_r$  ratio was high. If the  $S_o/S_r$  ratio had been low, the zinc and lead would also have been precipitated together with the copper and iron sulphides.

The formation of the chalcopyrite-pyrite-pyrrhotite and the sphalerite-galena assemblages thus occurred at relatively high and relatively low temperatures respectively. In addition there is a principal difference in the mode of emplacement between the two assemblages. In this respect the sulphide ores and other exhalites are generally divided into proximal deposits, in which the exhalative solutions debouched metals in the exhalation vent or very close to it, and distal deposits where the deposition occurred outside the volcanic vent. Certain authors, in the latter case, consider the distance between volcanic vent and ore deposit to be considerable (cf. Riddler 1973, Plimer 1978). According to Large (1977) the massive chalcopyrite-pyrite±pyrrhotite ores are typically proximal and of near-surface replacement origin, overlying pipes of hydrothermal origin, whereas the pyritic Pb-Zn-(Cu) sulphide ores range over the proximal-distal classification and generally result from direct precipitation onto the sea-floor. The distal ores are precipitated within restricted basins due to the metal-bearing brines having moved some distance from the fumarolic outlet. Plimer (1978) indicated that with increasing distance in time and space from the volcanic centre, the copper content in the iron sulphide ores decreases and the zinc, lead, silver, and

manganese contents increase. The trend from copper-dominant to zinc-lead-dominant iron sulphide ores is a result of increasing mixing of sea-water with the metal-bearing fluid with increasing distance from the volcanic centre. The foot-wall alteration pipes, *i.e.* stringer and dissemination ores with quartz-sericite and Mg-rich assemblages, are spatially connected with proximal metal deposits, whereas slight alteration to quartz-sericite and Fe-(Mn)-bearing assemblages are associated with distal deposits. According to the hypotheses by Large (*ibid.*) and Plimer (*ibid.*) the chalcopyrite-pyrite-pyrrhotite assemblages of Central Sweden should thus be proximal and the sphalerite-galena assemblages distal. However, as long as the site of volcanic centres and vents is not known for Central Sweden, there is no justification for making any distinction between proximal and distal ores. Nevertheless considering what has been stated above, proximal ores are represented by deposits in which the foot-wall (below a massive sulphide ore body) contains sulphides in a stockwork ('stringer zone') and is strongly metasomatically altered. The distal ores lack these features. The metamorphism has masked the primary structures in the sulphide ores of Central Sweden, consequently the reality of what has been referred to as a 'stringer zone' is not possible without detailed studies. It should be emphasized that most of the sulphide ores at present have a stratiform appearance, and it seems likely that any discordant structures, if present, have been totally obliterated by the metamorphism. However, in almost every deposit there are Mg-rich alteration rocks present, and if these are significant in the sense of proximal and distal ore formation, it would mean that most of the sulphide ores of Central Sweden are proximal. Only the Åmmeberg Zn-Pb ore in which Mg-alterations are not present, would consequently be of a distal nature (p. 32).

Even if great uncertainties still exist in interpreting the nature of the sulphide ores of Central Sweden, it is here postulated that the formation of the chalcopyrite-pyrite-pyrrhotite assemblage is of a higher temperature origin, deposited near to the volcanic vents, whereas the sphalerite-galena assemblage is a more distal formation precipitated at lower temperatures some distance from the volcanic vents and under 'deep-water' conditions. The sulphide ores of Central Sweden are mainly Zn-Pb ores whereas copper-bearing ones from the economic point of view are few. Examples of the latter, representing active production during the last few decades, are found at Ljusnarsberg (1.4% Cu, 1.5% Zn and 1.0% Pb) and at Tomtebo (1% Cu and 1% Zn) (Grip 1978). In common to what has been found by Sangster (1972) and Sangster and Scott (1976) for the Precambrian massive sulphide ores in Canada, there is a tendency for the economic sulphide accumulations in Central Sweden to occur towards the centre (deep water) portions of the depository basins, as defined by the various iron-formation facies.

The 'deep-water' Zn-Pb sulphide assemblages are almost totally restricted to limestones and dolomites which form intercalations in the K-rich volcanics. Without doubt the largest carbonate deposits are found in this part of the volcanic sequence. The origin of the carbonate rocks within the volcanic pile is still unclear; the carbonates are mostly considered as formed by chemical precipitation in connection with the volcanism (*cf.* Lundegårdh 1971, Magnusson 1973). Geijer (1967) discussed a pos-

sible contribution of carbonates to the sea by thermal waters, but assumed a biogenic origin as most probable for the carbonate beds in the volcanics of Central Sweden. This was *inter alia* based on the occurrence of algal reefs at the Sala silver mine (Collini 1965) which occurs in a Na-rich volcanite (Tegengren 1924). In addition, well-developed stromatolites have recently been found in the Dannemora manganese skarn iron ore lying in a potassic volcanite. The occurrence of these algal reefs would indicate, as already pointed out by Geijer (1967), a precipitation of the carbonates in a shallow shelf environment. This would be in contradiction to the earlier-made statement necessitating the formation of the manganese skarn ores in a "deep-water" environment, at least concerning the Dannemora ore. Fossil calcareous algae have always been considered as indicative of shallow well-oxygenated water formed in an intertidal zone, but new data show that blue-green marine algae can actively grow down to at least 1000 m depth (Monty 1977). In total darkness chemical reactions (with Fe, Mn and S) or bacterial metabolism ensure the required energy synthesis. According to Brock (1976), Hoffman (1976) and Playford *et al.* (1976) deep-water stromatolites grow to depths of 100 m or more below sea level. In consequence the stromatolites in the Sala and Dannemora carbonates do not necessarily indicate a shallow water deposition exclusively, and could as well in accordance with the model proposed above, have been deposited in more deep-water conditions. It is noteworthy that iron and manganese oxide concentrations have been encountered in deep-water stromatolites from the Cannin basin of Western Australia (Playford *et al.* 1976). Of special interest is that in the same area a lead-zinc ore body occurs above the deep-water stromatolites and is possibly genetically related to these.

#### PRACTICAL IMPLICATIONS OF THE MODEL PROPOSED

The model for the formation of the iron and sulphide ores of Central Sweden discussed in this paper, has some important practical implications. The common association of magnetite and sulphides in this region is of great significance when prospecting for sulphide ore. There is scarcely any sulphide mineralization which is devoid of magnetite, or which does not occur relatively close to iron ore. The only exceptions seem to be the Falun and Ämmeberg deposits (see below). This means that when prospecting for sulphide mineralizations magnetic anomalies are useful path-finders. However, most of Central Sweden has already been covered magnetically both on the ground and from the air and therefore the chance of finding hitherto unknown sulphide-bearing ore horizons by this method must be relatively restricted.

The other conclusion based on the present theory is that the horizons with manganese skarn iron ores in the K-rich volcanics can indicate the presence of zinc-lead ores. This is especially important for potential silver finds as the content of silver is roughly correlated to the content of lead, the silver being mainly bound to galena (Frietsch 1980a).

The Mg-rich alterations have long since been known as an exploration guide for the sulphide ores of Central Sweden. As previously pointed out (p. 18) not all Mg-rich rocks are ore-bearing. However more detailed knowledge of the regional extension of the Mg-alterations, than the very simple compilation in the sketch map in Fig. 2 (back cover), might be of great value for indicating new potential sulphide-bearing areas.

### THE FALUN AND ÅMMEBERG SULPHIDE DEPOSITS

The Falun deposit is in many respects unique among the sulphide ores of Central Sweden. It is the largest, representing about 35 million tons of ore, whereas most of the other deposits are small, around 1–3 million tons of ore. The ore minerals are in order of decreasing amount: pyrite, sphalerite, pyrrhotite, galena and chalcopyrite. Of these pyrite is quite dominating; the main body is a Cu-Zn-Pb-bearing pyrite ore with about 35% S. Of special interest is that iron oxides are almost totally lacking. Magnetite is present in small amounts outside the main ore body in the chalcopyrite-(pyrite-pyrrhotite-sphalerite) disseminations which form the rest of the deposit (Törnebohm 1893). Koark (1960) described loose blocks of a stratified quartz-banded iron ore with pyrite and sphalerite; the provenance of this ore type is not known, but is possibly connected with the main pyrite ore. Also on a more regional scale iron oxides are scarce in the Falun area (Fig. 2, back cover). There are only a few deposits of the non-manganiferous skarn ore type, all of small size (Geijer 1917, Hjelmqvist 1948). This lack of iron oxides is confirmed by the aeromagnetic measurements which show that significant anomalies are missing in the area. The Mg-rich altered rocks (mica schist and quartzite) represent the largest continuous occurrence of such rocks in Central Sweden. The alteration zone has an E–W extension of 11 km and comprises besides Falun the sulphide ores of Skyttgruvan, Näverberg and Domängruvan.

In summary the Falun ore differs from the other sulphide ores of Central Sweden by its large extent, the richness in pyrite, the absence of magnetite, and the large extension of Mg-rich alteration rocks. In consequence the Falun ore must have been formed under conditions different from those in the other deposits. No relevant explanation can be provided at present for the special character of the Falun ore. The only certainty is that the formation of the Falun ores occurred at a relatively low oxygen fugacity, otherwise iron oxides and not only iron sulphides would have formed. In addition, the deposits show traits of a "proximal" ore as outlined above, *i.e.* a massive pyrite ore body surrounded by chalcopyrite-pyrite-pyrrhotite disseminations in a strongly metasomatically altered wall rock. The Falun deposit has by Plimer (1978) been assigned to the proximal type.

The origin and characteristic features of the sulphide ores in Central Sweden can scarcely be treated without taking the Åmmeberg Zn-Pb ore into consideration. The deposit lies in the southern part of the region and separated from the other deposits (Fig. 1). The ore is sphalerite-galena banded and forms long narrow layers in a banded

supracrustal "leptite" which contains intercalations of limestone, Ca-Mg skarn and greenstone (Henriques 1964). The "leptite" represents a mixed sequence with lava rocks and pyroclastic-epiclastic-chemical sediments. To the north this unit is bordered by potassic volcanics and to the south by veined gneisses. The ore is clearly stratabound in the "leptite"-limestone-skarn sequence and no Mg-rich mineral assemblages are known. Between the veined gneisses and the ore there is a calcareous skarn-rich layer impregnated with pyrrhotite. The zinc-lead ore is considered as epigenetic resulting from the Late Svecokarelian migmatization (Geijer and Magnusson 1944, Magnusson 1948, 1970), whereas Henriques (1964) indicated that the ore is syngenetic and formed by submarine hydrothermal solutions.

There is little doubt of the stratabound nature of the Åmmeberg ore and its volcanic affiliation. However, the absence of Mg-rich alterations in the wall rock suggests conditions of deposition different from those prevailing in the main part of the sulphide ores of Central Sweden. In common with the Falun deposit, the Åmmeberg ore occurs in an area where iron ores are missing. The nearest ones lie at a distance of 2-3 km. In addition there is no magnetite in the Åmmeberg ore. The depositional environment was reducing as shown by the adjacent pyrrhotite-bearing horizon, and by the fact that no magnetite is present in the ore. A reducing environment of deposition is also favoured by the occasional occurrence of graphite, locally present in concentrations up to 0.3%, in the ore. The absence of Mg-rich alterations, the Pb-Zn dominance and the mixed volcanite-sediment character of the wall rock, points to the deposition of the Åmmeberg ore at some distance from the volcanic sources, representing a more "distal" formation.

#### COMPARISON OF THE SULPHIDE ORES OF CENTRAL SWEDEN WITH SOME PRECAMBRIAN AND PHANEROZOIC SULPHIDE ORES

The sulphide ores of Central Sweden show in many respects similarities with other Precambrian and Phanerozoic volcanogene sulphide ores in the world. The Precambrian massive sulphide ores of Canada occur, like the ores of Central Sweden, in calc-alkaline submarine volcanic rocks (Sangster 1972, Sangster and Scott 1976). The Canadian ores are genetically associated with an acid, explosive phase of volcanism represented by agglomerates and coarse breccias. Such rocks of any extension are not known in Central Sweden. Only locally, as described by Vivallo (1978) from the Garpenberg area, volcanic breccias are encountered. Other common host rocks for the sulphide ores in Canada are quartz porphyries and transitions between volcanites and sediments. The Canadian ores are overlain by, or grade into, a cherty iron formation with oxide, carbonate and sulphide facies. The relationship between the sulphides and the iron formations is not quite clear, but there seems to be a tendency for economic sulphide accumulations to occur towards the deeper parts of the basins as defined by the different iron formation facies. This indicates similar conditions to the ores of

Central Sweden as described above. In contrast to the ores of Central Sweden where sulphides are clearly associated with the iron ores, and the sulphide ores throughout are magnetite-bearing, the Canadian sulphide ores only occasionally contain substantial amounts of magnetite (Goodwin 1965, Lang *et al.* 1970, Sangster 1972), mainly in the stratigraphically lower parts (Large 1977). Occurrences with magnetite and sulphide associations are *e.g.* found in the Matagami area (Sharpe 1968).

In the Canadian ores the host rock alteration represents an increase in magnesium, iron and sulphur and a decrease in silica, potassium and sodium, thus in principle being similar to that in the Swedish ores. Mg-metasomatism is the dominant foot-wall alteration resulting in chloritization, although sericitization, silicification and carbonatization are also encountered. The chloritic alteration is subsequently transformed by metamorphism into hornblende, biotite, cordierite, and antophyllite, an assemblage common to the alteration rocks accompanying the sulphide ores of Central Sweden. In the Canadian deposits the foot-wall contains "stringer ore" ("vein ore") representing channels for the ore solutions. As already pointed out (p. 30) it has not yet been possible to demonstrate the occurrence of "stringer ore" associated with the sulphide ores of Central Sweden. Neither is it possible to demonstrate any metal zonation in the massive ores as in the Canadian deposits where the lower ("stringer") ore is characterized by chalcopyrite-pyrite in contrast to the upper (massive) ore where galena and sphalerite dominate. However, in common with the Canadian ores, the ores of Central Sweden are also poor in barite. In Sweden some exceptions do occur and barite is found in the sulphide ore of Garpenberg Norra (Grip 1978), in the quartz-banded iron ore of Saxen (Frietsch 1957), in the quartzitic iron ore of the Myrback type in Riddarhyttan (Geijer 1923), in the manganiferous skarn iron ore of Strömshagsgruvan, Vattholma (Geijer and Magnusson 1944, Åhman 1973), and in the manganese ores of the Långban type in Nordmark and Långban (Magnusson 1929, 1930).

The ores that occur in the Palaeozoic pyrite belt in Spain and Portugal (Strauss and Madel 1974, Strauss *et al.* 1977) are stratiform formations of syn-sedimentary-exhalative origin, associated with a submarine acid explosive volcanism, appearing in the main as pyroclastites with subordinate amounts of schists and basic lavas. In part the ores occur in the schists. There is a pre-tectonic alteration of feldspar tuffs into quartz-chlorite rocks and coeval with the sulphides, or somewhat younger, is a manganese formation consisting of ferruginous chert with primary manganese silicates and carbonates. The similarity with the sulphide ores of Central Sweden is thus relatively restricted.

The sulphide ores of Central Sweden differ from the Tertiary stratabound sulphide ores in Japan (the so-called Kuroko type) in several respects. In the Swedish ores sulphates such as anhydrite and gypsum are missing and barite occurs only rarely. This feature could, in accordance with what Sangster (1972) postulated for the Canadian ores, be due to a deficiency in oxygen in the Proterozoic atmosphere, and consequently no sulphates were formed. In the Japanese ore bornite and tetrahedrite are common,

whereas these minerals in the Swedish ores are rare and occur only in a few deposits. In the Japanese ores magnetite and pyrrhotite are absent (Large 1977). The Japanese ores occur in a sequence of volcanics interlayered with sediments, mainly mudstones, but siltstones and sandstones also play an important role (Sato 1974, Sato *et al.* 1974). At the top of the ore-bearing sequence there is a layer of ferruginous quartz which is quantitatively quite unimportant having a thickness of only some centimetres (Tanaka *et al.* 1977, Shimazaki 1977).

The deposition of the Canadian, Spanish-Portuguese and Japanese sulphide ores is at least partly governed directly or indirectly by major structures of an epeiorogenic nature. According to Sangster (1972), deposition of the Canadian ores is not only stratigraphically but also tectonically controlled, in that suitable volcanics, or the ores themselves, are aligned along local linears (*e.g.* the ores of the Noranda area). The ores in the Iberian belt are connected to acid volcanism, where the centres are located along lineaments (Strauss and Madel 1974). The Japanese ores occur mostly at the margins of sedimentary basins; the major intrusive igneous activity is controlled by large faults (Sato *et al.* 1974).

In summary, the sulphide ores of Central Sweden are both similar and dissimilar to the massive sulphide ores of Canada, Portugal-Spain and Japan; the Swedish ores seem most similar to the Canadian ones. A notable difference is that the Swedish ores are associated with large amounts of iron oxides and iron-manganese silicates, which are mainly coeval with the sulphides (*i.e.* with zinc and lead); the iron and manganese ores tend to dominate over the sulphide ores. Appreciable amounts of iron oxides seem only to be present in some of the Canadian sulphide mineralized regions, such as the Abitibi orogenic belt (Goodwin and Ridler 1970) and the Manitouwadge district (Sangster and Scott 1976). The iron-manganese-bearing (silicatic) eulysites overlying the main Mn-Fe-Zn-Pb deposition in Central Sweden are, however, very similar to small iron- and manganese-beds which, according to Stanton (1976), are a common feature in association with stratiform base-metal sulphide ores. There is a close connection both in space and time between the sulphide ores and these silica-iron-rich sediments. The iron occurs both as oxide (magnetite) and silicate, and manganese is often present, bound to silicates. There is a striking similarity between the eulysites of Central Sweden and the manganiferous oxide-silicate iron-formations with dispersed pyrite-pyrrhotite ('vasskies') that occur in Palaeozoic mafic volcanics and metasediments in the Caledonides of Norway (Carstens 1924, Nilsen 1978, Grenne *et al.* 1980, Boyle 1980). The presence of pyrite-pyrrhotite and their appearance in graphitic sediments supports what has been suggested for the Swedish eulysites, *i.e.* deposition in a reducing environment. Other examples illustrating the intimate association between iron-manganese-bearing sediments and sulphide deposits in mafic volcanics is given by Bamba (1974) and Fryer and Hutchinson (1976), in felsic volcanics by Whitehead (1973) and in mixed volcanic-sedimentary associations by Stumpfl (1979).

## SUMMARY

The non-apatitic iron ores, manganese ores and sulphide ores of Central Sweden are of volcanogene, syngenetic origin formed by exhalative-sedimentary processes in connection with an Early Proterozoic ( $> 1\ 900$  Ma old) calc-alkaline magmatism. The host rocks consist of felsic metavolcanics with intercalated limestones and dolomites. Within the volcanic sequence there are Na-rich and K-rich rocks, the latter occurring preferentially in a higher stratigraphic position. The alkali division is due to large-scale metasomatic alterations which took place during the latter stages of the volcanic activity. The chemical changes are most pronounced in the ore-bearing volcanics which indicates a genetic connection between the post-volcanic alterations of the volcanics and the ore-forming processes. The volcanics are both under- and overlain by argillite and greywacke metasediments which in the western part of Central Sweden occupy the central parts of long and narrow synforms. The volcanics and sediments were folded and metamorphosed during the Svecokarelian orogeny.

The ores were formed by hydrothermal fluids in association with the volcanism and subsequently deposited in submarine basins. The varying ore types reflect different conditions of deposition, mainly due to variations in temperature, redox potential, alkalinity and sulphur activity. The different ore types occur in a definite order with reference to their position in the volcanic sequence.

There is a close relationship between the different types of iron and manganese ore and their stratigraphic position and the Na-K composition of the host rock volcanics. The lower Na-rich volcanics contain non-manganiferous skarn iron ores and the upper, K-rich volcanics, contain manganiferous skarn iron ores, iron-manganese oxide-silicate ores of the Långban type and iron-manganese silicate rocks (eulysites). The latter also occur locally in the stratigraphically lowest part of the argillite and greywacke sediments that overlie the volcanics. Quartz-banded iron ores occur both in the Na- and the K-rich volcanics, mostly relatively high in the stratigraphy.

On the basis of the stratigraphic position of the different iron and manganese ore types combined with the known tectonic structures, it is possible to show that the main structural pattern of the ore-bearing part of Central Sweden is that of NE, or less commonly NNW, trending synforms and antiforms. The non-manganiferous skarn iron ores occur in the antiforms and the quartz-banded iron ores, the manganiferous skarn iron ores of the Långban type, and the eulysites occur in the synforms. The latter form long and narrow structures which can achieve a length of more than 100 km.

The iron and manganese ores formed under conditions of changing redox potential and alkalinity which were dependent on the water depth of the depositional basins. Essentially the ore-types reflect facies variations in accordance with James (1954) and Goodwin (1973a, 1973b) *i.e.* with increasing water depth oxide/carbonate/sulphide facies are formed. The deposition of the quartz-banded iron ores (oxide facies) indicates relatively oxidizing and acid conditions whilst the skarn iron ores were

deposited under more reducing and alkaline conditions. The non-manganiferous skarn iron ores (carbonate facies) were formed at a redox potential somewhat below zero and at slightly acid conditions. The manganiferous skarn iron ores (carbonate-silicate facies) and the eulysites (silicate-sulphide facies) were deposited under still more reducing conditions. The simultaneous precipitation of divalent iron and manganese in the two latter ore types requires a redox potential much below zero, otherwise manganese oxides would have formed. Supporting evidence for deposition under reducing conditions is represented by the presence of sulphides, mainly sphalerite and galena, and some graphite in the skarn iron ores; the eulysites contain pyrite-pyrrhotite. Both types of ore occur close to, and the eulysites partly within, the argillite and greywacke sediments which were formed in deeper water under euxinic conditions, this being indicated by their content of graphite and iron sulphides. In the Långban type of ore, iron oxides and manganese oxides plus divalent iron-manganese silicates are associated. This ore type, intermediate between the quartz-banded iron ores and the manganiferous skarn iron ores, was deposited under conditions changing from oxidizing to reducing. The first formed trivalent iron-manganese oxides plus silica settled under oxidizing conditions whereas the later formed divalent-trivalent iron and manganese oxides, plus the  $(\text{Fe}^{2+} - \text{Mn}^{2+})$  silicates, settled under reducing conditions. At a late stage of formation sulphur was introduced. Redox reactions between the sulphur and earlier manganese oxides resulted in the formation of sulphates which were precipitated as barite, a mineral which is otherwise rare in the ores of Central Sweden. The total amount of manganese in the Långban type of ore is quite subordinate to that in the manganiferous skarn iron ores.

The sulphide ores of Central Sweden contain varying amounts of zinc, lead and copper. In the volcanics the main ore minerals are pyrite, pyrrhotite and chalcopyrite, whereas sphalerite and galena dominate in the limestones and dolomites. Magnetite in varying amounts is always present. The wall rock is metasomatically altered to a Mg-rich composition and some of the iron ores, mainly of the non-manganiferous skarn type, are also accompanied by Mg-rich rocks. The alterations, in a regional context, have a stratabound appearance, forming long and narrow discontinuous zones, often connected with the iron ore-bearing synformal structures. This indicates that the Mg-rich rocks represent syngenetic formations within the volcanism. The age relations of the Mg-rich alterations are however ambiguous; the Mg-rich minerals have partly a post-tectonic appearance in the volcanics. The occurrence of local alterations, in cases with sulphides, in Early Svecokarelian plutonites (around 1 900 Ma old) and still younger metabasite dykes both intersecting the volcanics, indicates that the Mg-metasomatic alteration is a multiphase process, with the main phase syngenetic with the volcanism.

The iron ores are more or less blended with sulphide phases common to those comprising the sulphide ore deposits. The sulphides are restricted to the magnetite ores; the hematitic ones are mostly barren. The manganiferous skarn iron ores contain sphalerite and galena and occasionally arsenopyrite and chalcopyrite, whereas the

quartz-banded iron ores and the non-manganiferous skarn iron ores mainly contain pyrite, pyrrhotite and chalcopyrite. The quartz-banded ores mostly lack sulphides. The same concerns the iron-manganese ores of the Långban type among which only a few deposits contain small amounts of sulphides.

The close association between the sulphides, specific types of iron ore and volcanics indicates the stratabound nature of the sulphides, being coeval with the iron ores and the Mg-rich alteration rocks. The later appearance of the sulphides in the iron ores is due to greater mobility of the sulphides during regional metamorphism. Evidence in favour of a volcanogene provenance of the sulphides and associated Mg-rich rocks, is that they are not found in the argillite and greywacke sediments close to the volcanics.

The formation of the sulphides is dependent on numerous variables among which temperature, oxygen fugacity, alkalinity and sulphur activity are important. The pyrite-pyrrhotite-chalcopyrite assemblage associated with the non-manganiferous skarn iron ores is formed at higher temperatures (200–300°C) and oxygen fugacities (about  $10^{-36}$  atm) than the sphalerite-galena assemblage associated with the manganiferous skarn iron ores, being precipitated at a temperature of about 100°C and an oxygen fugacity of around  $10^{-60}$  atm. Even if great uncertainties still exist concerning the mode of emplacement, it seems likely that the pyrite-pyrrhotite-chalcopyrite assemblage represents a moderate temperature of formation deposited near the volcanic vents, whereas the sphalerite-galena assemblage is a low temperature formation precipitated under deeper water conditions at some distance from the volcanic vents.

The common association of magnetite and sulphides in Central Sweden is of great significance when prospecting for sulphide ores. Most of them contain magnetite or occur close to iron ores. There is thus a possibility of finding sphalerite-galena mineralizations in the near vicinity of manganese-bearing iron ores in the K-rich volcanics. As silver is partly bound to galena, the same ore horizon is of considerable importance. Thus, from the lithochemical point of view, the association K-Mn-Zn-Pb-(Ag) is of crucial importance and should be a useful exploration guide.

The Falun deposit, the largest deposit of sulphide ores in Central Sweden, forms an exception to the others by not being accompanied by magnetite, neither in the ore nor in the surroundings. It is possible that the Falun ore, which is dominantly pyritic, was formed at a high sulphur activity thus preventing the precipitation of iron oxides. In the Åmmeberg deposit the stratified sphalerite-galena ore occurs in a mixed volcanite-sediment sequence without any Mg-rich alterations. The ore does not contain magnetite and iron ores are generally missing in the area. This possibly indicates deposition of the ore in a reducing environment at a greater distance from the volcanic source than considered for the other sulphide ores of Central Sweden.

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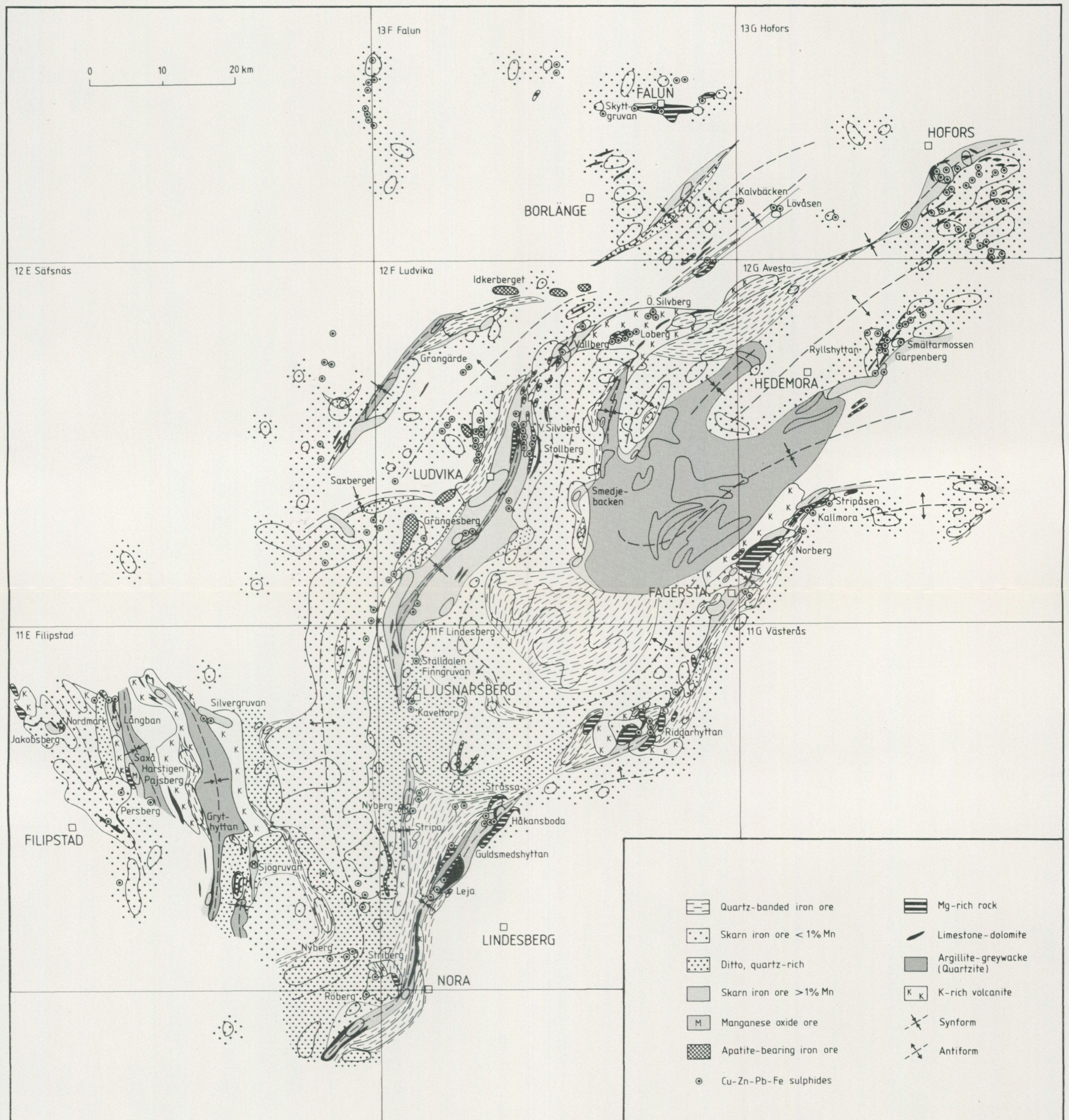


Fig. 2. The distribution of iron, manganese and sulphide ores and mineralizations in northwestern Central Sweden. Mainly based on data from Geijer and Magnusson (1944), Magnusson (1970) and geological map sheets. Irregular areas, bordered by thick solid lines, show the extension of the different formations. For the iron ores, a large number of deposits are mostly enclosed within the areas.

PRISKLASS D

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