

# Mn-silicate skarns from the Gåsborn area, West Bergslagen, central Sweden

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## Abstract

In the Gåsborn area, West Bergslagen, central Sweden, Mn-silicate–magnetite–jacobsonite skarns were formed as the result of three successive processes. (1) Deposition of exhalative–sedimentary manganese iron-ore-bearing sediments together with cherts and volcanics. (2) Intrusion of a synvolcanic anorogenic granite and some slightly younger gabbros and tonalites: under influence of these intrusives the manganese iron-ore-bearing sediments were metamorphosed into (a) rhodonite(I)–magnetite–pyrophanite–garnet assemblages; (b) (manganese) hedenbergite(I)–allanite–titanite–garnet–magnetite assemblages; (c) tephroite–jacobsonite–pyrophanite–garnet assemblages and (d) magnetite-bearing quartzites. (3) Release of hydrothermal fluids from the granite and subsequent alteration of the above assemblages into metasomatic infiltration skarns, consisting of rhodonite(II), garnet, hedenbergite(II), biotite, actinolite or edenite (with up to 20.11 wt.% MnO), chlorite, bementite, fluorite, helvite, rhodochrosite, hematite, rutile and accessory galena, sphalerite, wittichenite, aikinite, pyrrhotite, chalcopyrite and pyrite.

The maximum temperature ( $T$ ) and pressure ( $P$ ) during contact metamorphism are estimated at 550°C and 1.0 kbar respectively. The fluid under influence of which the metasomatic infiltration skarns were formed was relatively rich in Fe, Cl and F and carried little or no Mg and Mn.

During early diagenesis (beginning of stage 2)  $f_{O_2}$  was between the hematite/magnetite (hm/mt) and the hausmannite + hematite = jacobsonite buffers ( $h + m = j$ ). During stage 2, with increasing  $T$ ,  $f_{O_2}$  changed from above to below hm/mt. Magnetite and jacobsonite at some distance from the hydrothermal veins from which the metasomatic skarn-forming fluids were released, were altered during stage 3 into hematite. Magnetite in, and close to the hydrothermal veins was not altered to hematite, implying an increase in  $f_{O_2}$  to above hm/mt with increasing distance from these veins.

KEYWORDS: manganese silicate, skarn, magnetite, jacobsonite, Gåsborn, Sweden.

## Introduction

DURING the first part of this century Mn-silicate skarns from West Bergslagen were made famous due to the excellent description by (a.o.) Magnusson (1925, 1929, 1930, 1970), Geyer and Magnusson (1944), and Tegengren (1924). Magnusson (1970) described three skarn types in West Bergslagen. From oldest to youngest these are: reaction skarns that were formed by metamorphism of marbles and intercalated layers of Fe- and Mn-ores during the emplacement of synorogenic granites; metasomatic infiltration skarns that were formed under influence of hydrothermal fluids associated with the synorogenic granites; and contact skarns formed under the influence of postorogenic skarns.

More recently Oen *et al.* (1982) and Oen (1987) suggested that skarn formation in West Bergs-

lagen did not take place during orogenesis; instead they presented a model in which some skarns in West Bergslagen were believed to have formed in a sub-seafloor hydrothermal rift-related environment at diagenetic to sub-seafloor amphibolite facies metamorphic conditions.

This paper presents the mineralogy and mineral chemistry of some skarn-altered manganese iron ore-bearing metavolcanics and metacherts from the Gåsborn area, West Bergslagen. Evidence will be presented supporting the rift-related setting for skarn formation in West Bergslagen proposed by Oen *et al.* (1982) and Oen (1987).

## Geological setting

The 1.9–1.8 Ga Svecofennian (Svecofennian) volcano–sedimentary rocks in the Gåsborn area belong to the upper leptonite and slate group of the

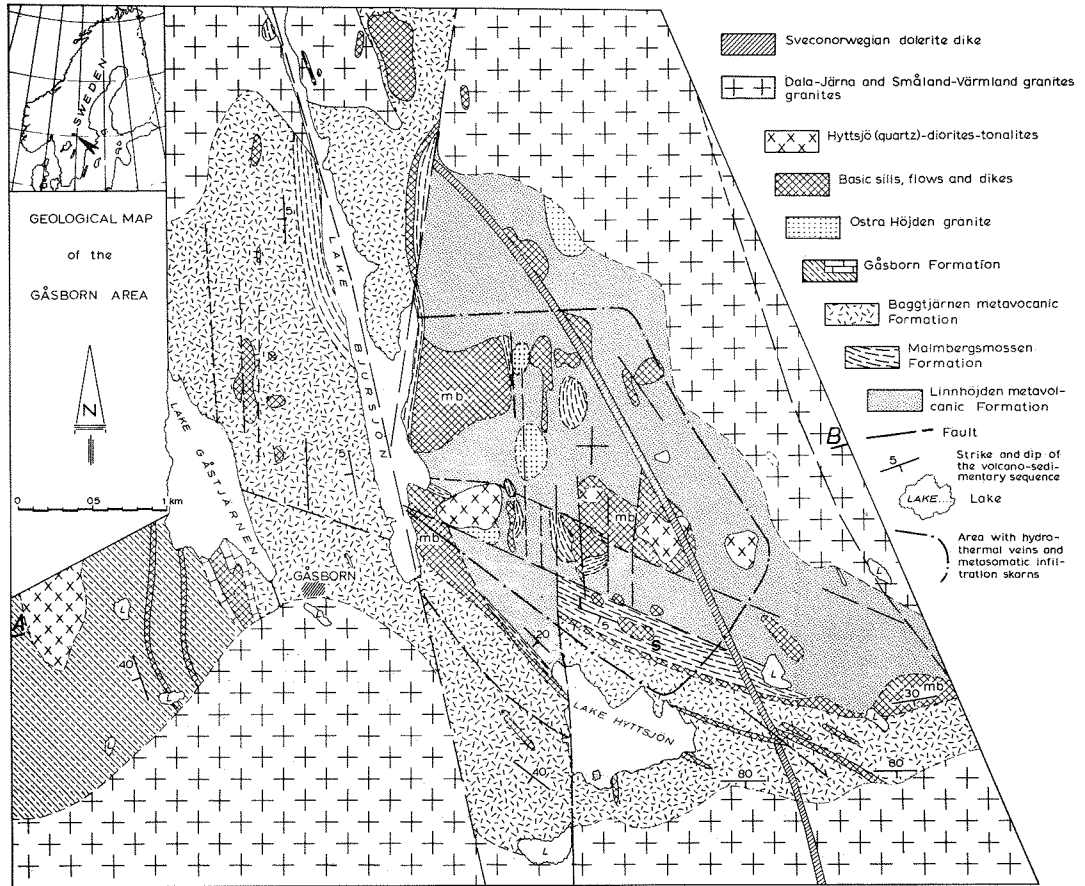


FIG. 1. Geological map of the Gåsborn area. I = Igelström mine; S = Stallmalm mine (Fig. 2). For profile A-B, see Fig. 7.

Bergslagen Supracrustal Sequence (Oen *et al.*, 1982; Oen, 1987).

According to Damman (1989a) the volcano-sedimentary succession in the Gåsborn area can be divided into four formations, from oldest to youngest (Fig. 1): the Linnhöjden metavolcanic formation; the Malmbergsmossen formation; the Baggtjärnen metavolcanic formation; and the Gåsborn formation. The Linnhöjden and Baggtjärnen metavolcanic formations consist of acid metavolcanics, containing some intercalated marble beds and metamorphosed basic lavas. The Malmbergsmossen formation consists of exhalative-sedimentary manganiferous iron-ore-bearing marbles, metavolcanics and metacherts, showing lateral facies transitions towards one another (Damman, 1988a). These rocks are centred around two zones of Mg-metasomatically-altered metavolcanics of the underlying Linn-

höjden metavolcanic formation that acted as conduit zones for hydrothermal fluids from which the manganiferous iron ores were deposited (Damman, 1988a). The Gåsborn formation consists of, from oldest to youngest: a marble bed, a series of metavolcanic greywackes and debris flows, and a series of alternating black phyllites and quartzites.

This volcano-sedimentary succession is intruded by: (1) basic sills associated with the basic lavas; (2) the synvolcanic Ostra Höjden granite (Fig. 1), belonging to the group of older granites of the Bergslagen district (Damman, 1988b, 1989a; Åberg *et al.*, 1983a,b; Oen *et al.*, 1984; Baker, 1985); and (3) quartz diorites and tonalites (Fig. 1) belonging to the Hyttsjö gabbro-tonalite suite (Oen *et al.*, 1982; Oen and Wiklander, 1982; Oen, 1987). Associated with the Ostra Höjden granite is a hydrothermal vein sys-

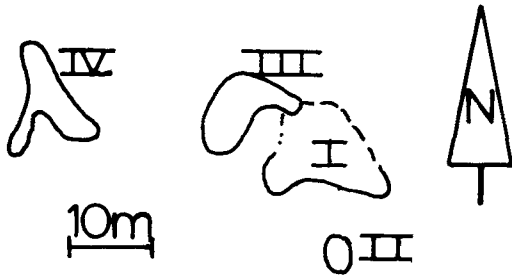


FIG. 2. Sketch map, showing outcrops in the Stallmalm mine.

tem, consisting of 5 cm–7 m wide and up to several hundred metres long quartz–feldspar veins (Damman, 1988b, 1989a). The Ostra Højden granite was emplaced during the formation of a small rift basin (Oen, 1987; de Groot *et al.*, 1988; Damman, 1989a), characterized by the occurrence of black phyllites and quartzites (Oen *et al.*, 1982; Oen, 1987; Fig. 1) that form the top of the Gåsborn formation (Damman, 1989a). The pile of metavolcanics between the Malmbjergsmossen formation, in which the top of the Ostra Højden granite is intruded (Fig. 1) and the black shales and quartzites of the Gåsborn formation has a thickness <3 km (Damman, 1989a), indicating that lithostatic pressures during emplacement of the Ostra Højden granite were <1 kbar.

The above complex of 1.9–1.8 Ga rocks is intruded in the N, E and S (Fig. 1) by younger, 1.81–1.74 Ga granites of the Småland–Värmland and Dala–Järna groups (Welin *et al.*, 1977; Patchett *et al.*, 1987; Jarl and Johansson, 1988) and by a 1.2–0.9 Ga Sveconorwegian dolerite dyke (Oen and Verschure, 1982).

#### Analytical procedures

Electron microprobe analyses were made with a Cambridge Instruments Co. Microscan 9 operated at an acceleration potential of 20 kV and a sample current of 25 nA. Raw data were corrected with the Mark 9 on-line ZAF computer program. Standards used were marialite (Cl), orthoclase (K), diopside (Ca, Si), ilmenite (Ti), rhodonite (Mn), fayalite (Fe), jadeite (Na), forsterite (Mg), corundum (Al), synthetic ZnO (Zn) and hauyne (S). Fluorine was analysed at a sample current of 40 nA, using fluorite as a standard.

Representative analyses of garnet, clinopyroxene, calcic amphiboles and bementite are presented in Tables 2–5. Structural formulae were calculated on the basis of 6 O for clinopyroxene, 12 O for garnet, and 23 O for calcic amphibole.

Total tetrahedral Si + Al is constrained to equal 8 in calculations of calcic amphiboles (Robinson *et al.*, 1982) and 6 in calculations of bementite (Peacor and Essene, 1980). Fe<sup>3+</sup> in garnet was calculated on the assumption that total Al + Fe<sup>3+</sup> has to equal 2. Fe<sup>3+</sup> in calcic amphibole was calculated on the assumption that the total of the cations in the M1–M3 sites has to equal 5 (Robinson *et al.*, 1982).

#### Petrography of the manganiferous iron ore bearing metavolcanics and metacherts

Manganiferous iron-ore-bearing metavolcanics and metacherts are found at the derelict Igelström (I, Fig. 1) and Stallmalm (S, Fig. 1) mines (Magnusson, 1930).

In the exposed part of the Stallmalm mine (Fig. 2) 5–80 cm thick manganiferous iron-ore layers occur concordantly between metavolcanite and metachert layers (Fig. 3). Some ore layers consist entirely of Mn-silicates and magnetite or jacobite; others contain only minor, disseminated Mn-silicates and magnetite in metavolcanic or metachert layers.

The manganiferous iron-ore layers in the Stallmalm mine can be divided into three types: rhodonite-rich layers; clinopyroxene-rich layers; and a tephroite-rich layer (Fig. 3). Dump samples from other, unexposed pits of the Stallmalm mine and the Igelström mine consist of these ore types and magnetite-bearing quartzites, implying that these four layer types represent the Gåsborn manganiferous iron ores.

At the contact between the ore layers and the surrounding metavolcanics (Fig. 3) and along small cross-cutting veinlets in the ore layers, the original mineral assemblages are replaced by a later assemblage, consisting of large quantities of garnet, rhodonite, actinolite or edenite, biotite, chlorite, bementite, fluorite, helvite, rhodochrosite, hematite, rutile, and some accessory sulphides (see below under garnet-rich layers).

#### Description of mineral assemblages

**Rhodonite-rich layers.** The rhodonite-rich layers consist of quartz, feldspar, magnetite, garnet, titanite, allanite and rhodonite. Quartz, feldspar and magnetite (sometimes with fine pyrophanite lamellae) occur enclosed by rhodonite, garnet, titanite and allanite (Table 1). Along cracks and rims magnetite frequently shows alterations into hematite. In thin section the garnets have colourless, spessartite-rich (Anal. 1+2, Table 2; Fig. 4a) cores and yellow, andradite-rich (Anal. 3+4, Table 2; Fig. 4a) rims. Rhodonite

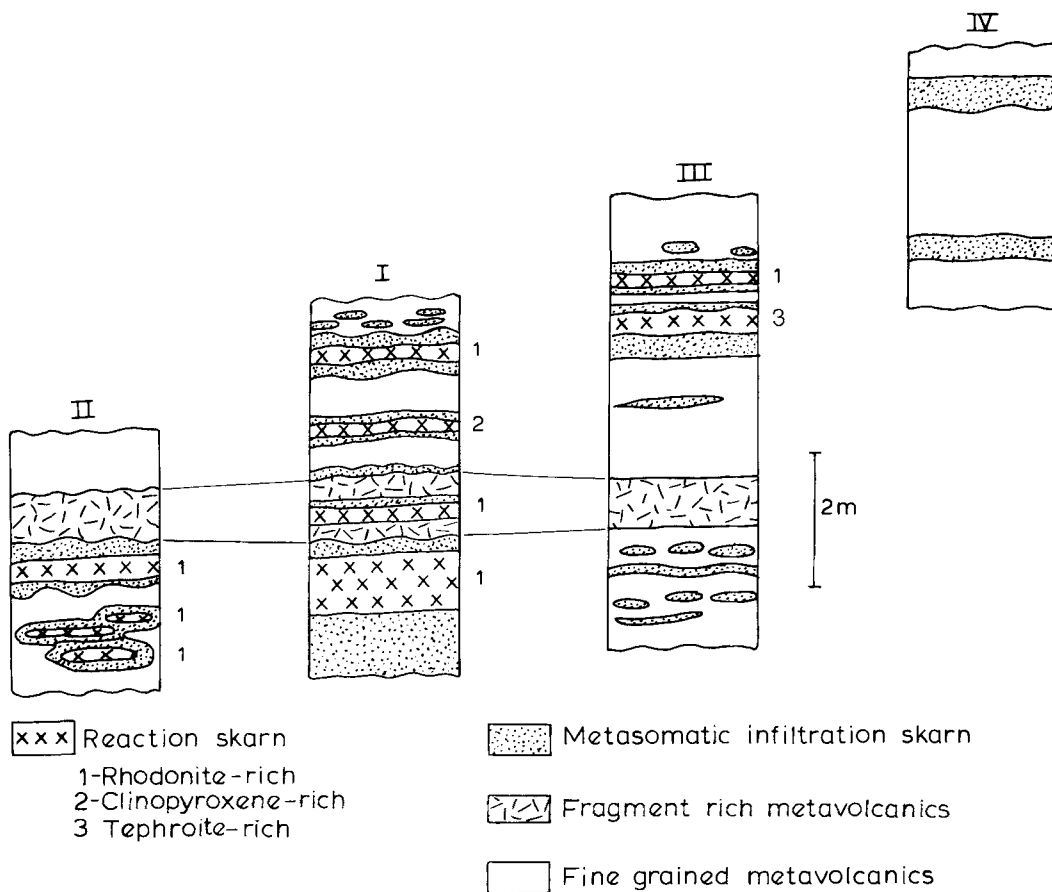


FIG. 3. Correlation between sections taken from outcrops (Fig. 2) in the Stallmalm mine.

( $\text{Ca}_{0.12-0.18}\text{Mn}_{0.62-0.81}\text{Fe}_{0.03-0.18}\text{Mg}_{0.03-0.05}\text{SiO}_3$ ) encloses garnet, allanite, titanite, quartz, feldspar and magnetite, and occurs as fine-grained sub-hedral crystals between the latter minerals.

**Clinopyroxene-rich layers.** The clinopyroxene-rich layers consist of strongly variable proportions of quartz, feldspar, magnetite, clinopyroxene, allanite, and garnet. Magnetite, quartz and feldspar occur in aggregates of tiny crystals of similar appearance as those in the rhodonite-rich layers. Clinopyroxene, allanite (with up to 6 wt. % MnO) and yellow garnet occur intergrown in aggregates enclosing magnetite, quartz and feldspar (Table 1). Clinopyroxenes in all samples show a composition between hedenbergite and manganian hedenbergite (Anal. 1 and 2, Table 3; Fig. 4b). The garnets are similar in composition to those in the rhodonite-rich layers. Small amounts of relict rhodochrosite are locally found between clinopyroxene and garnet.

**Tephroite-rich layers.** The tephroite-rich layer (Table 1) consists of tephroite ( $\text{Mn}_{1.73-1.76}\text{Fe}_{0.18-0.21}\text{Mg}_{0.06}\text{SiO}_4$ ), garnet and jacobite ( $\text{Zn}_{0.02-0.05}\text{Mn}_{0.35-0.66}\text{Fe}_{0.34-0.63}\text{Fe}_{1.88-1.99}\text{Ti}_{0.05}\text{Al}_{0.01}\text{O}_4$ ) partly replaced by hematite (see below under garnet-rich layers). Tephroite and jacobite occur embedded in garnet (Table 1) which is similar in composition to that occurring in the rhodonite- and clinopyroxene-rich layers.

**Magnetite-rich quartzites.** The oldest mineral in the magnetite-rich quartzites is hematite, which occurs as small inclusions in quartz. Magnetite occurs as allotriomorphic aggregates in the quartz matrix. Locally, transitions from hematite quartzite to magnetite quartzite suggest that the latter was formed by recrystallization of the former. Garnet, biotite and actinolite occur locally in-between magnetite and quartz. Along cracks and rims magnetite is partially replaced by hematite.

**Garnet-rich layers.** Garnet-rich layers typically

Table 1. Crystallization sequence of minerals in the reaction skarns and the metasomatic infiltration skarns

| Mineral          | Reaction skarns |       | Metasomatic infiltration skarns |       |
|------------------|-----------------|-------|---------------------------------|-------|
|                  | Old             | Young | Old                             | Young |
| Garnet           |                 |       |                                 |       |
| Quartz           | --              |       |                                 |       |
| Feldspar         | --              |       |                                 |       |
| Hematite         |                 |       |                                 | ----- |
| Magnetite        | -----           |       |                                 |       |
| Clinopyroxene    |                 |       | -----                           |       |
| Titanite         |                 | ----- |                                 |       |
| Allanite         |                 | ----- |                                 |       |
| Jacobsite        | -----           |       |                                 |       |
| Tephroite        |                 |       | -----                           |       |
| Rhodonite        |                 |       | -----                           |       |
| Calcic amphibole |                 |       |                                 | ----- |
| Biotite          |                 |       |                                 | ----- |
| Chlorite         |                 |       |                                 | ----- |
| Bementite        |                 |       |                                 | ----- |
| Pyrite           |                 |       |                                 | --    |
| Pyrrhotite       |                 |       |                                 | ----- |
| Chalcopyrite     |                 |       |                                 | ----- |
| Sphalerite       |                 |       |                                 | ----- |
| Galena           |                 |       |                                 | ----- |
| Wittichenite     |                 |       |                                 | ----- |
| Aikinite         |                 |       |                                 | ----- |
| Rhodochrosite    |                 |       |                                 | ----- |
| Helvite          |                 |       |                                 | ----- |
| Pyrophanite      |                 | ----- |                                 |       |
| Rutile           | ----            |       |                                 |       |
| Fluorite         |                 |       |                                 | ----- |

Table 2. Variation in garnet chemistry: 1-4) Reaction skarn core - rim; 5-7) Metasomatic infiltration skarn core - rim; 8) In hydrothermal vein

|                                | 1     | 2     | 3     | 4     | 5     | 6      | 7     | 8     |
|--------------------------------|-------|-------|-------|-------|-------|--------|-------|-------|
| SiO <sub>2</sub>               | 36.15 | 36.48 | 36.13 | 36.33 | 35.47 | 35.91  | 36.16 | 35.94 |
| Al <sub>2</sub> O <sub>3</sub> | 20.44 | 20.07 | 14.61 | 13.36 | 3.15  | 5.96   | 16.05 | 14.19 |
| TiO <sub>2</sub>               | 0.25  | -     | 0.62  | 0.64  | -     | 0.17   | 0.14  | -     |
| FeO                            | 6.00  | 8.36  | 11.81 | 20.68 | 24.07 | 21.60  | 10.24 | 14.40 |
| MnO                            | 28.36 | 27.49 | 21.13 | 20.68 | 9.37  | 11.87  | 27.16 | 16.02 |
| MgO                            | 0.54  | 0.78  | 0.16  | 0.16  | 0.11  | 0.17   | 0.39  | 0.14  |
| CaO                            | 8.08  | 6.66  | 14.41 | 14.40 | 24.32 | 22.55  | 8.96  | 17.35 |
| Supp. Fe <sup>3+</sup>         | -     | -     | 0.90  | 0.91  | 2.64  | 2.23   | 0.75  | 0.51  |
| Total                          | 99.82 | 99.84 | 99.72 | 99.65 | 99.73 | 100.46 | 99.85 | 98.55 |
| Si                             | 2.91  | 2.94  | 2.97  | 3.00  | 3.00  | 3.00   | 3.00  | 2.95  |
| Al                             | 1.94  | 1.91  | 1.41  | 1.30  | 0.32  | 0.59   | 1.55  | 1.37  |
| Ti                             | 0.01  | -     | 0.03  | 0.04  | -     | 0.01   | 0.01  | -     |
| Fe <sup>3+</sup>               | 0.05  | 0.09  | 0.56  | 0.66  | 1.68  | 1.40   | 0.46  | 0.63  |
| Fe <sup>2+</sup>               | 0.35  | 0.48  | 0.25  | 0.25  | 0.07  | 0.11   | 0.24  | 0.35  |
| Mn                             | 1.94  | 1.88  | 1.47  | 1.49  | 0.73  | 0.84   | 1.88  | 1.11  |
| Mg                             | 0.06  | 0.09  | 0.02  | 0.02  | 0.01  | 0.02   | 0.05  | 0.02  |
| Ca                             | 0.70  | 0.58  | 1.27  | 1.27  | 2.20  | 2.02   | 0.78  | 1.52  |
| Total                          | 7.96  | 7.97  | 7.98  | 8.03  | 8.01  | 7.99   | 7.97  | 7.93  |

occur as reaction zones between rhodonite-rich, clinopyroxene-rich or tephroite-rich layers and surrounding metavolcanics, along thin hydrothermal veinlets (see below) cross-cutting the rhodonite-rich, clinopyroxene-rich or tephroite-rich

layers, or as thin layers, consisting predominantly of garnet, without associated rhodonite, clinopyroxene or tephroite (Fig. 3). The reaction zones commonly contain relict rhodonite(I), clinopyroxenes, tephroite, jacobsonite or magnetite.

The oldest reaction minerals are yellow, andradite-rich garnet (Anal. 5, Table 2) and rhodonite(II) (Table 1). Rhodonite(II) frequently contains small exsolution lamellae of manganian hedenbergite (Anal. 3, Table 3). Yellow garnet is rimmed by reddish garnet (Anal. 6 and 7, Table 2; Fig. 4a), intergrown with biotite, actinolite or edenite, rhodochrosite, and helvite (Table 1). Biotite contains up to 5 wt.% MnO and up to 0.4 wt.% ZnO. In actinolite and edenite, Mn, Fe and Mg are randomly distributed over the M1–M3 sites (Fig. 4c). One actinolite, containing 20.11 wt.% MnO (Analysis 1, Table 4), represents the most Mn-rich amphibole reported in the literature to date. Rhodochrosite is frequently found intergrown with actinolite and edenite. Helvite is found in one sample only, as colourless subhedral crystals intergrown with actinolite (Table 1). Retrograde alteration of biotite and the calcic amphiboles results in partial replacement by chlorite or bementite (Analyses 1 and 2, Table 5). Quartz and fluorite in panidiomorphic aggregates occur together with chlorite and bementite. Locally hematite intergrown with rutile and a variety of accessory sulphides (wittichenite, aikinite, sphalerite, galena, chalcopyrite, pyrrhotite or pyrite) is found intergrown with chlorite and bementite, suggesting that the replacement of jacobsonite and magnetite by hematite in the rhodonite-rich, clinopyroxene-rich and tephroite-rich layers took place during the formation of the garnet-rich layers and veinlets (Table 1).

Locally a few small hydrothermal veinlets are found cross-cutting the rhodonite, clinopyroxene or tephroite-rich layers. In these veins the following minerals were formed, from oldest to youngest: microcline + quartz, clinopyroxene + quartz, clinopyroxene + garnet + quartz, garnet + calcic amphibole + biotite + quartz, calcic amphibole + biotite + quartz + fluorite (Table 1). Clinopyroxene and calcic amphibole are generally more Fe-rich than in the clinopyroxene-rich layers. Going from the centre to the rim of the hydrothermal veins the clinopyroxene and calcic amphibole show a decrease of their Fe content and an increase of their Mg and Mn contents (Fig. 4b,c). Locally a few magnetite crystals are found embedded in the silicates in the veins, but these, contrary to magnetite described previously, are not altered into hematite.

Two types of metavolcanics are found between the ore-bearing layers in the Stallmalm mine (Fig. 3): (1) fine-grained metavolcanics, consisting of subhedral quartz, albite and microcline crystals and some disseminated Mn silicates and oxides; and (2) a metavolcanic layer showing up to 5 cm

large metavolcaniclastic fragments embedded in a fine-grained matrix of quartz, albite, microcline, biotite and Mn silicates (Fig. 3).

## Discussion

The mineral assemblages in the Gåsborn Mn-ores can be divided into two groups:

- (1) a group of mineral assemblages which occur as thin rock layers parallel to the sedimentary bedding of the metavolcanics. This group comprises the mineral assemblages of: (a) the magnetite-bearing quartzites, (b) the tephroite-rich layers, (c) the rhodonite(I)-rich layers; and (d) the clinopyroxene(I)-rich layers (Table 1 and Fig. 4).
- (2) the garnet–rhodonite(II)–clinopyroxene(II)–calcic amphibole–biotite–helvite–chlorite–bementite–rhodochrosite–hematite–rutile–fluorite–sulphide assemblages in garnet-rich layers and along cross-cutting veinlets.

The minerals of the first group can be formed by metamorphic reaction (see below) of Mn-carbonates and/or hydroxides, ferruginous cherts and tuffites without addition of materials from an external source. Tuffitic material, cherts and some relict carbonates are still present in the Mn-ores. These rocks can either be considered simply as metamorphic Mn–silicate–oxide rocks or as recrystallized skarn or reaction skarn according to the classification of Einaudi *et al.* (1981).

The mineral assemblages of the second group replace those of the first group and occur in and along hydrothermal veins associated with the Ostra Höjden granite. In the latter veins clinopyroxene and calcic amphiboles show a change in chemistry, from Fe- and Cl-rich to more Mg- and Mn-rich, when going from the veins outward (Tables 3–4 and Fig. 4b,c). Similar changes in mineral composition are observed in clinopyroxene–garnet skarns which have developed along hydrothermal veins in marbles (Fig. 5; Damman and Kieft, 1989), and in orthoamphibole–biotite assemblages developed along hydrothermal veins cross-cutting the conduit zones for fluids from which the Gåsborn exhalative–sedimentary manganiferous iron ores were deposited (Fig. 5; Damman, 1988a, 1989b). The above observations suggest that the second group mineral assemblages have an origin similar to that of the clinopyroxene–garnet skarns in the marbles and the orthoamphibole–biotite assemblages. These formed under influence of Fe, F and Cl-rich hydrothermal fluids (Damman and Kieft, 1989) released from the cooling Ostra Höjden granite, implying that these are metasomatic

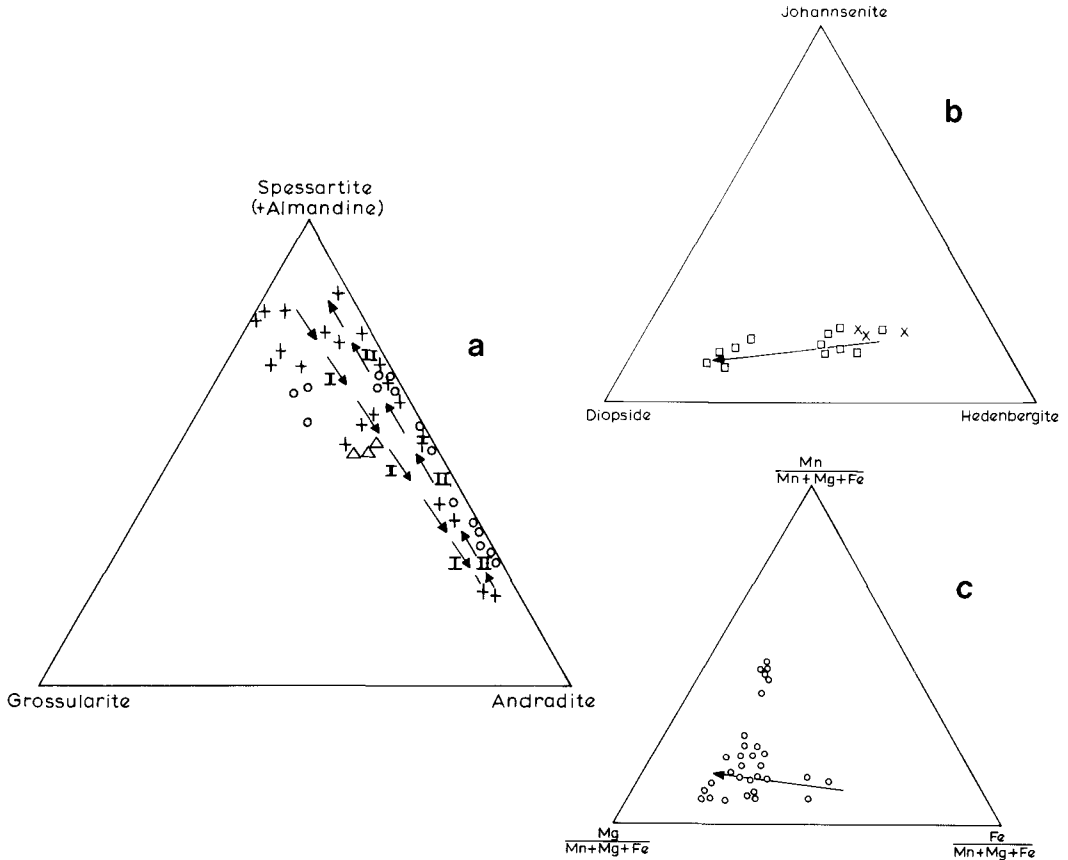


FIG. 4. Compositional variation in garnet (a), clinopyroxene (b) and calcic amphibole (c) in the Gåsborn Mn-silicate-magnetite-jacobsite assemblages. (a) +, prograde metamorphic garnets; O, metasomatic infiltration skarns; Δ, in vein; I, changes from core to rim in the composition of prograde metamorphic garnets; II, changes from core to rim in the composition of garnets in the metasomatic infiltration skarns. (b) Variation in clinopyroxene chemistry in the Gåsborn Mn-silicate-magnetite-jacobsite skarns. X, inclusions in rhodonite; □ skarns. The arrow points from a hydrothermal vein outward. (c) Distribution of Mn, Mg and Fe in the M1–M3 sites of calcic amphiboles in the Gåsborn Mn-silicate-magnetite-jacobsite skarns. The arrow points from a hydrothermal vein outward.

infiltration skarns according to the skarn classification of Einaudi *et al.* (1981).

#### Mineral forming reactions; estimation of *P–T* conditions

The formation of jacobite is discussed by Dasgupta and Manickavagasam (1981), Roy (1981), and Miyano and Beukes (1987), who showed that, with mixtures of hausmannite and hematite as starting materials, jacobite may already be formed at *T* as low as 100 °C. Easton *et al.* (1982) reported the formation of authigenic grossular-andradite-rich garnets in carbonate muds at *T* as

low as 170 °C. Hsu (1968, 1980) showed that the end-member spessartite is unstable at *T* < 400 °C. The above data suggest that the formation of spessartite-rich garnet in the Gåsborn Mn ores may have started at *T* < 400 °C. Other minerals (rhodonite(I), clinopyroxene, tephroite) can be produced through reactions, such as:

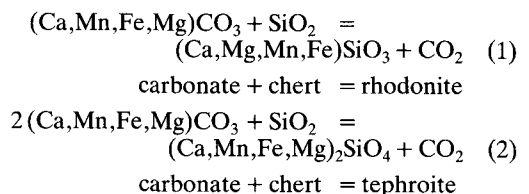
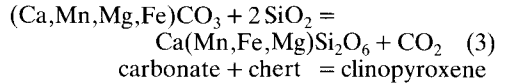


Table 3. Variation in clinopyroxene chemistry: 1+2) Cpx from a reaction skarn; 3) Inclusion in rhodonite; 4+5) In hydrothermal vein

|                                | 1      | 2     | 3     | 4     | 5     |
|--------------------------------|--------|-------|-------|-------|-------|
| SiO <sub>2</sub>               | 51.78  | 51.08 | 49.00 | 50.02 | 50.49 |
| Al <sub>2</sub> O <sub>3</sub> | 0.78   | 0.46  | 0.58  | 0.83  | 0.55  |
| FeO                            | 8.32   | 7.83  | 15.47 | 13.93 | 13.52 |
| MnO                            | 7.38   | 8.58  | 9.11  | 5.17  | 5.44  |
| MgO                            | 10.02  | 11.34 | 4.85  | 7.35  | 7.28  |
| CaO                            | 21.22  | 20.35 | 20.23 | 21.60 | 21.81 |
| Na <sub>2</sub> O              | 0.68   | 0.56  | 0.48  | 0.62  | 0.51  |
| Total                          | 100.27 | 99.72 | 99.72 | 99.52 | 99.60 |
| Si                             | 1.98   | 1.97  | 1.97  | 1.97  | 1.98  |
| Al                             | 0.03   | 0.03  | 0.03  | 0.03  | 0.02  |
| Fe                             | 0.26   | 0.24  | 0.52  | 0.46  | 0.44  |
| Mn                             | 0.24   | 0.27  | 0.31  | 0.17  | 0.18  |
| Mg                             | 0.37   | 0.63  | 0.29  | 0.43  | 0.42  |
| Ca                             | 0.87   | 0.83  | 0.87  | 0.91  | 0.91  |
| Na                             | 0.05   | 0.04  | 0.04  | 0.05  | 0.04  |
| Total                          | 4.00   | 4.01  | 4.03  | 4.02  | 4.01  |

Table 4. Variation in calcic amphibole chemistry: 1) Mn-actinolite; 2-4) In vein + outward

|                                | 1     | 2     | 3     | 4     |
|--------------------------------|-------|-------|-------|-------|
| SiO <sub>2</sub>               | 52.59 | 45.64 | 50.04 | 54.01 |
| Al <sub>2</sub> O <sub>3</sub> | 0.09  | 5.65  | 3.23  | 0.23  |
| TiO <sub>2</sub>               | -     | 0.09  | 0.08  | -     |
| FeO                            | 6.16  | 18.28 | 16.74 | 13.35 |
| MnO                            | 20.11 | 4.09  | 2.74  | 5.11  |
| MgO                            | 8.12  | 9.47  | 11.56 | 11.73 |
| ZnO                            | -     | -     | 0.09  | 0.19  |
| CaO                            | 10.92 | 11.36 | 11.58 | 11.72 |
| Na <sub>2</sub> O              | 0.06  | 1.48  | 0.83  | 0.14  |
| K <sub>2</sub> O               | 0.05  | 0.87  | 0.50  | 0.05  |
| Cl                             | -     | 0.10  | 0.60  | -     |
| F                              | 0.30  | 0.70  | 0.60  | 0.43  |
| Total                          | 98.40 | 97.73 | 97.45 | 96.56 |
| Si                             | 7.99  | 6.98  | 7.43  | 8.00  |
| Al <sup>IV</sup>               | 0.01  | 1.02  | 0.57  | -     |
| Al <sup>VI</sup>               | 0.01  | -     | -     | 0.04  |
| Ti                             | -     | 0.01  | 0.01  | -     |
| Fe <sup>3+</sup>               | -     | 0.72  | 0.53  | -     |
| Fe <sup>2+</sup>               | 0.78  | 1.61  | 1.55  | 1.72  |
| Mn                             | 2.59  | 0.53  | 0.34  | 0.66  |
| Mg                             | 1.84  | 2.15  | 2.56  | 2.63  |
| Zn                             | -     | -     | 0.01  | 0.02  |
| Ca                             | 1.78  | 1.86  | 1.84  | 1.90  |
| Na                             | 0.02  | 0.44  | 0.24  | 0.04  |
| K                              | 0.01  | 0.17  | 0.09  | 0.01  |
| Total                          | 15.03 | 15.49 | 15.18 | 15.02 |



These reactions have been studied both experimentally and in natural assemblages by Peters *et al.* (1973), Candia *et al.* (1975), Abrecht (1980) and Abs-Würmbach and Peters (1981). Their data, combined with an estimated maximum lithostatic pressure of 1.0 kbar (Damman, 1989a), suggest that the formation of rhodonite, tephroite and clinopyroxene started at a *T* of approximately 400–450°C. Rhodonite(I) contains up to 17 mol.% CaSiO<sub>3</sub>, suggesting a peak metamorphic *T* of 500–550°C (Abrecht and Peters, 1975). This *T* is in good agreement with the peak metamorphic temperature of around 560°C (at 1 kbar lithostatic pressure; Damman, 1989a; Damman and Kieft, 1989) during emplacement of the Ostra Höjden granite.

The metasomatic infiltration skarns consist of, from oldest to youngest: rhodonite(II) + garnet or clinopyroxene + garnet + quartz, garnet + calcic amphibole + biotite + quartz + helvite, chlorite + bementite + rhodochrosite + fluorite + sulphides (Table 1).

Rhodonite and clinopyroxenes also occur as high-*T* phases in the rhodonite-rich and clinopyroxene-rich assemblages that were formed prior to the metasomatic infiltration skarns. Petrographic observations suggest that a continuum exists between the formation of these assemblages and that of the metasomatic infiltration skarns, implying that:

- (1) the metamorphic Mn-silicates must have formed at increasing *T* under influence of the Ostra Höjden granite, while the metasomatic infiltration skarns are probably formed at decreasing *T* under influence of fluids released from the Ostra Höjden granite;
- (2) fluids from which the metasomatic infiltration skarns were formed, were released from the Ostra Höjden granite at peak metamorphic conditions; and
- (3) rhodonite(II), garnet and clinopyroxene(II) were most probably formed at *T* decreasing from around 560°C to around 400–450°C.

During retrograde skarn formation, biotite and calcic amphibole are replaced by chlorite, bementite and rhodochrosite, presumably at *T* of about 250–300°C.

#### Behaviour of $f_{\text{O}_2}$ during skarn formation in the Gåsborn area

The early, presumably diagenetic, presence of jacobsonite implies that  $f_{\text{O}_2}$  during diagenesis was



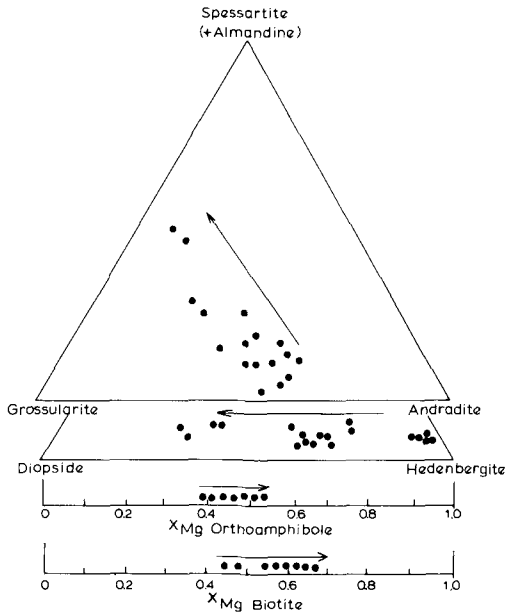


Fig. 5. Observed chemical variations in garnet and clinopyroxene in metasomatic infiltration skarns in marbles (Damman and Kieft, 1989) and coexisting orthoamphibole and biotite (Damman, 1989b) in the Gåsborn area. The arrow points from a hydrothermal vein outward.

between the hausmannite + hematite = jacobsite and hematite-magnetite buffers (Miyano and Beukes, 1987; Fig. 6). Magnetite instead of hematite is the stable oxide next to rhodonite, tephroite and clinopyroxene, implying that  $f_{O_2}$  with increasing  $T$  changed from above to below the hm/mt buffer (Fig. 6).

Clinopyroxene(I) (anal. 1 and 2, Table 3) has a composition of about  $Hed_{0.26}Di_{0.57}Joh_{0.17}$ , while clinopyroxene(II) that formed at peak metamorphic conditions in the hydrothermal veins has a composition of about  $Hed_{0.46}Di_{0.43}Joh_{0.11}$ . The  $f_{O_2}$ - $T$  stability field of such clinopyroxenes has been studied by Gamble (1976, 1978) and Burton *et al.* (1982). Their data suggest that at peak metamorphic conditions ( $T$  about 550°C,  $P$  about 1.0 kbar)  $f_{O_2}$  was  $<10^{-18.4}$  (Fig. 6). Clinopyroxene formation is followed by that of garnet, implying a slight increase in  $f_{O_2}$  with  $T$  (Burton *et al.*, 1982). Magnetite in metasomatic infiltration skarns close to veins is not altered into hematite, implying that  $f_{O_2}$  close to the veins must have stayed below hm/mt (II<sup>A</sup>, Fig. 6). During the formation of the metasomatic infiltration skarns, magnetite and jacobsite at some distance from

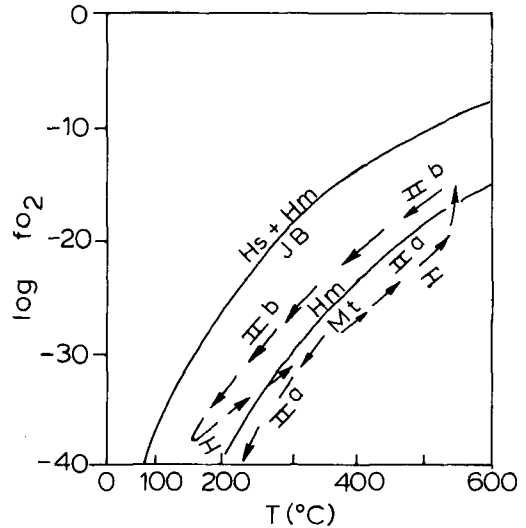


Fig. 6. Estimated variations in  $\log f_{O_2}$  as a function of  $T$  (°C) during the formation of the Gåsborn Mn-silicate-magnetite-jacobsite skarns. Boundaries of fields: magnetite (mt) = hematite (hm) and jacobsite (jb) = hausmannite (hs) + hematite (hm). I, prograde formation of metamorphic Mn-silicates, magnetite and jacobsite; II, retrograde formation of metasomatic infiltration skarns; IIa open hydrothermal veins; IIb, magnetite-rich and jacobsite-rich skarn.

the veins were altered into hematite, implying an increase in  $f_{O_2}$  with increasing distance from the veins (II<sup>B</sup>, Fig. 6).

In pyroxene-garnet skarns that were formed in Mn-poor marbles under the influence of hydrothermal fluids associated with the Ostra Höjden granite and the Mn-poor orthoamphibole-bearing rocks of the conduit zones for fluids from which the Gåsborn manganese iron ores were deposited, magnetite was not altered retrogressively into hematite. These data indicate that, during retrograde skarn formation in the Gåsborn area,  $f_{O_2}$  was controlled by the Mn content of the wall-rock, presumably due to the formation of redox-couples between Mn and Fe.

### The model

Based on data presented in this paper and by Damman (1988a,b; 1989a,b); Damman and Kieft (1989); Oen *et al.* (1982); Oen (1987); and de Groot *et al.* (1988) the following model for skarn and ore formation in the Gåsborn area is proposed (Fig. 7):

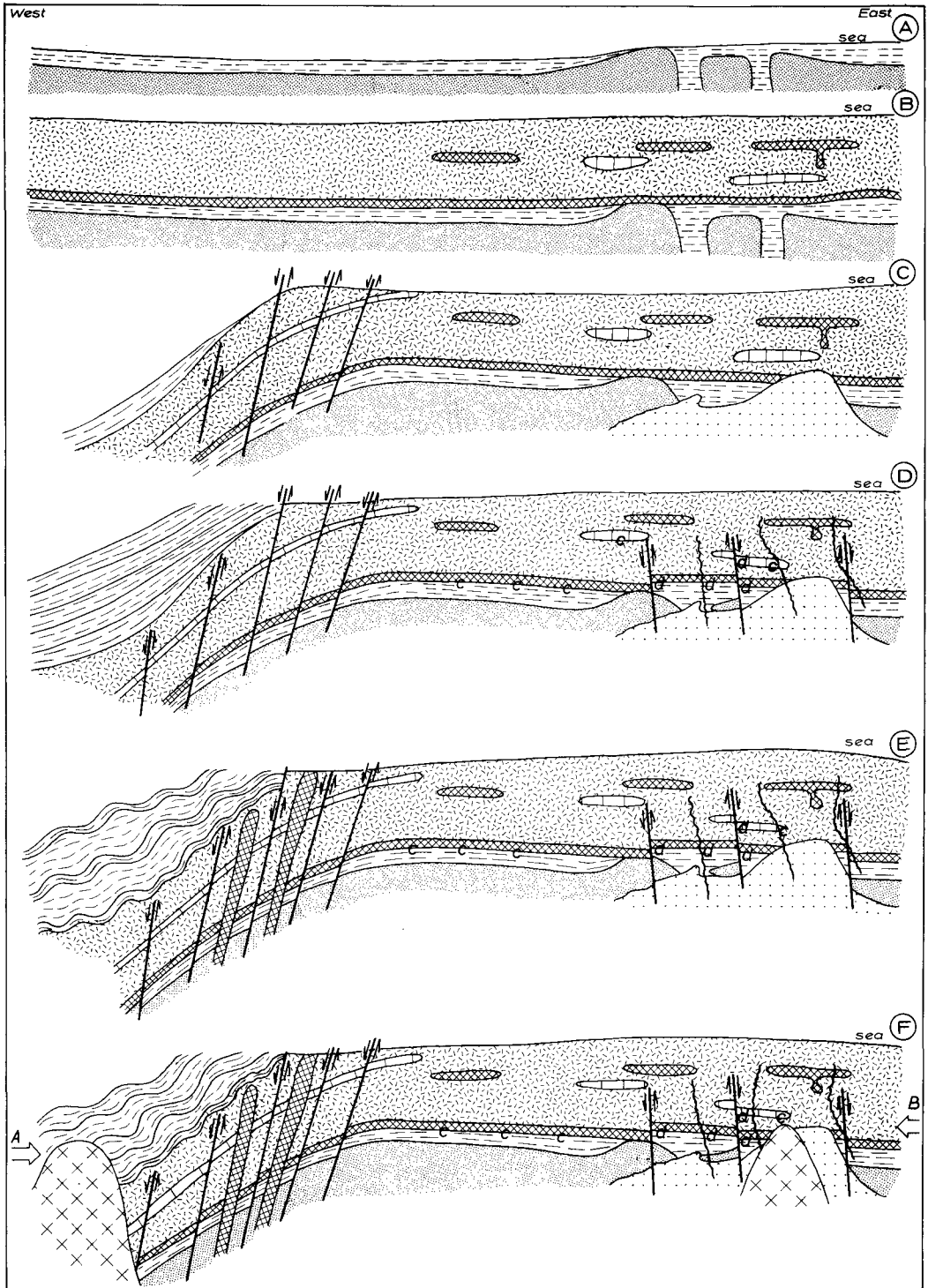


FIG. 7. A model for skarn and ore formation in the Gåsborn area, using profile A-B (Fig. 1) as a reference base. Lithological symbols as in Fig. 1.

- (1) Deposition of volcanic rocks of the Linnhöjden metavolcanic formation.
- (2) Deposition of the Malmbergsmossen formation, consisting of tuffitic sediments mixed with exhalative-sedimentary carbonates, cherts, iron and manganese ores; the exhalite facies sediments were deposited from fluids released into the sea from seafloor vents above Mg-metasomatic alteration pipes or conduit zones (Fig. 7a; Damman, 1988a).
- (3) Deposition of volcanics and intercalated marbles of the Baggtjärnen metavolcanic formation and the lower part of the Gåsborn formation (Fig. 6b). Extrusion of basic flows and intrusion of basic sills and dykes into the volcano-sedimentary pile. Beginning of diagenetic mineral growth as a function of burial at  $T > 100^\circ\text{C}$  (this paper).
- (4) Rifting and faulting of the basin floor (Oen, 1987; Damman, 1989a). Flexuring of the lower formations of the upper leptite and slate group and formation of a central basinal trough by downwarping of the area W and S of the flexure zone. Infilling of the central trough by the Gåsborn formation. Coeval, synrifting and syn-depositional, sub-seafloor intrusion of the Ostra Höjden granite (Oen, 1987; Damman, 1989a; Fig. 7c). Under influence of the Ostra Höjden granite, the country rock is heated to  $T$  of about  $550^\circ\text{C}$  (this paper; Damman and Kieft, 1989).
- (5) Initiation of a high-temperature hydrothermal system associated with the Ostra Höjden granite, formation of hydrothermal veins around the granite (Damman, 1988b; Fig. 1; Fig. 7d), formation of metasomatic infiltration skarns in marbles (Damman and Kieft, 1989) and manganese iron ores (this paper) and alteration of a quartz-albite-phengite-chlorite-magnetite assemblage in the hydrothermal conduit zones for fluids from which the Gåsborn manganese iron ores were deposited into a biotite-cordierite-cumingtonite-orthoamphibole-magnetite-hercynite-corundum assemblage (Damman, 1989b). During this stage temperatures drop from about  $550^\circ\text{C}$  to  $<200^\circ\text{C}$  (this paper; Damman and Kieft, 1989).
- (6) Intrusion of more basic sills and dykes; syn-depositional tilting and compressive deformation of the Gåsborn formation under influence of basin subsidence and updoming granites (Fig. 7e; Oen, 1987; de Groot *et al.*, 1988; Damman, 1989a).
- (7) Intrusion of Hyttsjö suite intrusives (Fig. 7f).
- (8) Epirogenetic movements followed by the intrusion of the Dala-Järna granites to the N, E and S of the Gåsborn area (Damman, 1989a).
- (9) Formation of large shear zones (Fig. 1).
- (10) Intrusion of Sveconorwegian dolerite dykes (Fig. 1).

Table 5. Bementite analyses

|                                | 1     | 2     |
|--------------------------------|-------|-------|
| SiO <sub>2</sub>               | 37.76 | 37.20 |
| Al <sub>2</sub> O <sub>3</sub> | 0.49  | 0.19  |
| FeO                            | 6.14  | 3.15  |
| MnO                            | 40.28 | 46.52 |
| MgO                            | 2.90  | 1.04  |
| ZnO                            | 0.14  | 0.08  |
| CaO                            | 0.47  | 0.12  |
| Cl                             | 0.08  | 0.07  |
| Total                          | 88.26 | 88.37 |
| Si                             | 5.91  | 5.96  |
| Al                             | 0.09  | 0.04  |
| Fe                             | 0.80  | 0.44  |
| Mn                             | 5.35  | 6.34  |
| Mg                             | 0.68  | 0.26  |
| Zn                             | 0.01  | 0.01  |
| Ca                             | 0.07  | 0.02  |
| Total                          | 12.91 | 13.07 |

### Genetic considerations

Magnusson (1930, 1970) and Damman (1988a) suggested that the Gåsborn manganese iron ores belong to the so-called Långban-type manganese deposits of the Bergslagen district. Magnusson (1930, 1970) described four stages of mineralization in Långban-type deposits, from oldest to youngest: (1) metasedimentary ores and early skarns; (2) major period of skarn formation association with the intrusion of synorogenic granites; (3) formation of sköls; and (4) formation of low-temperature hydrothermal minerals as infillings of fissures.

The data presented in this paper show a more or less similar series of mineralizing events in the Gåsborn area: (1) exhalative sedimentary deposition of ferruginous cherts, manganese hydroxides and carbonates together with fine-grained tuffitic material, followed by diagenetic to low-grade metamorphic mineral formation, starting with the formation of jacobsonite and spessartine-rich garnets (Table 1); (2) formation of rhodonite, tephroite, jacobsonite and (manganese) hedenbergite (Table 1) at increasing temperature (to about  $550^\circ\text{C}$ ) under the influence of the Ostra Höjden granite; (3) release of hydrothermal fluids from the Ostra Höjden granite and formation of high- $T$  metasomatic infiltration skarns consisting of rhodonite, clinopyroxene, garnet, calcic amphiboles, biotite, rhodochrosite and helvite (Table 1); (4) formation of chlorite, bementite, hematite, fluorite, rhodochrosite, wittichenite, aikinite, sphalerite, galena, pyrrhotite,

chalcopyritic and pyrite at decreasing  $T$  from the cooling hydrothermal solutions.

The above data suggest, in the author's opinion, that the sequence of events (Fig. 1) which led to the formation of the Gåsborn manganese iron ores can now also be used to explain the genesis of other deposits of the Långban type.

The inferred low lithostatic pressure (<1 kbar; Damman, 1989a) during formation of the Gåsborn Mn-silicate skarns and the continuity of skarn-forming events at diagenetic to low-pressure amphibolite facies metamorphic conditions disagree with the orogenic model for skarn formation as proposed by Magnusson (1970); instead they agree excellently with the rift-related model for skarn formation presented by Oen *et al.* (1982) and Oen (1987).

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