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W–Mo POLYMETALLIC MINERALIZATION AND ASSOCIATED CALC-SILICATE ASSEMBLAGES IN THE GÅSBORN AREA, WEST BERGSLAGEN, CENTRAL SWEDEN

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ABSTRACT

Marbles embedded in metavolcanic rocks in the Gåsborn area, West Bergslagen, central Sweden, contain reaction skarns, calc-silicate bands and metasomatic infiltration skarns. All were formed under influence of the high-level, anorogenic Ostra Höjden granite of the Bergslagen older granite suite. The reaction skarns and calc-silicate bands, consisting of carbonates, magnetite, talc, phlogopite, tremolite, diopside, chondrodite, forsterite, clinohumite, spinel and serpentine, were formed prior to or during the emplacement of the granite by metamorphism of marbles and intercalated lenses of metavolcanic rock and metachert. The metasomatic infiltration skarns, consisting of clinopyroxene of composition $Hd_{20-91}Di_{02-79}Jh_{02-07}$, garnet of composition $And_{05-59}Gr_{30-91}Sp_{02-17}Alm_{02-19}$, vesuvianite, pargasitic, hastingsitic, and actinolitic calcic amphiboles, epidote-group minerals, chlorite, quartz, calcite, phlogopite, and fluorite, with accessory scheelite, molybdenite, roquesite, sulfosalts, galena, sphalerite, chalcopyrite, pyrrhotite, cubanite, pyrite, marcasite, arsenopyrite, löllingite, native Bi, native Pb, native Sn, uraninite and pyrochlore, were formed under influence of hydrothermal fluids expelled from the granite. During the formation of the reaction skarns and calc-silicate bands, the lithostatic pressure (P_L) was less than 1 kbar, T increased from <400°C to about 550°C, $X(CO_2)$ was less than 0.3, and $f(O_2)$, less than 10^{-23} bars. During the formation of the metasomatic infiltration skarns, T dropped from 550°C to <250°C, and $X(CO_2)$ was less than 0.3. Log $f(O_2)$ in hydrothermal veins along which the skarns were formed was about −18.6, decreasing slightly with decreasing T. Clinopyroxene, garnet, vesuvianite and calcic amphiboles in the metasomatic infiltration skarns were formed over a small T interval (550–500°C); all other minerals in the metasomatic infiltration skarns were formed at lower temperatures.

Keywords: anorogenic granite, reaction skarns, calc-silicate bands, hydrothermal fluids, metasomatic infiltration skarns, Bergslagen, Sweden.

SOMMAIRE

Les marbres qui se trouvent dans l'encaissant métavolcanique de la région de Gåsborn, province du Bergslagen occidental, dans le centre de la Suède, contiennent des skarns réactionnels, des horizons calco-silicatés et des skarns dus à une infiltration métasomatique, tous formés suite à la mise en place du massif anorogénique épizonal de Ostra Höjden dans la suite des granites anciens de Bergslagen. Les skarns réactionnels et les bandes calco-silicatées, qui contiennent carbonates, magnétite, talc, phlogopite, trémolite, diopside, chondrodite, forsterite, clinohumite, spinelle et serpentine, ont été formés avant ou pendant la mise en place du granite aux dépens de marbres et d'intercalations de roches métavolcaniques et de métacherts. Les skarns d'infiltration, qui contiennent un clinopyroxène de composition $Hd_{20-91}Di_{02-79}Jh_{02-07}$, un grenat de composition $And_{05-09}Gr_{30-91}Sp_{02-17}Alm_{02-19}$, vésuvianite, amphiboles calciques pargasitique, hastingsitique et actinolitique, minéraux du groupe de l'épidote, chlorite, quartz, calcite, phlogopite et fluorite, avec scheelite, molybdenite, roquesite, sulfosels, galène, sphalérite, chalcopyrite, pyrrhotite, cubanite, pyrite, marcasite, arsenopyrite, löllingite, bismuth natif, plomb natif, étain natif, uraninite et pyrochlore accessoires, ont été formés sous l'influence de fluides hydrothermaux issus du granite. Pendant la formation des skarns réactionnels et des bandes de calc-silicates, la pression lithostatique était inférieure à 1 kbar, et la température a augmenté, de moins de 400°C à 550°C environ; la valeur de $X(CO_2)$ était inférieure à 0.3, et celle de $f(O_2)$, inférieure à 10^{-23} bars. Pendant la formation des skarns dus à l'infiltration métasomatique, la température a baissé de 550°C à moins de 250°C, et $X(CO_2)$ avait une valeur inférieure à 0.3. La fugacité d'oxygène dans les fissures hydrothermales le long desquelles ces skarns se sont formés était d'environ $10^{-18.6}$ bars, et a diminué légèrement avec diminution de la température. Dans ce type de skarn, clinopyroxène, grenat, vésuvianite et amphiboles calciques ont cristallisé dans un intervalle restreint de température (500–550°C); tous les autres minéraux sont apparus à une température plus basse.

(Traduit par la Rédaction)

Mots-clés: granite, skarns réactionnels, bandes à calc-silicates, fluides hydrothermaux, skarns dus à une infiltration métasomatique, Bergslagen, Suède.

INTRODUCTION AND GEOLOGICAL SETTING

Tungsten and molybdenum mineralization in Bergslagen constitute the largest resources of these metals in Scandinavia (Ohlsson 1979). The genesis of the W–Mo mineralization in West Bergslagen has been discussed by Hübner (1971), Ohlsson (1979), Hellingwerf & Baker (1985), Baker *et al.* (1987), Cheilletz (1988), Billström *et al.* (1988) and Baker & Hellingwerf (1988), among others. These authors all agree that the W–Mo mineralization is epigenetic in origin, and derived from granite-related hydrothermal solutions.

According to Hübner (1971) and Billström *et al.* (1988), some cases of W–Mo mineralization in Bergs-

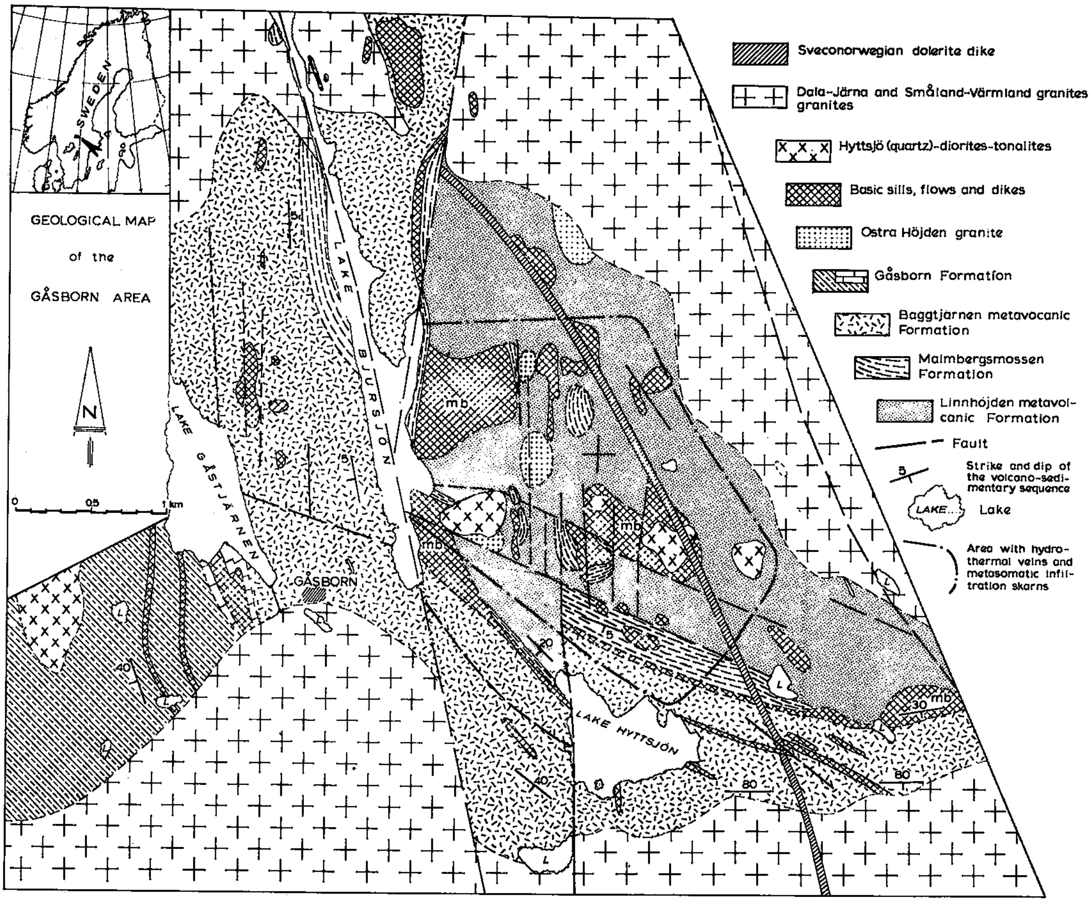


FIG. 1. Geological map of the Gåsborn area.

lagen are related to 1.81–1.74 Ga (Welin *et al.* 1977, Patchett *et al.* 1987, Ohlander & Zuber 1988, Jarl & Johannson 1988) late Svecofennian granites of the Dala–Järna and the Småland–Värmland suites. According to Hellingwerf & Baker (1985), Baker *et al.* (1987) and Baker & Hellingwerf (1988), most examples of W–Mo mineralization in Bergslagen are not related to these granites, but to granites of the 1.9–1.86 Ga (Welin *et al.* 1977, Åberg *et al.* 1983a,b, Oen *et al.* 1984) Bergslagen older granite suite.

A two-stage model, comprising the formation of early barren reaction skarns and late, W-mineralized metasomatic infiltration skarns, without a genetic relationship to any of the types of granite occurring in West Bergslagen, was presented by Cheilletz (1988).

The 1.9–1.86 Ga volcano-sedimentary succession in the Gåsborn area, central Sweden (Fig. 1), consisting of, from old to young (Damman 1989a), the Linnhöjden metavolcanic Formation, the Malmbergsmossen Formation, the Baggtjärnen metavolcanic Formation, and the Gåsborn Formation (Fig. 1), belongs to the upper leptite and slate group of the Bergslagen supracrustal sequence (Oen *et al.* 1982, Oen 1987). The Linnhöjden Formation, the Baggtjärnen Formation and the lower part of the Gåsborn Formation consist of metavolcanic rocks, containing thin intercalated marble lenses; the Malmbergsmossen Formation consists of exhalative-sedimentary manganiferous iron-ore bearing marbles, metavolcanic rocks and metacherts (Damman 1988a); the upper part of the Gåsborn Formation consists of metavolcanic greywackes and alternating phyllites and quartzites (Damman 1989a).

This volcano-sedimentary succession is intruded by (Fig. 1): (1) basic sills and dykes associated with basic lavas intercalated between the metavolcanic rocks, (2) the Ostra Höjden granite of the Bergslagen older granite suite (Damman 1989a), (3) gabbros, diorites and tonalites, belonging to the approximately 1.84 Ga Hyttsjö gabbro–tonalite suite (Oen *et al.* 1982, Oen & Wiklander 1982, Oen 1987), (4) Dala–Järna and Småland–Värmland granites and (5) a Sveconorwegian (Oen & Verschure 1982) dolerite dyke.

The Ostra Höjden granite and related hydrothermal veins (Fig. 1; Damman 1988b, 1989a,b) were emplaced during the formation of a small rift basin characterized by the occurrence of phyllites and quartzites that form the top of the Gåsborn Formation (Fig. 1; Oen 1987, Damman 1989a,c). The intrusive bodies of the Hyttsjö suite, the Dala–Järna and Småland–Värmland granites and the Sveconorwegian dolerite dyke all were emplaced after deposition of the Gåsborn Formation (Damman 1989a,c).

Marbles occurring throughout the Gåsborn area (Fig. 1) contain reaction skarns, calc-silicate bands and metasomatic infiltration skarns (skarn nomenclature after Einaudi *et al.* 1981). This paper discusses the genesis of the skarns, with special emphasis on mineral chemistry, and relates skarn formation to the emplacement of the Ostra Höjden granite. In addition, the Gåsborn W–Mo polymetallic mineralization will be compared to other examples of epigenetic W–Mo mineralization occurring worldwide.

ANALYTICAL PROCEDURES

Electron-microprobe analyses were made with a Cambridge Instruments Microscan 9 operated at an acceleration potential of 20 kV and a probe current of 25 nA for silicates, and at 15 kV and a probe current of 40 nA for sulfides. Raw data were corrected with the Mark 9 on-line ZAF computer program. The following standards were used for silicate analysis: marialite (Cl), orthoclase (K), diopside (Ca,Si), ilmenite (Ti), rhodonite (Mn), fayalite (Fe), jadeite (Na), corundum (Al), synthetic Ba-aluminate (Ba), synthetic RbBr (Rb), synthetic *REE* oxide glasses (*REE*), and synthetic ZnO (Zn). Fluorine was measured at a probe current of 40 nA, using fluorite as a standard. The following standards were used for sulfide analysis: pyrite (Fe,S), chalcopyrite (Cu,Fe,S), sphalerite (Zn,Fe,S), Co metal (Co), Mo metal (Mo), Ag metal (Ag), synthetic CdS (Cd), synthetic InSe (In), Sb_2S_3 (Sb), galena (Pb) and bismuthinite (Bi,S).

Representative compositions of clinopyroxene, garnet, calcic amphiboles, and epidote-group minerals are presented in Tables 2–5. Structural formulae are calculated on the basis of 6 O for pyroxene, 12 O for garnet, 23 O for calcic amphiboles, and 25 O for epidote-group minerals.

The proportion of total tetrahedral Si + Al is constrained to equal 8 in calculations of calcic amphiboles and phlogopite. Fe^{3+} in garnet is calculated on the assumption that total $Al + Fe^{3+}$ equals 2, and, in calcic amphiboles, on the assumptions that all ^{VI}Al, Fe^{3+}, Ti, Fe^{2+}, Mg, Mn and Zn present occur in the *M*1–*M*3 sites of the calcic amphiboles, and that the total of the cations in these sites equals 5 (Robinson *et al.* 1982). In those calcic amphiboles with total cations in the *M*1–*M*4 sites below 7, Na is assigned from the *A* site to the *M*4 site. Fe^{3+} in epidote-group minerals is calculated on the assumption that total $Al + Fe^{3+}$ equals 3. Abbreviations of mineral names used in the text are those of Kretz (1983).

DISTRIBUTION OF THE DIFFERENT TYPES OF SKARN, AND THEIR AGE RELATIONS

Marbles intercalated between metavolcanic rocks in the Gåsborn area contain reaction skarns, calc-silicate bands and metasomatic infiltration skarns (skarn nomenclature after Einaudi *et al.* 1981). Reaction skarns and calc-silicate bands occur in marbles throughout the Gåsborn area (Damman 1985). The reaction skarns occur along the contacts of marble and intercalated layers of metavolcanic rock or chert; the calc-silicate bands occur as thin layers, disseminated throughout the marble. Metasomatic infiltration skarns are mainly found in the center of the Gåsborn area, where exhalative–sedimentary manganiferous iron-ore-bearing marbles of the Malmbergsmossen Formation (Fig. 1; Damman 1988a) are cross-cut by hydrothermal veins associated with the Ostra Höjden granite (Fig. 1; Damman 1988b, 1989a,b).

The metasomatic infiltration skarns form irregular masses, which vary in width between 20 cm and approximately 5 m (Damman 1985), locally showing bands of different minerals. The most strongly zoned masses are up to 30 cm thick and occur along the contacts of hydrothermal veins associated with the Ostra Höjden granite with marble (Damman 1985, 1989a). From the center of the Gåsborn area outward (Fig. 1), the hydrothermal veins and the metasomatic infiltration skarn decrease markedly in importance. Outside the area of hydrothermal veining (Fig. 1), metasomatic infiltration skarns are found only as thin layers at the contacts of marbles and intercalated layers of metachert and metavolcanic rock, where they replace previously formed reaction skarns. Where both reaction skarns or calc-silicate bands and metasomatic infiltration skarns are present, the first two types of skarn always occur as relict inclusions in the latter, indicating that the formation of the reaction skarns and calc-silicate bands must have started before that of the metasomatic infiltration skarns.

PETROGRAPHY OF THE SKARNS

Reaction skarns and calc-silicate bands

The reaction skarns and calc-silicate bands consist of calcite, dolomite, magnetite, talc, phlogopite, tremolite, diopside, forsterite, spinel, chondrodite, clinohumite and serpentine (Table 1). Calcite and

TABLE 1. PARAGENETIC ZONING OF SKARNS IN MARBLES IN THE GÅSBORN AREA

Mineral	The reaction skarns and calcsilicate bands	The metasomatic infiltration skarns, external zonation from old → young	The metasomatic infiltration skarns, internal zonation from old → young
Carbonate	--		
Diopside	--- --	-----	
Hedenbergite		------	-------------
Olivine	---		
Spinel	---		
Chondrodite	---		
Clinohumite	---		
Vesuvianite		-----	
Tremolite	--- --		
Actinolite		------	
Edenite		-------	-------
Hastingite		-------	------
Pargasite		-------	
Garnet		------	-----
Scapolite			-----
Plagioclase			-----
Quartz			--------------
Microcline			----
Allanite		-----	----
Epidote			------
Clinozoisite			----
Phlogopite	--- --	--------	----
Fluorite		--------	----
Chlorite			-----
Phengite			-----
Margarite		-----	
Scheelite		-----	
Talc	--		
Serpentine	--		
Molybdenite		------	-------
Sulfosalts		------	-------
Galena		------	-------
Sphalerite		------	-------
Chalcopyrite		------	------
Pyrrhotite		------	------
Arsenopyrite		---	---
Loellingite		---	----
Cubanite		---	----
Marcasite		---	-----
Bismuthinite		-------	--------
Native Bi		---	----
Native Sn		---	
Native Pb		---	
Pyrite		---	----

dolomite occur as subhedral crystals up to 1 cm across that form a matrix in which all other minerals are embedded. Magnetite occurs in granoblastic aggregates between calcite and dolomite. Talc occurs in very fine-grained, colorless to pale brown relict masses in the cores of phlogopite and tremolite crystals. Phlogopite is found as pale brown, colorless, subhedral to euhedral crystals, up to 500 μm in diameter, which (1) replace talc, (2) form monomineralic bands parallel to the bedding of the marbles, (3) occur disseminated in the marbles, and (4) form aggregates around diopside, forsterite, clinohumite, chondrodite and tremolite (Table 1). Tremolite occurs as subhedral, colorless to pale green pleochroic crystals, up to 5 mm in diameter, surrounding 1) phlogopite and 2) diopside, forsterite, chondrodite and clinohumite (Table 1). Diopside forms colorless, subhedral crystals, up to 2 mm in diameter, which occur disseminated in the marble and in thin layers at the contact between marble and intercalated lenses of metachert or metavolcanic rock. Locally, forsterite is found as inclusions in diopside poikiloblasts (Table 1). Forsterite also occurs as colorless, anhedral crystals, up to 2 mm across, disseminated in the marble. Spinel occurs as tiny, pale green crystals disseminated in the marbles, or intergrown with forsterite, clinohumite or chondrodite. Clinohumite occurs as colorless or pale yel-

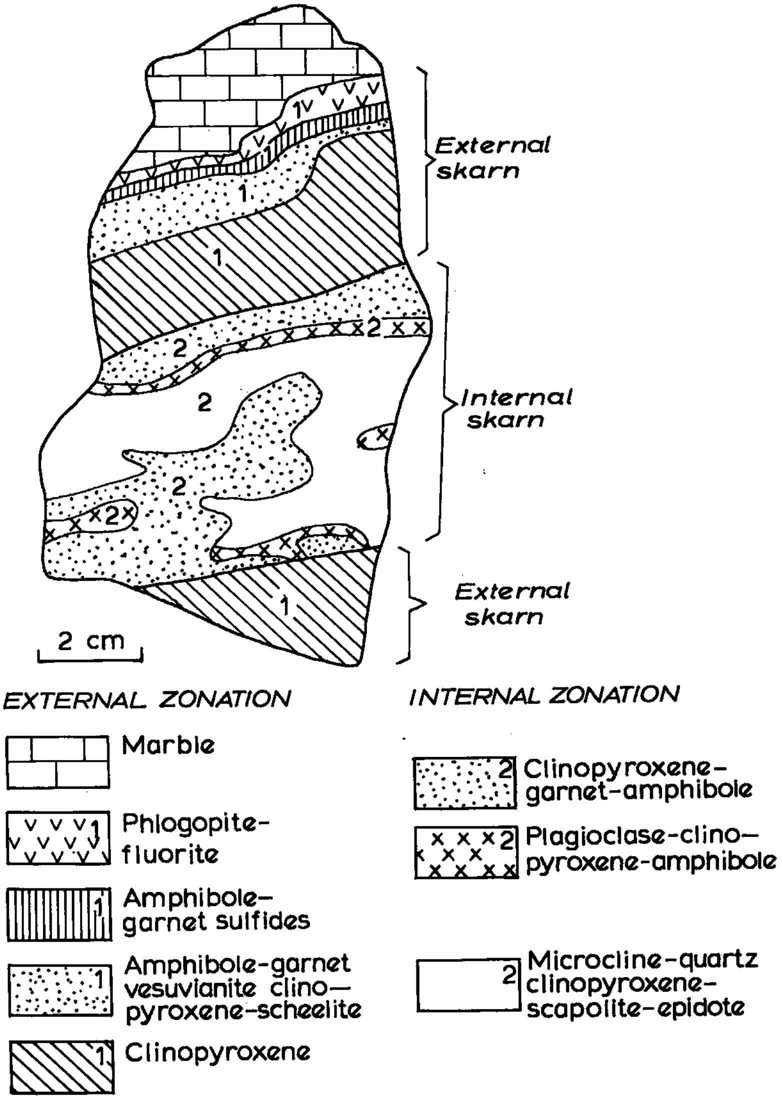


FIG. 2. Zonation of skarn minerals in and around a hydrothermal vein.

low pleochroic poikiloblasts intergrown with forsterite (Table 1). Chondrodite occurs as subhedral, colorless crystals, up to 400 μm in diameter, disseminated in the marble. Serpentine occurs as colorless aggregates, replacing forsterite, chondrodite, clinohumite and diopside.

The above observations suggest the following sequence of crystallization, from old to young, for the reaction skarns and the calc-silicate bands: calcite, dolomite, magnetite - talc - phlogopite - tremolite - diopside - forsterite, spinel, clinohumite, chondrodite - diopside - tremolite - phlogopite - serpentine (Table 1).

The metasomatic infiltration skarns: external arrangement

In and around hydrothermal veins associated with the Ostra Höjden granite, two arrangements of minerals are present in metasomatic infiltration skarns, an external arrangement from the vein-wall outward, and an internal arrangement in the hydrothermal veins (Fig. 2).

The hydrothermal veins are bordered (Fig. 2) by a zone of irregular aggregates of dark green pleochroic hedenbergite crystals, intergrown with magnetite. The hedenbergite-magnetite-rich band is rimmed on its outer side (Fig. 2) by a band consisting of >95 vol.% of garnet and <5 vol.% of scheelite and vesuvianite. Garnet occurs as large poikiloblasts, up to 5 cm across. Scheelite and vesuvianite occur intergrown with garnet. Garnet locally also occurs in thin veinlets that cut across the hedenbergite (+ magnetite) zone, or as rims around individual hedenbergite crystals. The garnet-rich bands are rimmed on their outer side (Fig. 2) by a band consisting of >95 vol.% of calcic amphiboles, together with <4 vol.% epidote-group minerals (allanite, epidote, clinozoisite, zoisite) and margarite, and <1 vol.% Pb–Bi–Ag- and Pb–Bi–Cu-sulfosalts, cassiterite, galena, (In-bearing) sphalerite, chalcopyrite, arsenopyrite, löllingite, molybdenite, pyrrhotite, bismuthinite, pyrite, cubanite, marcasite, native Pb, native Sn, and native Bi. The calcic amphiboles occur as subhedral to euhedral, dark blue-green pleochroic poikiloblasts, up to 2 cm across, commonly enclosing hedenbergite, garnet and vesuvianite, but they may be found intergrown with garnet as well. Allanite and margarite occur intergrown with the calcic amphiboles; epidote, clinozoisite and zoisite commonly occur as a thin rim around the former minerals. Molybdenite occurs as subhedral to euhedral crystals intergrown with calcic amphibole or as infillings of thin veinlets, consisting solely of molybdenite. Sulfosalts and galena commonly occur intergrown with one another. Locally sphalerite is intergrown with galena. Sphalerite may be mantled by a thin rim of chalcopyrite. Chalcopyrite, locally associated with roquesite (Kieft & Damman 1989), also occurs as small inclusions in sphalerite. Chalcopyrite is commonly intergrown with pyrrhotite or cubanite (or both). Arsenopyrite, occurring as euhedral crystals, contains small inclusions of löllingite and pyrrhotite. Cassiterite occurs as tiny crystals, intergrown with the sulfosalts. Native Bi is intergrown with arsenopyrite, or it occurs as a separate phase, without any other intergrown sulfides or native elements. Locally, native Bi is surrounded by a rim of bismuthinite. Native Pb and native Sn occur intergrown with sulfosalts or as tiny inclusions in pyrrhotite. Pyrite commonly replaces pyrrhotite, giving pyrrhotite a typical bird's-eye texture. Marcasite replaces pyrite along cracks and rims. Calcic amphiboles, allanite and sulfides also occur as late infillings of the garnet-rich veins that cut across the hedenbergite–magnetite masses. The calcic-amphibole-rich bands are rimmed on their outer side (Fig. 2) by a band consisting of phlogopite and fluorite. Phlogopite occurs as pale brown pleochroic anhedral crystals up to 400 μm across, that are embedded in the fluorite mass at the outer contact with the marble.

The above data suggest the following sequence of crystallization from a hydrothermal vein outward (Table 1): hedenbergite, magnetite – garnet, vesuvianite, scheelite – calcic amphiboles, epidote-group minerals, margarite, sulfides, native metals – phlogopite, fluorite.

Metasomatic infiltration skarns: internal zonation in the hydrothermal veins

The hydrothermal veins consist of 80–85 vol.% quartz, plagioclase and microcline, approximately 15 vol.% garnet and hedenbergite, <5 vol.% scapolite, epidote-group minerals, chlorite, calcite, phengite and fluorite and accessory sulfides, uraninite and pyrochlore (Table 1). Quartz and plagioclase occur as anhedral inclusions in hedenbergite and garnet. Hedenbergite occurs as dark green, euhedral inclusions, up to 2 mm across, in garnet. Garnet occurs as allotriomorphic masses that have grown from the vein walls inward (Fig. 2). Locally, garnet is rimmed by intergrown plagioclase and hedenbergite (Fig. 2). Garnet, hedenbergite and plagioclase locally contain small inclusions of hastingsite (Fig. 2, Table 1). The central part of the veins comprises a mixture of hastingsite, microcline, quartz, albite, scapolite and hedenbergite (Fig. 2, Table 1). Microcline and quartz commonly are granophyrically intergrown. Along cracks and rims, microcline is replaced by albite, locally giving it a cloudy appearance. Scapolite occurs as anhedral, colorless poikiloblasts, up to 5 cm across, which replace previously formed feldspars along cracks and rims. Hastingsite is dark blue-green pleochroic and either occurs intergrown with scapolite, as individual crystals, or as a thin rim around all other minerals. Hastingsite commonly contains numerous small inclusions of zircon and titanite. Uraninite, pyrochlore and several sulfides occur as tiny crystals intergrown with hastingsite. Thin rims of hastingsite around scapolite indicate that amphibole crystallization must have outlasted that of scapolite. A thin rim of hedenbergite around scapolite and hastingsite indicates that clinopyroxene formation persisted throughout a large part of the period of vein formation (Table 1). Epidote-group minerals, chlorite, phengite, calcite and fluorite (Fig. 2, Table 1) occur in small aggregates, replacing all minerals previously formed. Phengite is widely intergrown with epidote. Chlorite occurs as tiny, pale green pleochroic crystals, replacing calcic amphibole and pyroxene. Calcite forms panidiomorphic aggregates interstitial to the other minerals. Fluorite occurs in late crystallizing, panidiomorphic aggregates between the other minerals or as a replacement product of calcite.

The above observations suggest the following sequence of crystallization in the hydrothermal veins: quartz, plagioclase – hedenbergite – garnet, hedenbergite, hastingsite, plagioclase – hastingsite, microcline, quartz, albite, scapolite, hedenbergite, uraninite, pyrochlore, sulfides – epidote-group minerals, chlorite, phengite, calcite and fluorite (Table 1).

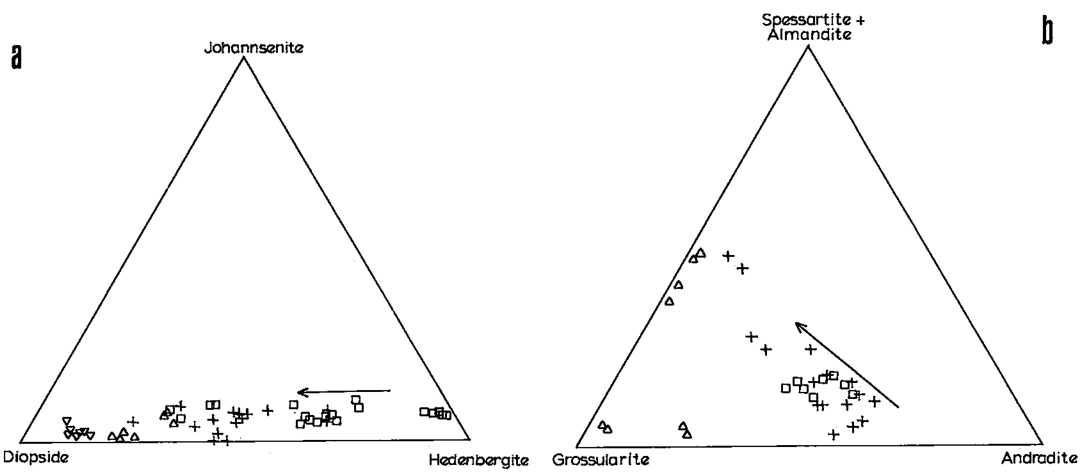


FIG. 3. Compositional variation in clinopyroxene (a) and garnet (b) in the Gåsborn area. Symbols: ∇ clinopyroxene from the reaction skarns and the calc-silicate bands, △, + and □ clinopyroxene and garnet from the metasomatic infiltration skarns, □ data from the inside of the vein of Figure 2 outward, + other compositions from the area of hydrothermal veining, △ compositions from outside the area of hydrothermal veining. The arrow shows the change in chemistry from a vein outward.

CHEMICAL COMPOSITION OF THE SKARN-FORMING MINERALS

Silicate-bearing marbles consist of >95 vol.% calcite, and <5 vol.% dolomite, rhodochrosite and siderite. Silicate-free marbles consist of highly variable proportions of calcite and dolomite, together with minor siderite and rhodochrosite.

Chondrodite, $Mg_{4.73}Fe_{0.22}Mn_{0.03}Ti_{0.01}(SiO_4)_2(OH,F)_2$, clinohumite, $Mg_{8.20}Fe_{0.49}Mn_{0.20}Ti_{0.20}(SiO_4)_4(OH,F)_2$, and spinel, $Sp_{80-82}Hc_{17}Gah_{1-2}$ show constant chemical compositions.

Forsterite shows a large variation in composition, from relatively Fe-rich ($Fo_{50-55}Fa_{40-45}Te_5$) in association with magnetite to Mg-rich ($Fo_{90}Fa_{10}$) where magnetite is absent.

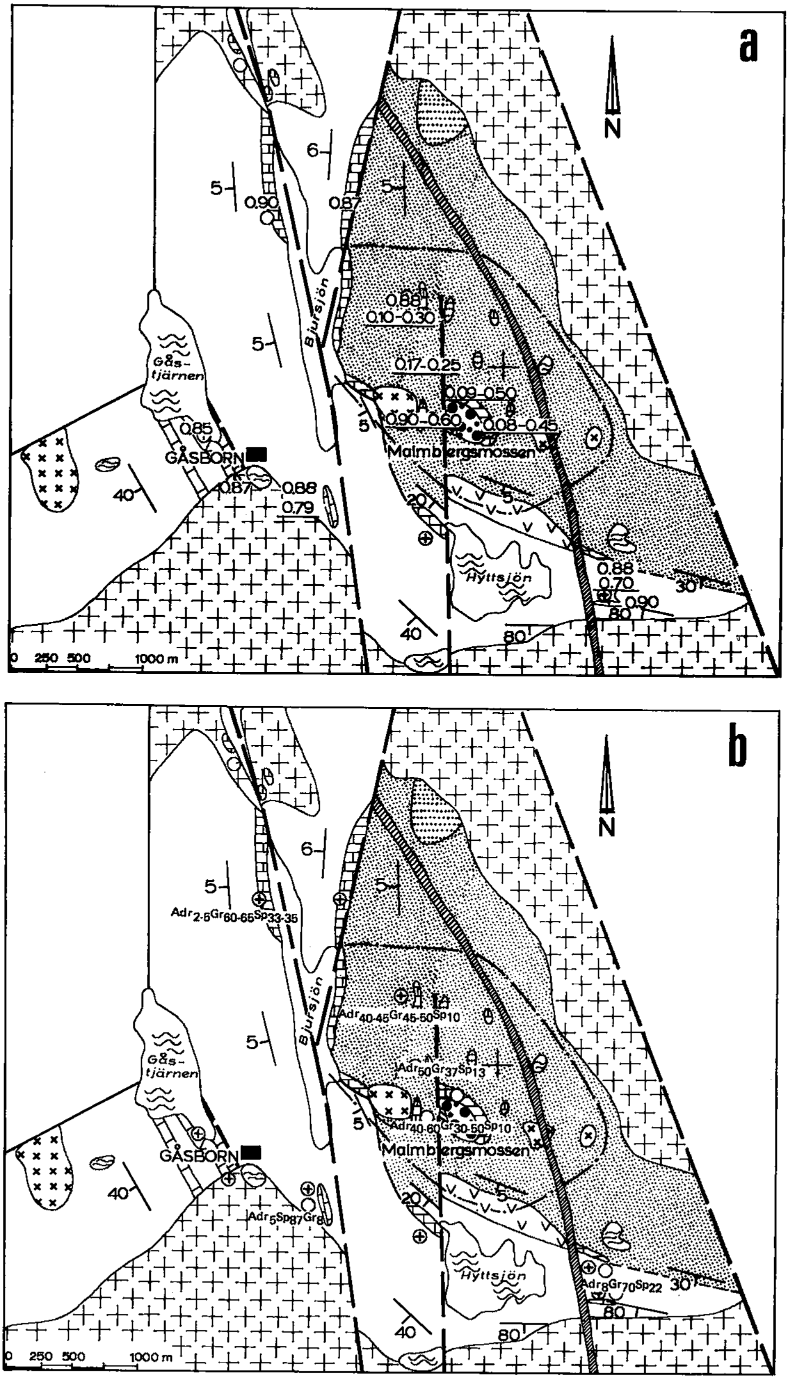
Clinopyroxene compositions vary from diopside to hedenbergite, with only minor other components (Fig. 3a). Diopside in the reaction skarns and the calc-silicate bands (Figs. 3a, 4a; anal. 1,2, Table 2) shows only minor compositional variations. On the scale of a single hand-sample (Fig. 2), clinopyroxene compositions in the metasomatic infiltration skarns vary from approximately $Hd_{91}Di_2Jh_7$ in the hydrothermal veins (Figs. 2, 3a; anal. 3, Table 2) to approximately $Hd_{25}Di_{62}Jh_{13}$ farthest from the veins (Figs. 3a, 4a; anal. 6, Table 2). On the scale of the whole Gåsborn area, clinopyroxene compositions in the metasomatic infiltration skarns also show a gradual change in composition, from more hedenbergite-rich in the center to more diopside-rich in the outer parts of the area (Figs. 3a, 4a; anal. 7–9, Table 2).

Garnet in the metasomatic infiltration skarns shows a wide compositional variation from the hydrothermal veins outward, conforming to the variation in composition of the clinopyroxenes. In the hydrothermal veins (Fig. 2), garnet has a composition of approximately $Adr_{59}Gr_{30}Alm_5Sp_6$ (Figs. 3b, 4b; anal. 1, Table 3). From the veins outward, the grossularite component increases at the expense of the andradite component, whereas the almandine and spessartine components remain approximately constant (Fig. 3b; anal. 2,3, Table 3). From the area of hydrothermal veining outward (Fig. 1), the andradite component decreases, the spessartine component increases slightly, and the almandine and grossularite components increase strongly (Figs. 3b, 4b; anal. 4–6, Table 3). Garnet contains between 0.18 and 1.10 wt.% F, which appears uncorrelated with other elements in the garnet. Garnet formulae recalculated on the assumptions that total $Ca+Mg+Mn+Fe^{2+}$ equals 3 and that total $Al+Fe^{3+}$ equals 2 (Table 3) show that the total amount of Si is always less than 3, suggesting that F, together with some OH groups, are incorporated by the substitution reaction $(SiO_4)^{4-} = \square + (OH,F)_4^{4-}$ (Valley *et al.* 1983).

Vesuvianite contains relatively large amounts of *REE* (La_2O_3 0.21 wt.%, Ce_2O_3 0.6%, Pr_2O_3 0.1%, Nd_2O_3 0.2%), F (up to 2 wt.%) and Cl (up to 0.4 wt.%).

Calcic amphiboles belong to the following groups (Rock & Leake 1984): tremolite, actinolite, hastingsite ($Na+K$ in the A site >0.5, $Fe^{3+} > {}^{VI}Al$), pargasite ($Na+K$ in the A site >0.5, $Fe^{3+} < {}^{VI}Al$) and hastingsitic hornblende (same as hastingsite, except $6.25 < Si < 6.5$).

Tremolite occurs in the reaction skarns and calc-silicate bands, and the other calcic amphiboles characterize the metasomatic infiltration skarns. Tremolite shows a more or less constant composition (anal. 1,2, Table 4), whereas the calcic amphiboles in the metasomatic infiltration skarns show a wide variation in composition. In the hydrothermal veins (Fig. 2), they are very Fe-rich (anal. 3, Table 4), changing outward, on the scale of a single hand-



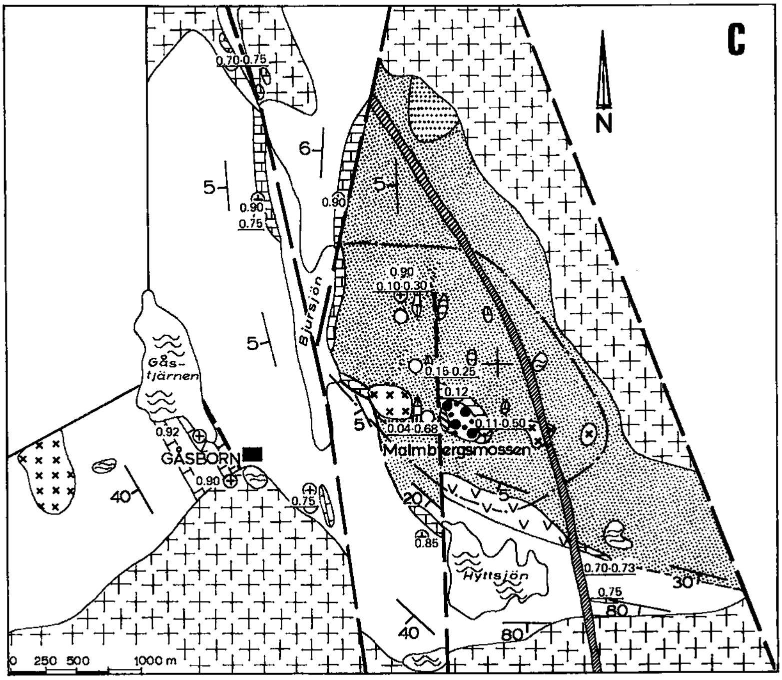


FIG. 4. Variation in clinopyroxene chemistry (a), garnet chemistry (b) and Mg/Fe ratio of calcic amphibole (c) in the Gåsborn area.

specimen, to more Mg-rich compositions (Fig. 4c; anal. 3–7, Table 4). In the area of hydrothermal veining (Fig. 1; anal. 3-7, Table 4), the calcic amphiboles are hastingsitic hornblende, hastingsite and Mg-hastingsite ($Fe^{3+} > {}^{VI}Al$, 6.25–5.9 Si p.f.u. (Rock & Leake 1984). With increasing distance from the area of hydrothermal veining (Fig. 1), the Mg/Fe ratio of the calcic amphiboles increases (Fig. 4c), and ${}^{VI}Al$ becomes greater than Fe^{3+}, indicating a change to pargasitic compositions (Anal. 8,9, Table 4; see Rock & Leake 1984). Actinolite only occurs as a thin rim around hastingsite in the area of hydrothermal veining.

In calcic amphiboles from every single locality within the Gåsborn area (each locality characterized by its own symbol), Cl shows a moderate positive correlation with Fe (Fig. 5a), and F with Mg (Fig. 5b) (Munoz 1984, Volfinger *et al.* 1985).

Matsubara & Motoyoshi (1985) suggested that the K content of calcic amphiboles that formed under granulite-facies conditions is related to their X_{Mg}. In this suite (Fig. 6), which was formed under low-pressure amphibolite-facies conditions (see below), K contents and X_{Mg} vary widely, but they do not show a correlation.

Scapolite occurs in or very close to the hydrothermal veins with which the metasomatic infiltration skarns are associated. In the central part of the Gåsborn area, scapolite has a composition of about $Marialite_{60}Meionite_{40}$, changing outward to about $Marialite_{35}Meionite_{65}$.

Epidote-group minerals are strongly zoned, with a pistacite-rich ($Ep_{66}Czo_{34}$) core and a clinozoisite-rich ($Ep_{21}Czo_{79}$) rim (Table 5).

Chlorite occurs as a late-stage mineral in the metasomatic infiltration skarns (Table 1). All analyzed grains show intermediate compositions (X_{Mg} 0.45–0.55) and contain variable amounts of F (0.53–1.01 wt.%). Phengite is invariably associated with chlorite and also contains variable amounts of F (0.59–0.70 wt.%.)

Phlogopite in the reaction skarns and calc-silicate bands contains between 0.89 and 1.52 wt.% F; in the metasomatic infiltration skarns it contains between 1.61 and 4.94 wt.% F, 0.04–0.26% Ba and 0.14–0.86% Rb.

The following sulfides and native metals and scheelite have been found only in the metasomatic infiltration skarns. Sulfosalts occur only in those of the central part of the Gåsborn area (Table 6) and show a large compositional variation. The following sulfosalts have been identified by means of electron-microprobe analyses:

1) Minerals of the bismuthinite–aikinite (Bi_2S_3–$PbCuBiS_3$) series. Several analyzed phases correspond to known members of this group. Other ana-

TABLE 2. VARIATION IN CLINOPYROXENE CHEMISTRY IN THE GÅSBORN AREA

wt.%	1	2	3	4	5	6	7	8	9
SiO_2	53.06	54.36	47.86	49.36	49.07	50.56	50.40	52.59	52.38
Al_2O_3	1.90	1.18	1.23	0.99	1.29	1.42	3.04	0.81	0.73
FeO	3.78	3.05	26.69	20.84	17.51	9.33	9.29	7.21	6.42
MnO	0.34	0.36	2.23	3.49	3.46	3.97	0.71	0.60	1.16
MgO	15.51	16.43	0.37	3.37	6.09	11.27	11.63	13.68	14.25
ZnO	-	-	-	0.17	0.16	-	-	-	-
CaO	24.95	25.40	22.13	22.42	22.69	23.35	25.27	24.84	24.73
Na_2O	-	-	0.28	0.29	0.15	0.10	-	-	
Total	99.55	100.78	100.79	100.92	100.41	100.00	100.34	99.76	99.67
Si	1.95	1.97	1.95	1.97	1.95	1.94	1.90	1.97	1.96
Al	0.08	0.05	0.06	0.04	0.06	0.06	0.14	0.04	0.03
Fe	0.12	0.09	0.91	0.69	0.56	0.29	0.29	0.22	0.20
Mn	0.01	0.02	0.07	0.11	0.12	0.13	0.02	0.02	0.04
Mg	0.85	0.89	0.02	0.20	0.34	0.62	0.65	0.76	0.79
Zn	-	-	-	0.01	0.01	-	-	-	-
Ca	0.98	0.99	0.97	0.96	0.97	0.97	1.00	1.00	0.99
Na	-	-	0.04	0.04	0.01	0.01	-	-	-
Total	3.99	4.00	4.02	4.02	4.02	4.02	4.00	4.00	4.01

Samples 1 and 2: diopside from the reaction skarns and the calc-silicate bands; 3-9: variation in clinopyroxene composition in the metasomatic infiltration skarns. Compositions 3-6: changes in clinopyroxene composition from a hydrothermal vein outward (Fig. 2); 7-9: composition of clinopyroxene in metasomatic infiltration skarns from the outer parts (Fig. 1) of the Gåsborn area.

TABLE 3. VARIATION IN GARNET COMPOSITION IN THE GÅSBORN AREA

wt.%	1	2	3	4	5	6
SiO_2	36.12	36.49	36.30	37.21	38.44	38.85
Al_2O_3	8.64	9.74	13.30	17.24	21.28	21.33
TiO_2	-	-	-	0.85	-	-
Fe_2O_3	20.11	17.44	12.75	6.80	0.68	1.50
FeO	2.37	2.66	4.23	0.92	0.61	0.75
MnO	2.13	3.06	1.82	1.34	7.90	1.03
MgO	0.10	-	0.13	0.22	-	-
CaO	31.14	29.85	30.40	34.32	23.06	35.35
F	0.32	0.26	0.40	0.56	-	0.45
Total	100.93	99.50	99.33	99.46	99.97	99.26
Si	2.91	2.94	2.88	2.91	3.00	2.95
Al	0.82	0.94	1.24	1.55	1.96	1.91
Ti	-	-	-	0.05	-	-
Fe^{3+}	1.18	1.06	0.76	0.40	0.04	0.09
Fe^{2+}	0.16	0.18	0.28	0.06	0.56	0.05
Mn	0.15	0.21	0.12	0.09	0.52	0.07
Mg	-	-	0.02	0.02	-	-
Ca	2.68	2.61	2.58	2.83	1.92	2.88
Total	7.90	7.94	7.88	7.91	8.00	7.95

Fe^{3+} in formula units is calculated on the assumption of 2 ($Al+Fe^{3+}+Ti$). Fe_2O_3 in wt. % is recalculated from Fe^{2+} by means of the formula: $Fe_2O_3 = (FeO/1.2865) \times (Fe^{3+}/(Fe^{2+}+Fe^{3+})) \times 1.43$.

lyzed phases show compositions between those of members of this group, suggesting that they are submicroscopic intergrowths involving one or more sulfosalts and galena.

2) Galenobismuthite ($PbBi_2S_4$), locally slightly argentiferous.

3) Minerals of the lillianite–gustavite solid-solution series. Many of the analyzed sulfosalts belong to this series. The compositions are highly variable, with limited replacement of Ag by Cu.

4) Phases with compositions between those of the bismuthinite–aikinite series and the lillianite–gustavite series. These phases commonly consist of very fine intergrowths, rendering accurate analysis of the individual phases impossible. The compositions obtained consequently correspond to a mixture of phases, among which gustavite–lillianite and galena may be present. In contrast to the lillianite–gustavite series, the phases of intermediate composition may contain high concentrations of Cu, with Cu/(Cu + Ag) in excess of 0.5 p.f.u.

Galena in the center of the Gåsborn area (Fig. 1) commonly contains small amounts of Ag and Bi (Table 6). With increasing distance from the center outward, Bi becomes depleted, the amount of Ag decreases, and Sb becomes enriched in galena (Table 6).

Sphalerite commonly occurs intergrown with galena or chalcopyrite (or both). In the center of the Gåsborn area (Fig. 1), sphalerite contains 0.1–2.0 wt.% In and highly variable amounts of Fe, Mn and Cd in solid solution (Kieft & Damman 1989; Table 6). With increasing distance from the center outward, the In content of sphalerite strongly decreases, but its Fe, Mn and Cd contents stay approximately the same (Kieft & Damman 1989). Locally, small inclusions of chalcopyrite and roquesite are formed in sphalerite owing to late "chalcopyrite disease" (Kieft & Damman 1989).

Chalcopyrite, pyrrhotite, cubanite, pyrite, molybdenite and marcasite are found in practically all samples of metasomatic infiltration skarn analyzed for the present study. In the center of the Gåsborn area (Fig. 1), chalcopyrite locally contains small amounts of In and Ag in solid solution and small exsolution lamellae of an unidentified In–Zn-rich phase (Kieft & Damman 1989).

Arsenopyrite and included löllingite from the central part of the Gåsborn area contain 0.1–8.5 wt.%

TABLE 4. VARIATIONS IN Ca-AMPHIBOLE COMPOSITION IN THE GÅSBORN AREA

wt.%	1	2	3	4	5	6	7	8	9
SiO_2	56.69	56.36	36.74	37.21	40.41	39.65	40.61	38.67	39.44
Al_2O_3	1.23	1.65	11.69	13.35	11.31	12.29	12.04	15.30	15.55
TiO_2	-	0.10	-	-	-	-	-	0.66	0.79
Fe_2O_3	-	-	8.14	6.14	4.70	3.60	4.72	3.02	4.74
FeO	3.19	1.73	24.45	19.46	19.36	12.65	9.76	7.75	5.31
MnO	0.30	-	1.55	0.86	1.20	2.18	2.09	0.73	0.56
MgO	21.88	22.86	0.56	4.93	5.98	9.98	11.50	13.06	13.80
ZnO	-	-	0.19	0.11	0.09	0.20	-	-	-
CaO	13.10	13.57	10.96	11.82	11.90	12.17	12.22	12.30	12.35
Na_2O	0.21	0.31	1.05	0.64	1.31	1.62	2.14	1.00	1.96
K_2O	0.17	0.08	2.55	3.68	2.08	2.45	1.72	3.42	1.77
Cl	-	-	1.29	0.80	0.35	0.25	0.16	0.57	0.32
F	2.89	0.23	0.48	0.72	0.47	1.42	1.40	1.32	1.20
Total	99.66	96.89	99.65	99.72	99.16	98.46	98.36	97.80	97.79
Si	7.88	7.80	6.02	5.90	6.29	6.16	6.18	5.84	5.86
^{IV}Al	0.12	0.20	1.98	2.10	1.71	1.84	1.82	2.16	2.14
^{VI}Al	0.08	0.07	0.28	0.40	0.37	0.41	0.34	0.37	0.59
Ti	-	0.01	-	-	-	-	-	0.07	0.09
Fe^{3+}	-	-	1.00	0.73	0.55	0.42	0.54	0.34	0.53
Fe^{2+}	0.37	0.20	3.34	2.57	2.52	1.64	1.24	0.97	0.66
Mn	0.04	-	0.22	0.12	0.16	0.29	0.27	0.09	0.07
Mg	4.51	4.72	0.14	1.17	1.39	2.22	2.61	2.96	3.06
Zn	-	-	0.02	0.01	0.01	0.02	-	-	-
Ca	1.95	2.00	1.92	2.00	1.98	2.00	1.99	2.00	1.97
Na	0.06	0.08	0.33	0.20	0.40	0.49	0.63	0.29	0.57
K	0.03	0.01	0.53	0.68	0.41	0.49	0.33	0.66	0.34
Total	15.04	15.09	15.78	15.88	15.79	15.98	15.95	15.95	15.88

1+2 - tremolite from reaction skarns; 3-9 (K)-hastingsite- and pargasite formed with increasing distance outward (3 → 9) in metasomatic inflitration skarns.
Calcic amphibole stochiometries calculated on the basis of 23 O.
Fe^{3+} in formula units calculated on the assumptions that ^{VI}Al, Ti, Fe^{3+}, Fe^{2+}, Mg, Mn and Zn all belong in the M1-M3 sites of the calcic amphiboles, and that the total of these elements equals 5 (Robinson et al. 1982). For calculations of wt. % Fe^{3+}, see table 3.

Co. Scheelite only occurs in metasomatic infiltration skarns from the central part of the area (Table 6) and contains less than 1 wt.% Mo. Native Bi, Pb and Sn and cassiterite also only occur in the central part of the area (Table 6), but these minerals all are too fine grained for accurate quantitative analysis.

TIMING OF SKARN FORMATION, MINERAL-FORMING REACTIONS, AND ESTIMATES OF *P–T* CONDITIONS DURING SKARN FORMATION

Petrographic observations presented above show that skarn formation in the Gåsborn area takes place in two episodes: an early episode characterized by the formation of reaction skarns and calc-silicate bands, and a later episode characterized by the formation of metasomatic infiltration skarns (Cheilletz 1988). In the metasomatic infiltration skarns, mineralogical and chemical zonations are found, going from hydrothermal veins associated with the Ostra Höjden granite outward, and from the center to the outer edges of the Gåsborn area (Figs. 1–4, Tables 2–4). These data suggest that (1) the reaction skarns and the calc-silicate bands were most probably formed during prograde (contact) metamorphism prior to or during the emplacement of the Ostra Höjden granite, as a result of reactions between marble and intercalated lenses of metavolcanic rock or metachert, and (2) the metasomatic infiltration skarns most probably formed from hydrothermal fluids associated with the Ostra Höjden granite. During emplacement of the Ostra Höjden granite, the lithostatic pressure (P_L) is estimated to have been approximately 1 kbar (Damman 1989a).

FORMATION OF MINERALS IN THE REACTION SKARNS AND THE CALC-SILICATE BANDS

The earliest silicate present in the reaction skarns and the calc-silicate bands is talc, which may have been formed in dolomite marbles according to the reaction (Fig. 7):

$$\text{3 dolomite} + \text{4 quartz} + H_2O = \text{talc} + \text{3 calcite} + CO_2 \qquad (1)$$

At a P_L of 1.0 kbar (Damman 1989a), this reaction occurs at $T < 435°C$ and $X(CO_2) < 0.5$ (Walther & Helgeson 1980). Phlogopite and tremolite occur as thin rims around the talc–feldspar–quartz–dolomite masses, suggesting that they are formed by the following reactions:

$$\text{K-feldspar} + \text{3 dolomite} + H_2O = \text{phlogopite} + \text{calcite} + CO_2 \qquad (2)$$

and

$$\text{5 talc} + \text{6 calcite} + \text{4 quartz} = \text{3 tremolite} + 6\,CO_2 + 2\,H_2O \qquad (3)$$

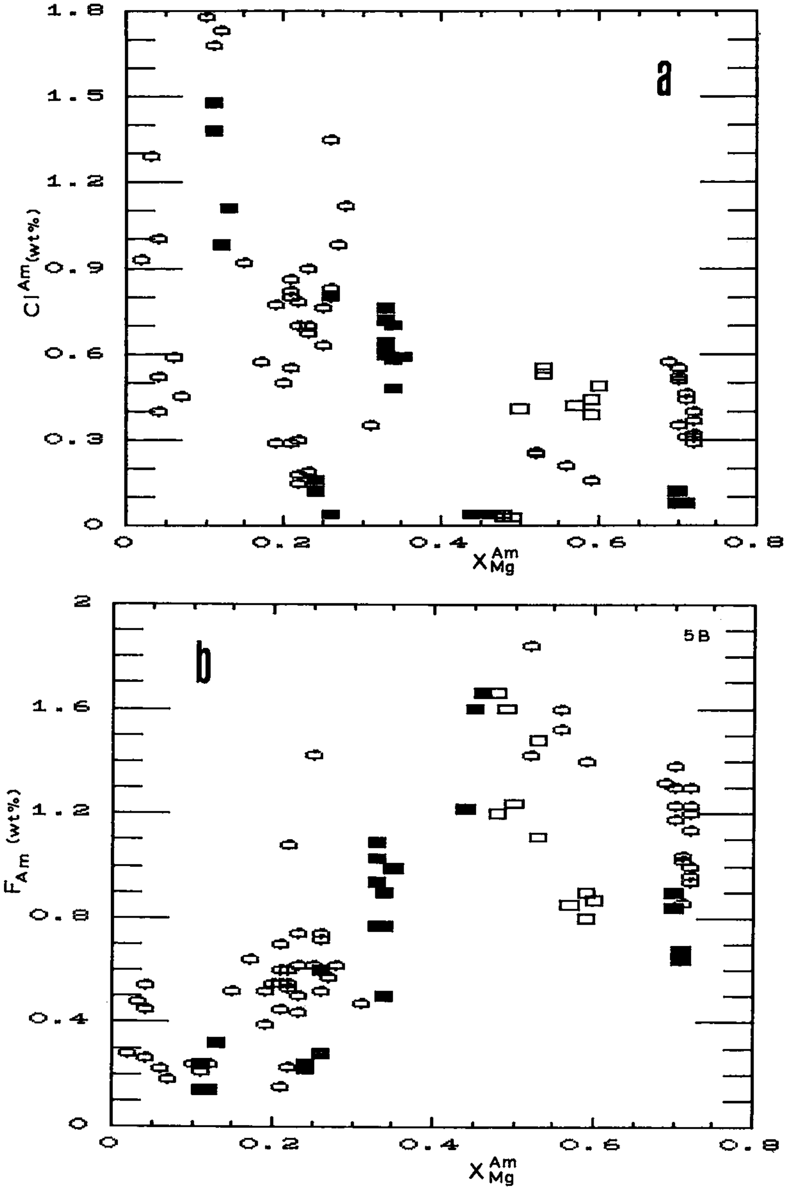


FIG. 5. X_{Mg}–Cl (a) and X_{Mg}–F (b) for all pargasite and hastingsite in the Gåsborn area. Each symbol represents a different sample of skarn.

The minimum *T* for reaction (2), at a low $X(CO_2)$, is estimated at *ca.* 350°C, increasing to about 450°C as $X(CO_2)$ increases to 0.5 (Bucher-Nurminen 1982; see Fig. 7). The minimal temperature for reaction (3), at a low $X(CO_2)$, is estimated at *ca.* 300°C, increasing to about 435°C as $X(CO_2)$ increases to 0.5 (Walther & Helgeson 1980; see Fig. 7). Talc, phlogopite and tremolite in the Gåsborn area always contain small amounts of F, the presence of which increases their upper stability limit to higher temperatures, but does not affect their low-temperature stability limit with respect to their F-free analogues (Mercolli 1980). The next mineral to form, diopside, locally contains relict tremolite, but is also found without tremolite inclusions, suggesting the existence of two possible reactions for its formation:

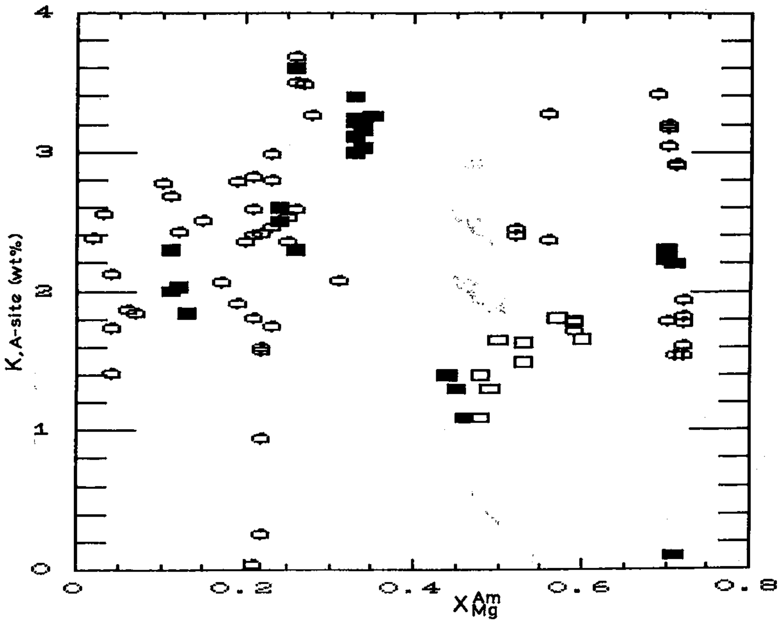


FIG. 6. K-X_{Mg} for all pargasite and hastingsite analyzed from the Gåsborn area. For symbols, see Figure 5.

TABLE 5. CHEMICAL COMPOSITION OF EPIDOTE

	1	2	3
SiO_2	36.59	37.56	39.22
Al_2O_3	24.15	25.99	30.93
Fe_2O_3	11.80	9.73	2.96
MnO	0.58	0.72	0.07
CaO	23.28	23.26	24.80
Total	96.40	97.26	97.98
Si	3.00	3.00	3.00
Al	2.35	2.42	2.82
Fe^{3+}	0.65	0.58	0.18
Mn	0.03	0.04	0.01
Ca	2.00	1.99	2.03
Total	8.03	8.03	8.04

Core (1) to rim (3).
Fe^{3+} (formula units) calculated on the assumption that Al+Fe^{3+} equals 3. For calculations of Fe^{3+} (wt. %), see table 3.

TABLE 6. DISTRIBUTION OF NATIVE METALS, SCHEELITE AND SULFIDES IN PYROXENE-GARNET SKARNS IN THE GÅSBORN AREA

Mineral	Central part of the Gåsborn area (Fig. 1)	Outer parts of the Gåsborn area (Fig. 1)
Scheelite	X	
Molybdenite	X	X
Sulfosalts	X	
Roquesite	X	
Galena	Ag,Bi-bearing	Sb-bearing
Cassiterite	X	
Sphalerite	In-bearing	In-poor
Chalcopyrite	X	X
Pyrrhotite	X	X
Arsenopyrite	X	
Loellingite	X	
Cubanite	X	
Marcasite	X	X
Bismuthinite	X	
Pyrite	X	X
Native Pb	X	
Native Bi	X	
Native Sn	X	

X = present.

$$\text{tremolite} + \text{calcite} + 2\ \text{quartz} = 5\ \text{diopside} + 10\ CO_2 + 4\ H_2O \qquad (4)$$

$$\text{or } 2\ \text{quartz} + \text{dolomite} = \text{diopside} + CO_2 + H_2O \qquad (5)$$

The minimum T for reaction (4), at a low $X(CO_2)$ and a P_L of 1.0 kbar (Damman 1989a), is estimated at 400°C, increasing to *ca.* 520°C as $X(CO_2)$ increases to 0.5 (*cf.* Rice 1980b, Walther & Helgeson 1980; see Fig. 7). In several localities, the next mineral to form, chondrodite, contains 6.66–7.09 wt.% F (X_F 0.62–0.65). The low-T stability limit of chondrodite is determined by the reaction

$$\text{tremolite} + \text{dolomite} = \text{chondrodite} + \text{calcite},$$

and its high-T limit, by the reaction

$$\text{tremolite} + \text{chondrodite} = \text{forsterite} + \text{calcite}.$$

In chondrodite-bearing rocks, neither forsterite nor diopside is found stable next to chondrodite, implying that temperatures in these rocks were less than 560°C and that $X(CO_2)$ was less than 0.3 (Rice 1980b; see Fig. 7). In other localities, forsterite and clinohumite, containing 2.09–2.37 wt.% F (X_F

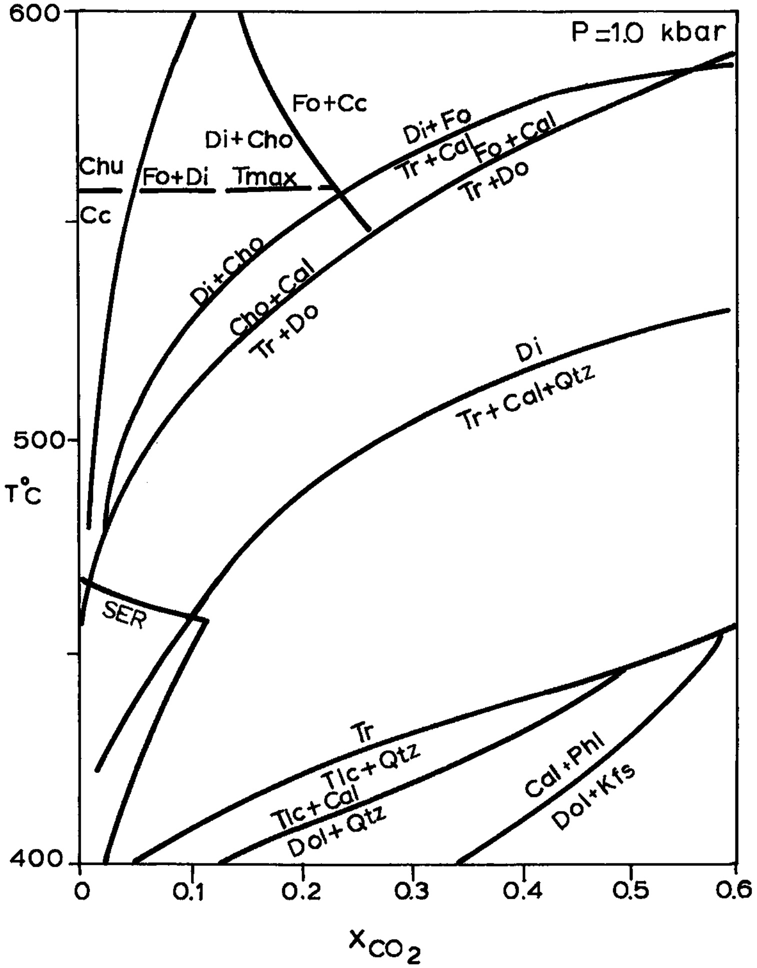


FIG. 7. Estimated stability fields of calc-silicates in the reaction skarns and the calc-silicate bands.

0.50–0.55), are formed instead of chondrodite. Diopside is not found stably next to forsterite, confirming that the maximum *T* of the country rock during emplacement of the Ostra Höjden granite was less than 560°C, but implying that $X(CO_2)$ in these rocks was less than 0.1 (Rice 1980a; see Fig. 7). Wherever magnetite and Fe-rich olivine are found together, olivine is formed at the expense of magnetite, implying that $f(O_2)$ was below FMQ [log $f(O_2)$ $<$-23 at *T* of *ca.* 530°C]. The replacement of forsterite, chondrodite and clinohumite by serpentine implies that H_2O must have remained the dominant fluid during retrograde calc-silicate formation (Johannes 1969; see Fig. 7).

The above *P–T* estimates are based on Fe-free end members. However, all minerals analyzed contain, besides Mg, small amounts of other elements, of which Fe is by far the most important. Incorporation of Fe in olivine lowers its stability field with respect to that of forsterite (Deer *et al.* 1982). The effect of Fe-incorporation on the stability fields of chondrodite and clinohumite is not known with certainty, but is believed to lower them as well (Deer *et al.* 1982). These data imply that the peak metamorphic temperature of 560°C calculated above should be considered as a maximum temperature.

MINERAL-FORMING REACTIONS IN THE METASOMATIC INFILTRATION SKARNS

The *P–T* stability fields of hedenbergite-rich clinopyroxene and andradite-rich garnet, the earliest minerals in the metasomatic infiltration skarns, have been discussed by Liou (1973), Gustafson (1974)

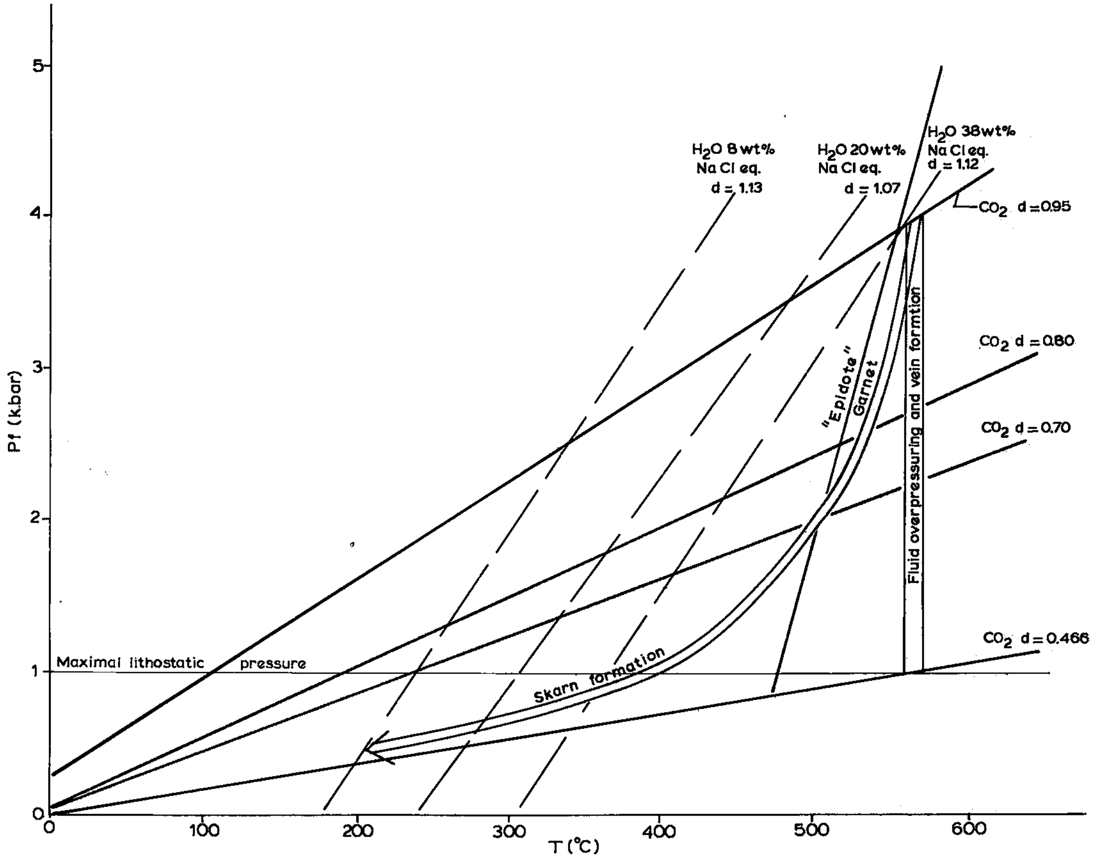


FIG. 8. Estimated P–T path during the formation of the metasomatic infiltration skarns.

and Burt (1972), among others; they showed that these minerals can form over a large P–T interval, rendering them rather useless for an estimate of peak metamorphic conditions during the formation of the metasomatic infiltration skarns. Results of a fluid-inclusion study of the Ostra Höjden granite and related hydrothermal veins and skarns (Damman 1989b) suggest that the temperature during crystallization of the hydrothermal veins was about 560°C and that the fluid pressure in the hydrothermal veins was approximately 4 kbars. This temperature estimate is in good agreement with the peak metamorphic temperature of 550°C derived from calc-silicates in reaction skarns and calc-silicate bands that were formed by contact metamorphism due to the Ostra Höjden granite (Fig. 7). The agreement suggests that a temperature of 550–560°C, a lithostatic pressure of about 1 kbar, and a fluid pressure of approximately 4 kbars can be considered good estimates of the conditions of peak metamorphism during the formation of metasomatic infiltration skarns in the Gåsborn area.

The $f(O_2)$–T and $f(S_2)$–T stability fields of hedenbergite, hedenbergite–johannsenite and hedenbergite–diopside solid solutions have been studied by Gamble (1976, 1978) and Burton *et al.* (1982). According to Burton *et al.* (1982), the $f(O_2)$–T stability field of the end member Hd_{100} with respect to andradite, magnetite and quartz is determined by the relationship $\log f(O_2)_{P,T} = (-26457/T) + 12.12 + 0.087(P-1)/T$ (P in bars and T in K), and that of Hd_{85}–Jh_{15}, by the relationship $\log f(O_2)_{P,T} = (-26457/T) + 13.42 + (P-1)/T$. According to Gamble (1976, 1978), the incorporation of up to 50 mole % diopside component in hedenbergite does not significantly change these relationships. The hedenbergite found in the hydrothermal veins in the Gåsborn area always contains only minor Na and Al, probably too little to have a serious influence upon its stability field. At an initial fluid pressure of 4 kbars and a T of 550–560°C (Fig. 8; Damman 1989a), the above data imply that $\log f(O_2)$ during the formation of the hedenbergite-bearing assemblages in the hydrothermal veins must have been about −18.6

(Burton *et al.* 1982). The presence of vesuvianite in the skarns along the hydrothermal veins and the presence of epidote-group minerals in the veins suggest that $X(CO_2)$ of the skarn-forming fluid was low (Taylor & Liou 1978, Hochella *et al.* 1982).

In the metasomatic infiltration skarns, epidote-group minerals were formed after garnet, clinopyroxene, vesuvianite and calcic amphibole. The stability of epidote-group minerals with respect to that of garnet was discussed by Liou (1973) and Taylor & Liou (1978), who showed that their stability is strongly dependent on $f(O_2)$, $X(CO_2)$ of the fluid, P and T. According to their calculations, the replacement of garnet by epidote with a composition of about $Ep_{66}Czo_{34}$ (anal. 1, Table 6) at a log $f(O_2)$ of −18.6 (see above) takes place at about 500°C under a fluid pressure of 2 kbars. This replacement temperature increases with increasing P_f and decreases with decreasing P_f (Liou 1973). The fact that epidote-group minerals were formed after clinopyroxene, garnet, vesuvianite and calcic amphibole indicates that they were formed at a temperature considerably below the maximal T during hydrothermal vein formation, which is estimated at 550–560°C (Damman 1989a; Fig. 8). If we assume that the replacement of clinopyroxene, garnet, vesuvianite and the calcic amphiboles by epidote took place at 500°C (a higher temperature is considered unlikely, because the inferred T interval for the formation of the clinopyroxenes, garnet, vesuvianite and the calcic amphiboles would be unrealistically small), the data of Liou (1973) and Taylor & Liou (1978) imply that during the T interval of 560–500°C, the fluid pressure in the hydrothermal veins must have dropped from about 4 kbars (Damman 1989a,b) to less than 2 kbars (Fig. 8).

The epidotes become progressively enriched in Al, from core to rim (Table 5), indicating a decrease in T of formation and a slight decrease in $f(O_2)$ of the fluid (Liou 1973). The stability fields of chlorite, quartz and F-rich phlogopite (Fleming & Fawcett 1976, Munoz 1984, Beddoe-Stephens *et al.* 1987) unfortunately all extend from temperatures of <600°C to about 200°C, reducing their value as tem-

TABLE 7. CRITERIA USED IN THE CLASSIFICATION OF GRANITE-RELATED W-Mo SKARN MINERALIZATION

	Einaudi et al. (1981)		Sato (1982)		Kwak & Tan (1987)	
Prograde stage	Reduced skarns	Oxidized skarns	Reduced skarns	Oxidized skarns	Reduced skarns	Oxidized skarns
Pyroxene/garnet	10:1 to 2:1	1:1 to 1:10				
Pyroxene composition						
mole % hedenbergite	60-90	20-70				
mole % johannsenite	5-20	0-5				
Garnet composition						
mole % andradite	10-50	50-80				
Late garnet composition			Grossularite-rich	Andradite-rich	Grossularite-almandine	Andradite
mole % andradite	0-50	80-100				
mole % spessartite	5-35	0-5				
mole % almandine	5-40	0				
Retrograde stage						
Typical assemblages	Biotite-plagioclase-opaques-calcite; hornblende-opaques-quartz-calcite	Epidote-chlorite-calcite-quartz; actinolite-opaques-quartz-calcite				
Amphibole composition						
mole % ferrotremolite	5-80	30-60				
mole % tremolite	0-30	30-70				
mole % ferropargasite	70-100	5-20				
Diagnostic opaques	Pyrrhotite-magnetite (pyrite-native Bi)	Pyrite (magnetite -pyrrhotite-bismuthinite)	Pyrrhotite	Pyrite-magnetite		Magnetite
Scheelite			Mo-free	Mo-bearing		
Bulk of skarn			Fe^{3+}-poor	Fe^{3+}-rich		
Accompanying granitoids			Ilmenite series	Magnetite series		

TABLE 8. IMPORTANT CHARACTERISTICS OF GRANITES AND RELATED W-Mo MINERALIZATION IN WEST BERGSLAGEN

Occurrence	Gåsborn	Others (Baker & Hellingwerf 1988)
Clinopyroxene composition		
Proximal	Hedenbergite-rich	Hedenbergite-diopside solid solution series; minor other components.
Distal	Diopside-rich	
Garnet compositions		
Proximal	Andradite-rich	Andradite-grossularite; minor spessartite and almandite
Distal	Grossularite-rich	
Calcic amphibole		
Proximal	(K)-hastingsite	(K)-hastingsite
Distal	(K)-pargasite	
Scheelite composition	Mo-poor	Mo-poor
Diagnostic opaques	Magnetite-pyrrhotite-molybdenite-sulfosalts	Molybdenite-pyrrhotite
Late sulfides	Pyrite after pyrrhotite	Pyrite after pyrrhotite
Acompanying granites	High-level, A-type granite	High-level, A-type granite

perature indicators. An intersection of isochores for trails of late aqueous and gaseous inclusions in quartz in the hydrothermal veins suggests a final temperature and pressure of skarn formation of about 200°C and around 0.5 kbar, respectively (Fig. 8, after Dammman 1989b), implying that 1) chlorite, quartz, calcite, phlogopite and fluorite formed at a temperature between <500°C and 200°C, and 2) over this T interval fluid pressures dropped from 2 kbars to about 0.5 kbar (Fig. 8).

DISCUSSION

At the beginning of this paper, we mentioned that all authors who have discussed the genesis of W–Mo mineralization in West Bergslagen (Hübner 1971, Ohlsson 1979, Hellingwerf & Baker 1985, Baker *et al.* 1987, Cheilletz 1988, Billström *et al.* 1988, Baker & Hellingwerf 1988) agree that the mineralization is of epigenetic origin and was deposited from granite-related hydrothermal solutions. Furthermore, we mentioned that to date there is no agreement among these authors with regard to the specific suite of granite (the older Bergslagen granites: Hellingwerf & Baker 1985, Baker *et al.* 1987, Baker & Hellingwerf 1988) or the younger Bergslagen granites (Hübner 1971, Billström *et al.* 1988) that is believed to be responsible for the W–Mo mineralization.

The two-stage model for the formation of W–Mo skarns presented in this paper, *i.e.*, formation of early, barren reaction skarns and calc-silicate bands, and late W–Mo mineralized metasomatic infiltration skarns, both by interaction with hydrothermal fluids related to a granite of the older Bergslagen granite suite, agrees with and combines the model of Cheilletz (1988) for W–Mo skarn formation in West Bergslagen with that of Hellingwerf & Baker (1985), Baker *et al.* (1987) and Baker & Hellingwerf (1988). No evidence is found in favor of a relationship with the Dala–Järna or Småland–Värmland granites of the younger Bergslagen granite suite, which occur N, E and S of the Gåsborn area (Fig. 1), as was suggested by Hübner (1971) and Ohlsson (1979).

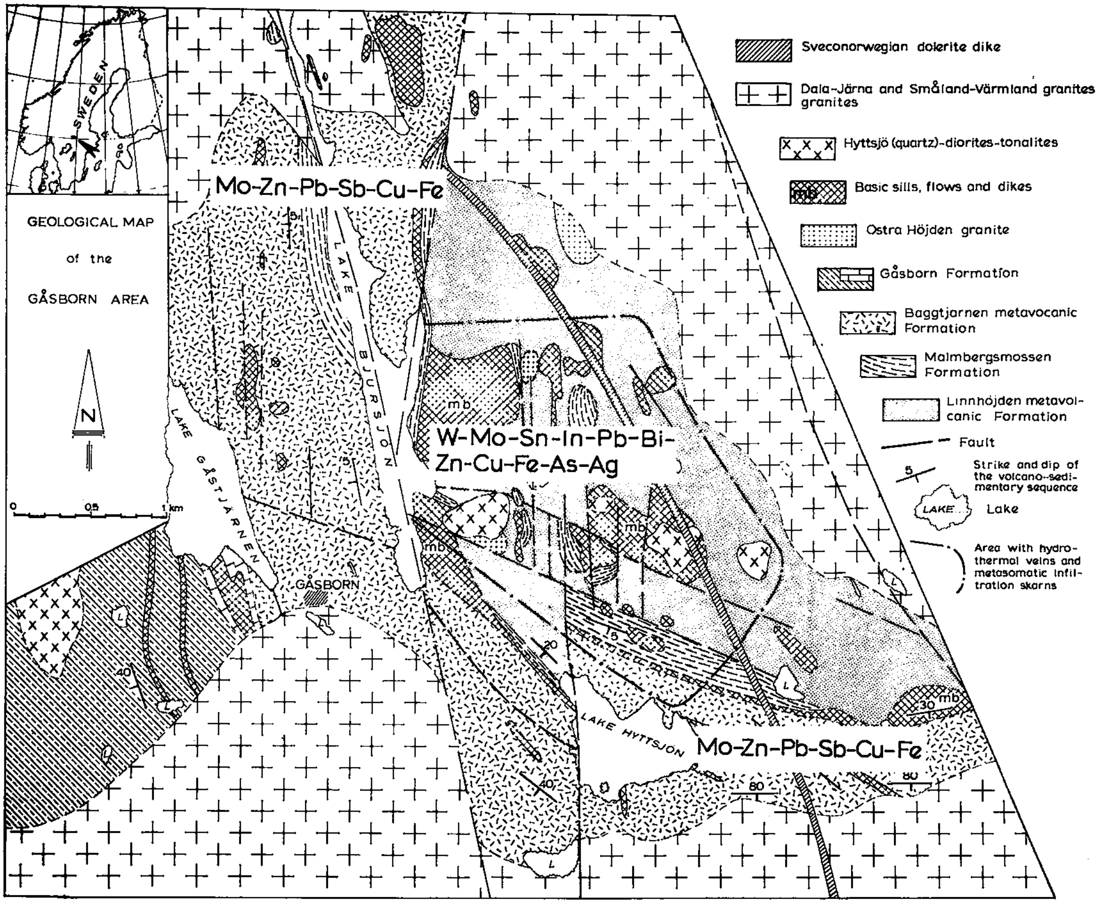


FIG. 9. Distribution of W, Mo, Pb, Bi, Ag, Sn, Sb, Zn, As, In, Cu, and Fe in metasomatic infiltration skarns in the Gåsborn area.

During the last decade, several attempts have been made to classify skarns associated with W–Mo mineralization into the scheelite type (*i.e.*, reduced type) or "molybdoscheelite" type (*i.e.*, oxidized type), based on the chemistry and abundance of the skarn-forming minerals and the predominance of either magnetite or ilmenite in the accompanying intrusive bodies (Einaudi *et al.* 1981, Sato 1982, Kwak 1987; Table 7). For comparison, the most important characteristics of W–Mo skarns described in this paper, as well as those occurring in other parts of West Bergslagen (Baker & Hellingwerf 1988), are presented in Table 8.

The chemistry of the older Bergslagen granites is thoroughly discussed by Baker (1985) and Baker & Drukker (1988), who showed that these are mainly high-level, high-silica, anorogenic granites (A-type; Loiselle & Wones 1979), showing characteristics of both igneous (I-type) and sedimentary (S-type) granites. According to Baker (1985), these granites cannot, owing to pervasive hydrothermal alteration, be classified as of either the ilmenite or magnetite series of granites (Sato 1982; Table 7).

Table 8 shows that clinopyroxene occurring in zones of W–Mo mineralization in West Bergslagen forms a solid-solution series between hedenbergite and diopside, with only minor other components, and that garnet in these deposits consists of andradite and grossularite, with only minor other components. In the Gåsborn area, the clinopyroxene and garnet compositions change rapidly, from hedenbergite-rich and andradite-rich (with up to 60 mole % andradite) in the central part of the area (Fig. 1) to diopside-rich and grossularite-rich in the outer parts (Tables 2, 3, Figs. 3a, b). Table 7 also shows that all the scheelite in West Bergslagen is Mo-poor, and that pyrite only occurs as a product of the late alteration of pyrrhotite. The relatively high andradite content of the most proximal garnet in the Gåsborn area suggests that the fluids from which these skarns were deposited were most probably Fe-rich and mildly oxidizing. A further comparison of data presented in Table 8 with Table 7 suggests that the skarns themselves can best be considered to be reduced skarns in the classifications of Sato (1982), Einaudi *et al.* (1981) and Kwak (1987).

Table 6 shows that of the ore-forming elements in the W–Mo polymetallic skarns in the Gåsborn area, W, Sn, Bi, In, As and Ag occur only in the central part of the Gåsborn area (Fig. 9), Mo, Pb, Cu, Zn, Fe occur in all parts of the area, and Sb occurs as a trace element in galena in the outer parts of the area only. A comparison of Table 6 with Figures 5a and 5b shows that this zonation in ore-forming elements is parallel to the observed decrease in Cl and the observed increase in F contents of calcic amphibole, from the center of the Gåsborn area outward. These observations suggest that W, Sn, In, Bi, As and Ag were most probably transported in the skarn-forming solutions as Cl complexes (Manning 1984, Eugster 1985), whereas Mo, Pb, Cu, Zn, Fe and Sb may just as well have been transported as F complexes.

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