

## Tungsten skarn mineralizations in a regional metamorphic terrain in northern Norway: a possible metamorphic ore deposit

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**Abstract.** Scheelite- and molybdenite-bearing scapolite skarn and plagioclase skarn occur as stratabound mineralizations in a terrain which has suffered regional metamorphism. Scapolite skarn formed as replacement skarns in plagioclase-bearing hornblendic gneiss whereas plagioclase skarn precipitated in fractures as vein skarn mineralizations. The genesis of these skarn deposits are closely connected to an episode of boudinage on the limbs of a large-scale dome-shaped fold. Fluid inclusion studies revealed that the ore-forming fluids were composed of CO<sub>2</sub> with 2 to 17 mole% CH<sub>4</sub>, which formed due to decarbonation reactions during peak metamorphism at the end of the Caledonian orogenesis. Thermodynamic considerations indicate that scapolite and plagioclase formed above 550 °C and 2 Kbar pressure and were followed by precipitation of scheelite between 400 and 570 °C.

A new occurrence of tungsten skarn mineralizations confined to a regional metamorphic terrain has been discovered in the northern part of the Norwegian Caledonides in the Bjellatind area (Fig. 1). The mineralizations have been classified as an example of regional tungsten skarn in accordance with the classifications established by Kwak (1987, ch. 10). This relatively unknown type of tungsten skarn differs in several aspects from classic occurrences, e.g. Can Tung (Canada) and Pine Creek (USA). They occur more than 5 km from the nearest plutonic rocks as stratabound discontinuous bodies and can be followed for several kilometers along the strike. Macroscopic and microscopic zonation are poorly developed and scheelite is frequently associated with the anhydrous mineral assemblage. Tungsten is the major economic element although minor copper, lead, zinc and molybdenum may occur.

### Geological setting

The studied lithology is an integrated part of the Uppermost Allochthon in the Scandinavian Caledonides (Fig. 2). According to Stephens et al. (1985) this unit was emplaced during the terminating event of the Caledonian orogenesis, where intra-oceanic island arcs and black arc associations, together with allochthonous Precambrian basement gneisses advanced toward the east, in Silurian and Devonian times.

### Lithology

An allochthonous Precambrian basement gneiss body is the dominating lithological feature in the Bjellatind area. It was originally named the Bjellatind granite – but Rutland and Sutherland (1967) proved it to be a quartz

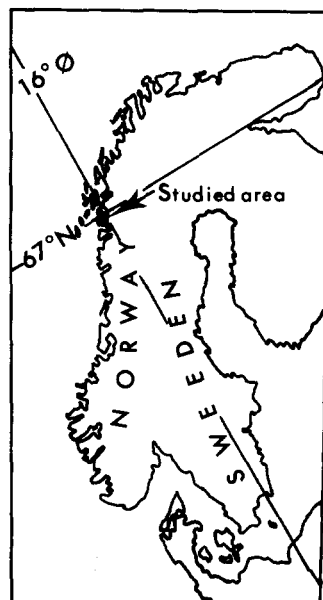


Fig. 1. Localization of the studied area

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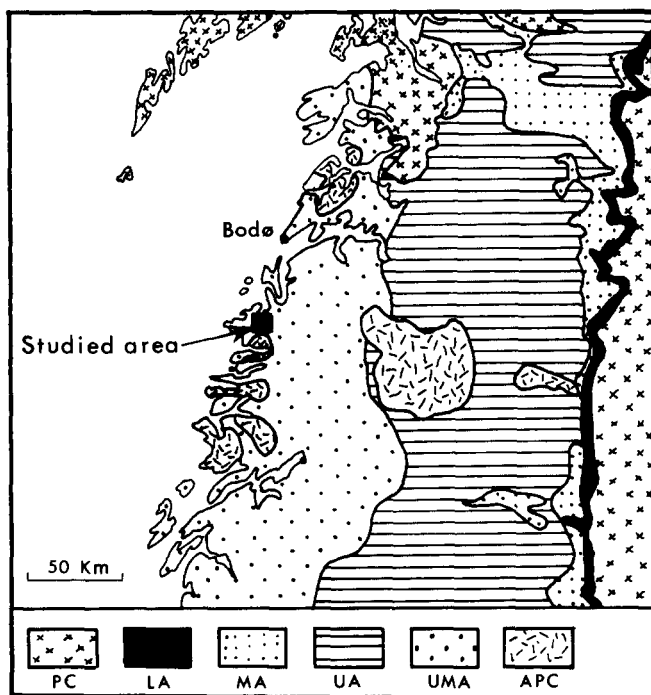


Fig. 2. Relation between major allochthonous units in the central north part of the Scandinavian Caledonides and the Bjellatind area (simplified after Stephens et al. 1985). *PC*, autochthonous Precambrian basement; *LA*, lower allochthon; *MA*, middle allochthon; *UP*, upper allochthon; *UMA*, uppermost allochthon; *APC*, allochthonous Precambrian basement in *UMA*

monozonitic gneiss, exposed in the overlying metasedimentary rocks. Based on radiogenic isotopes studies Wilson and Nichollson (1973) concluded that the gneisses along the coast in northern Norway attained their pre-aledonian shape during the Sveconorwegian orogeny ( $1731 \pm 73$  my.) while the overlying metasedimentary pile is regarded as late Precambrian – Paleozoic in age.

Because the tungsten skarn deposits have only been observed in the metasedimentary sequence above the Bjellatind granite, the following descriptions will deal with that lithology only. According to Ackermann et al. (1960) it has suffered extensive deformation and metamorphism culminating in upper amphibolite facies during peak metamorphism at the end of the Caledonian orogenesis. This metamorphic episode produced porphyroblastic fabrics synkinematic with a gentle deformation episode where large scale dome-shaped folds were formed (Holmes 1965). The total thickness of the metasediments varies between 250 and 450 m and is enclosed between the Bjellatind granite and a huge psammitic unit above it (Fig. 3). The lower part of the rockpile is composed of garnet two-mica schist, psammites, carbonaceous schists, marbles and gneisses, while the upper part is dominated by metapellites composed of biotite, muscovite, kyanite, amphibole, plagioclase and quartz.

One of the most chaotic units is located in the central part of the studied sequence. It is a 50- to 110-m-thick intercalated complex of schists, marbles, gneiss, skarns and psammites, comprising thin units rarely exceeding 6 m in thickness. There seems to be only one common feature characterizing this whole unit, namely that all the

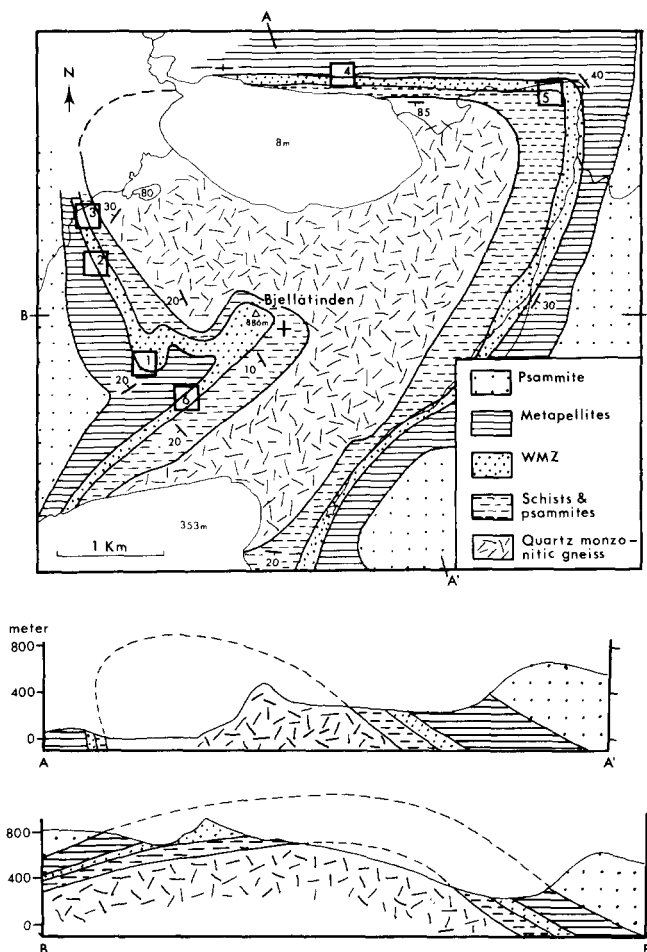


Fig. 3. Geological setting of the Bjellatind area. Numbers in squares refer to tungsten skarn deposits

tungsten skarn mineralizations observed in the Bjellatind area are restricted to this complex, and because this is so it has been named the Wolfram-molybdenum zone, hereafter abbreviated to the WMZ (Figs. 3 and 5).

The lower half of the WMZ is composed of numerous thin units of hornblende schist, carbonaceous schist, marbles and amphibolites. Frequent signs of pyrrhotite are a common feature here.

A calcite-tremolite marble dominates the upper half of the WMZ. It is divided in two by a thin hornblende schist localized in the upper half of the marble horizon (Fig. 5).

The WMZ is enclosed by a structurally competent hornblende gneiss (Fig. 5), comprising well-developed hornblende-biotite folia and meter-long leucosomes composed of plagioclase, quartz and hornblende.

### Structural setting

The dominating structural element in the Bjellatind area is a dome-shaped culmination defined by two fold axes running perpendicular to each other (Fig. 4). This structure is one of the large-scale dome-shaped folds, which has been described by Holmes (1965). The fold-axis trending N-S define an asymmetric gentle antiform where the eastern limb is inclined 35/E and the western limb dip

25/W, while the E-W-trending fold axis defines an asymmetric open antiform inclined to the north with the southern limb dipping 20/S and the northern limb dipping 85/S and thus comprising an inverted stratigraphic package (Fig. 3, profiles). The two structures combined with each other express a dome-shaped culmination.

Stratigraphic logging revealed that the total thickness of metasedimentary units decreased gradually from

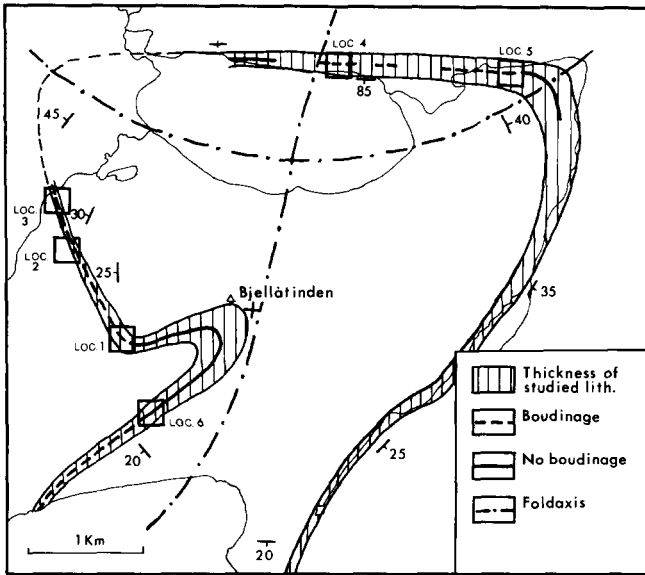


Fig. 4. Structural elements in the two antiforms which together define the dome-shaped culmination. Numbers in squares; same as Fig. 3

450 m in the hinge zones to a minimum of 250 m on the western, northern and eastern limbs (Figs. 4 and 5). The lithologies on the northern and western limbs seems to have suffered most during the formation of the dome. The metasedimentary rocks have however responded very differently to the stress. Marbles, and to some extent carbonaceous schists, are partly or completely decomposed, while more competent rocks such as hornblending gneiss and psammities have suffered chocolate tablet boudinage and fracturing. Figure 5 shows, in a schematic fashion, how marble in the WMZ disappears completely from the hinge to the western limb of the dome, while hornblending schist is boudinaged.

The parts of the limbs where these remarkable structural features are present has been denoted the boudinage zone.

That part of the WMZ which is located inside the boudinage zone is characterized by massive skarn bodies of both barren and ore-bearing skarns, as well as by shrinkage, boudinage and fracturing. The skarn bodies appear in areas where remnants or marble or other carbonaceous rocks have "survived" the deformation event. This is primarily the case in the transition zone from hinge to limb where the stress field not has been insufficient to decompose the marble completely (Fig. 5). Replacement skarns seem to be the dominating calcisilicate in these areas – while vein-skarn mineralizations precipitated in fractures are – is the only skarn that which have been observed inside the limbs where marble is absent.

Replacement skarns include massive, almost pure, garnet skarn, diopside-tremolite skarn, zoizite skarn and

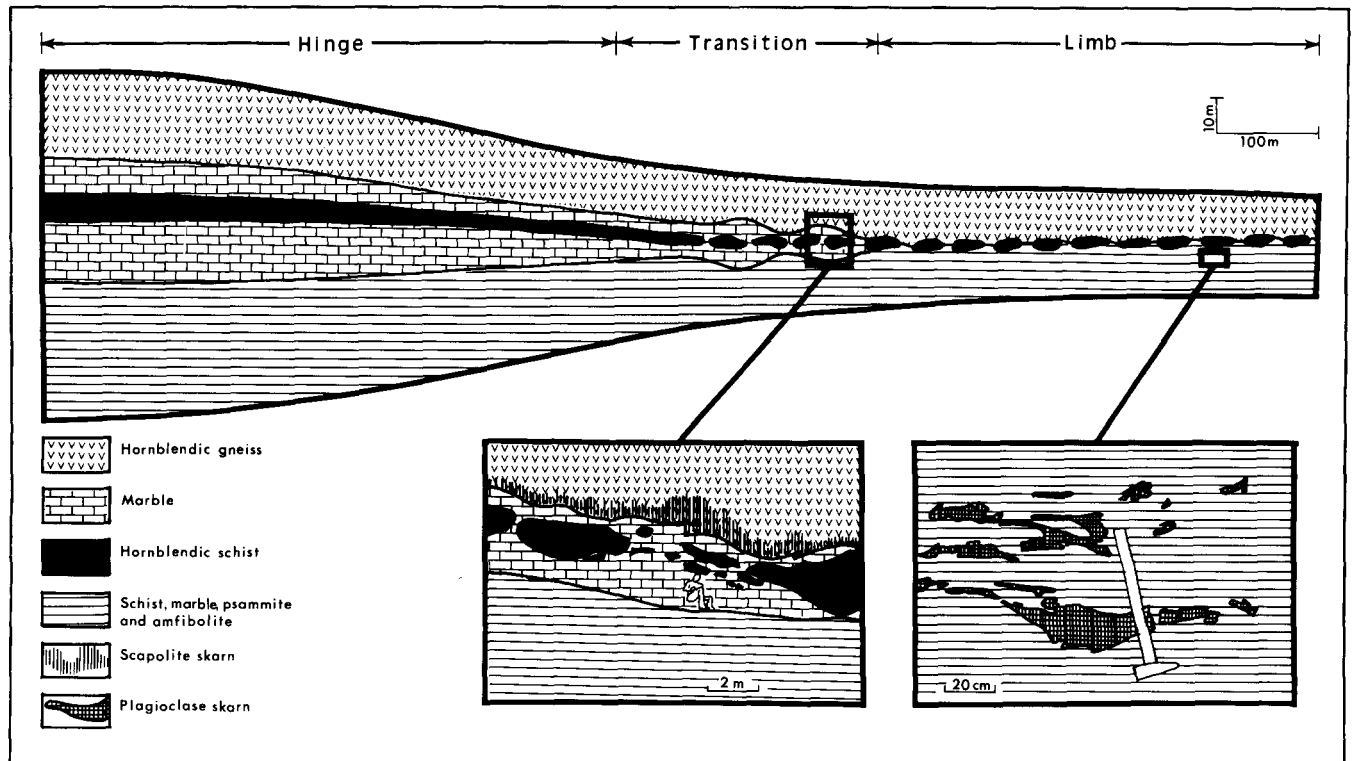


Fig. 5. Schematic cross-section through the WMZ showing relation between structural features and the tungsten skarn deposits. The section shows a profile from hinge to limb of the dome-shaped

culmination. The section has been straightened out partly after Busch (1989)

scapolite skarn. Vein skarns have only been observed as plagioclase skarn, filling fractures with quartz and plagioclase.

### Tungsten skarn mineralizations

Mapping, stream sediment sampling and panwashing revealed in six tungsten mineralized localities (Figs. 3 and 4). All six of them were confined to the part of the WMZ located inside the boudinage zone. They could be followed in scattered outcrops over a distance of 6 km.

#### Scapolite skarn

Scapolite skarn occurs in the transition zone between hinge and limb where remnants of marble are present and are in contact with hornblending gneiss or hornblending schist (Fig. 5). The skarn itself has formed at the expense of hornblending gneiss by replacement of this rock.

The lower 40 cm of hornblending gneiss has almost been completely altered to scapolite skarn, but the total amount of scapolite decreases gradually away from the marble-hornblending gneiss intersection, up to 1 m inside the hornblending gneiss where it finally disappears.

The following mineral assemblage characterizes scapolite skarn (volume share of total rock shown in brackets): scapolite (70%); quartz (15%); biotite (5%); clinozoizite (5%); plagioclase (5%) and accessory apatite, muscovite, sphene, calcite, pyrrhotite, molybdenite and scheelite.

Scapolite occurs as pale-yellow coarse-grained and euhedral crystals, with inclusions of armored plagioclase inherited from the hornblending gneiss. Microprobe measurements by Busch (1990) revealed that scapolite was a calcic end-member with 65 to 73 mole% meionite.

The medium-grained lepidoblastic biotite crystals are, like plagioclase, inherited from hornblending gneiss, but show little or no signs of alteration. This feature is particularly evident in hornblending schist where scapolite replaces plagioclase but encloses biotite in a helitic fashion.

Clinozoizite replaces scapolite in a later W-Mo-free skarnification episode. Replacement has been observed from the stadium where clinozoizite appears as a rim-edging scapolite to a situation where scapolite only exists as heavily altered relicts in aggregates of clinozoizite.

Scheelite and molybdenite are coarse-grained and sub- to euhedral, and follow the abundance of scapolite in that they are most abundant where scapolite replacement has been most extensive. Molybdenite is additionally observed in quartzshlieren intermingled with the skarn rock. Scheelite is pale-green or brown in normal light and emanates blue in short-wave UV-light. Molybdenite forms fine- to coarse-grained flaky aggregates.

Apatite, calcite, muscovite, sphene and pyrrhotite are disseminated as fine- to medium-grained sub- to euhedral crystals.

#### Plagioclase skarn

Plagioclase skarn is a vein skarn formed in subconcordant fractures and in cavities in the WMZ all over the

boudinage zone. It varies from 1 to 40 cm in thickness and rarely extends for more than a few meters along the strike (Fig. 5, right insert). In that part of the boudinage zone where marble has decomposed completely, plagioclase skarn is primarily observed in fractures crosscutting psammites and schists in the immediate vicinity of hornblending gneiss. Plagioclase skarn has also been observed in the transition between hinge and limb in close association with scapolite skarn. The veins in these locations are restricted to the lower 2 m of hornblending gneiss as highly irregular flame-shaped bodies that occasionally intersect the marble below hornblending gneiss. Prospecting by UV-light showed that scheelite was most abundant in the scapolite skarn which was intersected by plagioclase skarn.

The mineral assemblage is quartz (75–95%), plagioclase (5–25%) and accessory scheelite and molybdenite. Plagioclase, quartz and scheelite frequently occur as coarse-grained single crystals with well-developed crystal faces. The concentration of plagioclase decreases where the veins approach the marble below hornblending gneiss.

Plagioclase (An<sub>30</sub> (Busch 1990)) and quartz are coarse-grained sub- to euhedral and frequently occur as single crystals growing from the wallrock into cavities and fractures. Single crystals of quartz extending for more than 40 cm along the wallrock of a cavity have been observed.

Scheelite forms sub- to euhedral, medium- to coarse-grained crystals that frequently share grain boundaries with plagioclase. The crystals are brown or green in normal light and emanate blue fluorescence in shortwave UV-light.

Molybdenite crystals are disseminated all over the veins, but are most abundant in the contact zone between the veins and the host rock where hornblending schist is intersected.

### Geochemistry of ore-bearing skarns

In contrast to tungsten skarns, formed in close proximity to calcalkaline plutonic rocks, the anomalous element-assemblage in the ore-bearing skarns from the Bjellatind area is very simple. The skarns were analyzed using XRF, INAA and AAS for 53 different elements, tungsten and molybdenum were however the only elements that were enriched.

The highest concentrations of tungsten were detected in scapolite skarn, where the average concentration

**Table 1.** Trace element composition of ore-bearing skarns

Element	Scapolite skarn	Average	Plagioclase skarn
Cu (ppm)	11	–	8
Ni (ppm)	19	<5	4
Zn (ppm)	29	<5	12
Pb (ppm)	<5	–	<5
As (ppm)	<1	<1	<1
W (ppm)	17 500	15 100	8000
Mo (ppm)	1 130	262	2000

across 2 m of stratigraphy were 1.5% tungsten and 0.026% molybdenum.

Though rock units from all over the studied area were analyzed for tungsten and molybdenum, none of them was anomalous with respect to these two elements.

Table 1 shows some elements which have been picked out to show the concentrations of ten different elements that are thought to be relevant in connection with tungsten skarns.

### Ore-forming fluids

Microthermometric measurements of fluid inclusions were performed in an attempt to characterize the fluid phase that equilibrated with the ore-forming minerals.

Fluid inclusion studies were accomplished on a Chaix-Meca freezing heating stage designed for operations between  $-180$  and  $600^\circ\text{C}$ . It was adapted on a Leitz Orthoplane microscope.

### Carbon dioxide inclusions

$\text{CO}_2$  is the major fluid component in both scapolite skarn and plagioclase skarn. Fluid inclusion studies revealed that primary inclusions in scapolite, plagioclase, quartz and scheelite were composed of  $\text{CO}_2$  with 2–17 mole%  $\text{CH}_4$ .

Scapolite, plagioclase, quartz and scheelite host numerous primary  $\text{CO}_2$ - $\text{CH}_4$  inclusions randomly distributed in the crystals. Although the abundances vary significantly from one crystal to the next, the inclusions are elongated and are orientated parallel to the crystallographic c-axis in the host mineral and form negative crystal cavities. The size of the inclusions in scapolite and plagioclase varies from 4 to 20 microns, whereas the inclusions in scheelite rarely exceed 5 microns. Some of the  $\text{CO}_2$ - $\text{CH}_4$  inclusions carry small needle-shaped daughter minerals which have not been identified so have not.

The final melting of  $\text{CO}_2$  ice falls in the range between  $-59.7$  and  $-56.9^\circ\text{C}$  and final homogenization took place in the liquid phase between  $2.5$  and  $27.9^\circ\text{C}$ . Figure 6 shows that inclusions in plagioclase and scapolite homogenize at higher temperatures than those in scheelite and quartz.

### $\text{H}_2\text{O}$ - $\text{NaCl}$ inclusions

Fluid inclusions composed of saline water were observed in many of the studied samples. They are normally observed as secondary inclusions forming intergranular trails crosscutting both scapolite, plagioclase, scheelite and quartz. Diopside skarn, however, does carry inclusions of this kind with a primary origin and hosted in diopside.

The primary inclusions in diopside are randomly distributed in the individual crystals. They occur as rather large inclusions measuring 10 to 30 microns, forming

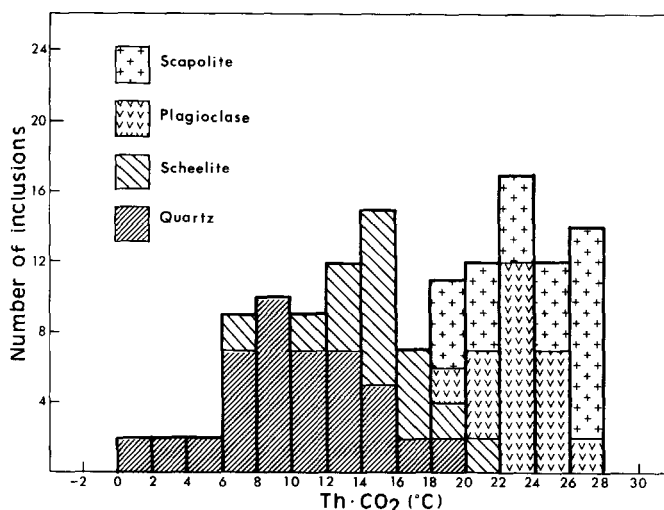


Fig. 6. Homogenization-temperatures for primary  $\text{CO}_2$  inclusions in ore-forming minerals

Table 2. Composition of the fluid phase in ore-bearing skarns

Primary carbon dioxide inclusions				
Host mineral	$T_{m_{\text{CO}_2}}$ ( $^\circ\text{C}$ )	$T_{h_{\text{CO}_2}}$ ( $^\circ\text{C}$ )	$X_{\text{CH}_4}$	Hom. phase
Plagioclase <sup>a</sup>	-58.5	18.3–25.9	0.1	Liquid
Quartz <sup>a</sup>	-58.0–-59.7	2.5–18.2	0.08–0.14	Liquid
Scapolite <sup>b</sup>	-56.9–-58.1	18.2–27.9	0.02–0.06	Liquid
Scheelite <sup>a,b</sup>	-57.7–-58.0	7.7–20.0	0.06–0.08	Liquid

<sup>a</sup> Vein skarn, <sup>b</sup> Scapolite skarn

Table 3. Composition of the fluid phase in a barren skarn

Primary $\text{H}_2\text{O}$ - $\text{NaCl}$ inclusions				
Host mineral	$T_{m_{\text{fin}}}$ · $\text{H}_2\text{O}$ ( $^\circ\text{C}$ )	Eq. NaCl	$T_{h_{\text{tot}}}$ ( $^\circ\text{C}$ )	Hom. phase
Diopside	-20.0–-16.5	19–23 wt%	273.8–351.1	Liquid

irregular crystal cavities and showing a vapor bubble that at room temperature shares 10 to 15% of the inclusion.

The vapor bubble and the liquid phase are the only phases which are visible under the microscope, but formation of a clathrate between vapor and liquid at temperatures between  $-10.0$  and  $+20.0^\circ\text{C}$  indicates that the vapor bubble is composed of  $\text{CO}_2$ .

Melting, as well as nucleation of ice, was quite difficult to observe, possibly because of microcrystalline ice nucleation. Melting of ice was not observed at any time what the exact composition of the salt is at present is unknown. Final melting of ice was in 15 measurements determined to fall between  $-20.0$  and  $16.5^\circ\text{C}$ , corresponding to a salinity equivalent of 19 to 23 wt.% NaCl.

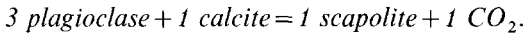
### Minimum P and T of ore skarn formation

The minimum P-T conditions of ore skarn formation can be approached if isochores calculated for fluid inclusions

in scapolite are combined with data for the stability of these two minerals in P-T-X space.

Scapolite in scapolite skarn formed at the expense of plagioclase from hornblende gneiss and calcite from the marbles in equilibrium with a virtually pure CO<sub>2</sub> fluid.

Goldsmith et al. (1970, 1976, 1977), Aitken (1983) and others have investigated stability relations between plagioclase and calcic scapolite under upper amphibolite-granulite facies condition. Equilibrium between plagioclase, calcite and scapolite can be expressed by the equation:



It appears that the CO<sub>2</sub>/H<sub>2</sub>O ratio and the temperature were critical parameters determining dissolution/precipitation of scapolite and plagioclase, while pressure had little or no impact on the stability of these minerals. Aitken determined the minimum stability temperature of scapolite to be 525 °C, assuming more than 13 mole% CO<sub>2</sub> in the fluid phase. Oterdoom and Gunter (1983) used laboratory studies and field data to determine the behavior of scapolite under varying T-X conditions and concluded that plagioclase + calcite reacted from scapolite at T > 550 °C.

Isochores for fluid inclusions in ore forming minerals were calculated on a FORTRAN 77 program developed by Crawford and Nicholls (1985); who used the so-called Modified Redlich-Kwong hard-sphere model (MRK) to calculate the path of isochores in P-T space.

The isochores for fluid inclusions in scapolite, plagioclase, scheelite and quartz are shown in Fig. 7. The isochores are calculated for the minimum and maximum homogenization temperatures for the fluid inclusions studied in the mineral. There will then, be two isochores demarcating the whole range of homogenization-temperatures for fluid inclusions in the particular mineral. If it is assumed that the mineral has formed in equilibrium with the solution present in the primary fluid inclusions,

the isochores will then define an area in P-T space where this mineral could have formed. Scapolite formation, for example, took place somewhere between the two isochores denoted 18.2 (min. Th) and 27.9 (max. Th), but the areas that are bordered by the two isochores can be further reduced because scapolite would be stable above 550 °C only. Furthermore if it is assumed that the ore-forming minerals formed during constant pressure, the intersections of an isotherm through the 18.2 isochore at 550 °C represent the minimum P and T for scapolite formation, approximately 2 Kbar and 550 °C. Formation of the other ore forming minerals shown in Fig. 7 took place above the isobar at 2 Kbar P and in between the isochores that define the range of homogenization temperatures for fluid inclusions in each mineral.

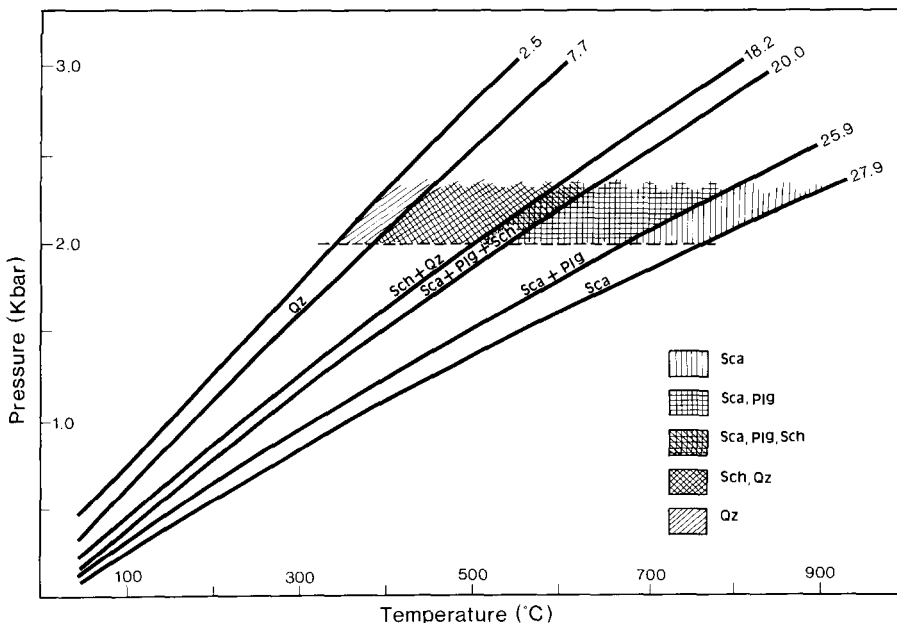
## Discussion

Regional tungsten skarn makes up 5% of the tungsten skarn occurrences known in the world (Kwark 1985) and is thus a minor but significant type of ore deposit. In spite of this, it has achieved little attention in the literature.

The intention of the following discussion is to outline the characteristic features for the tungsten skarns in the Bjellatind area, and to present a model to explain part of their genesis.

### *Relations between tungsten skarns, host rock and structures*

The tungsten skarn mineralizations in the Bjellatind area do not show any genetic relations to igneous plutonic rocks. A metadiorite situated 7 km south of Bjellatinden is the closest plutonic rock to the ore skarns.



**Fig. 7.** Isochoric path for fluid inclusions composed of CO<sub>2</sub>. Numbers refer to minimum and maximum homogenization-temperatures for each mineral. Scapolite (Sca) 27.9–18.2, plagioclase (Plg) 25.9–18.2, scheelite (Sch) 20.0–7.7, quartz (Qz) 18.2–2.5. The signatures refer to minerals that are stable between the different isochores and above minimum P (~2 Kbar)

Both scapolite skarn and plagioclase skarn are situated in the same stratigraphic level in the metasedimentary sequence. The mineralizations appear as vein skarns confined to fractures or infiltration skarns replacing marble and hornblende gneiss. Relations of this kind prove they are epigenetic though they are stratabound to the WMZ.

Formation of the boudinage zone with its complex of structures, fabric elements and redistribution or dissolution of certain rock units, is closely related to development of the dome-shaped culmination.

All the skarn bodies that have been observed in the studied area are located inside the boudinage zone. Diopside skarn has frequently been boudinaged and garnet skarn fractured due to deformation after formation. Plagioclase skarn has locally been boudinaged, while deformational features are absent in scapolite skarn, probably because it has infiltrated a very competent rock unit that lacks any structural features that can be due to the boudinage event. It does, however, carry the characteristic porphyroblastic fabric that syndate formation of the dome-shaped folds and the boudinage zone.

Formation of ore bearing and barren skarn occurred consequently during the same event as the one where the dome-shaped folds and the porphyroblastic fabric developed.

#### *Relations between fluids and ore skarns*

Fluid inclusions composed of carbon dioxide and methane are confined to plagioclase, scapolite, quartz and scheelite as primary inclusions trapped during the growth of these crystals, whereas H<sub>2</sub>O-NaCl fluid inclusions in the same minerals occur along secondary intergranular trails. Diopside hosts H<sub>2</sub>O-NaCl inclusions with a primary origin, but does not contain any CO<sub>2</sub>-CH<sub>4</sub> inclusions.

The most likely interpretation of these observations is to assume that the CO<sub>2</sub>-CH<sub>4</sub> system predates the H<sub>2</sub>O-NaCl system.

Diopside, then, is thought to have grown in contact with a fluid system which postdates the fluids in the ore skarns, and has thus been formed after scapolite skarn and plagioclase skarn.

The paragenetic sequence could not be interpreted from the petrographic studies. It is, however, evident from Fig. 7 that precipitation of the ore-forming minerals during falling temperatures is: (1) scapolite; (2) scapolite + plagioclase; (3) scapolite + plagioclase + scheelite; (4) scheelite + quartz; and (5) quartz.

#### *Fluid pathways*

The fact that the ore-bearing skarns are confined to fissures (plagioclase skarn) or the adjacent rocks (scapolite skarn) indicates how the fracture system has been an important pathway for the ore bearing fluids. The overall movement of the ore bearing fluids has presumably been towards lower pressures and temperatures in the hinge of

the dome shaped culmination. The hinge zone itself is, however, barren, probably because the fracture system fades out in the transition between limb and hinge and thus prevents the flow of ore-bearing fluids. It is possible to observe how the fluids tend to migrate further upwards, since scattered skarn mineralizations appear in the slightly permeable weakness zones between lithologies of different character. But they never reach the hinge zone itself.

#### *Skarnification processes and geochemistry*

Scapolite, plagioclase, quartz and scheelite were precipitated when a methane-bearing carbon dioxide fluid migrated through fractures and reacted with hornblende gneiss and impure marble. The reducing character of the ore forming fluid is indicated by the methane component. The presence of pyrrhotite and absence of any ferric minerals support the assumption that skarnification took place under reducing conditions.

The formation of scapolite, plagioclase and quartz can be regarded as a volume-volume replacement process, in which the infiltrated host rock provides the necessary elements for crystal formation. Small-scale diffusion of ionic species was, therefore, sufficient for growth of scapolite, plagioclase and quartz.

Whereas precipitation of scapolite, plagioclase and quartz is explained by the local rearrangement of ionic species, formation of scheelite is unlikely to have occurred by small-scale diffusion. Tungsten ore grades exceed concentrations in the surrounding rock by a factor of 10<sup>4</sup>. The CO<sub>2</sub>-CH<sub>4</sub> fluids must consequently have scavenged a distant tungsten source and transported it to the site of nucleation. This theory does, however, present two obstacles: the source is unknown, and several laboratory experiments reveal that the solubility of tungsten in a CO<sub>2</sub> fluid is very low or even close to zero. Most of the experiments evaluate the behavior of tungsten in magmatic systems, where equilibrium between two or more of the components – CO<sub>2</sub>, H<sub>2</sub>O, NaCl and silicate melt – is under consideration (Barabanov 1971; Foster 1976; Stempok et al. 1982; Manning 1984). The experiments indicate how tungsten tends to dissolve as polytungstates or heteropolytungstates in a saline solution, but dissolves in the melt if the fluid is composed of CO<sub>2</sub> or nonsaline water. Manning (1984) concluded that transportation of tungsten as carbonic complexes is of little or no importance in a H<sub>2</sub>O-CO<sub>2</sub>-NaCl-melt system.

This conclusion is in general disagreement with the results from fluid inclusion studies done on scheelite, scapolite, plagioclase and quartz from the Bjellatind area. These showed that the fluid which equilibrated with the ore-bearing minerals were composed of carbon dioxide and methane.

#### *Classification*

The tungsten skarn occurrences in the Bjellatind area can, according to Kwak (1985) be classified as an exam-

ple of regional tungsten skarn. The classification is based on the following significant features.

The mineralizations are confined to a regional metamorphic terrain which has suffered upper amphibolite facies metamorphism.

They occur more than 7 km from any intrusive plutonic rocks.

They are confined to one stratigraphic level as discontinuous deposits that can be followed for more than 6 km along the strike.

Microscopic as well as macroscopic zonation in ore-forming minerals as well as skarn ore bodies is not observed.

Scheelite is the only tungsten mineral.

Ore minerals are associated with the anhydrous mineral assemblage, namely scapolite and plagioclase.

Geochemistry of the ore-forming fluid and the mineral assemblage indicates reducing conditions during ore skarn formation.

The variety of anomalously enriched elements is restricted to tungsten and molybdenum only.

#### *Origin of ore-bearing fluids*

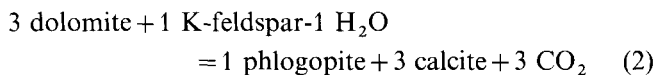
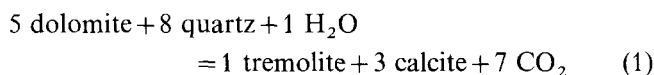
It is unreasonable to assume any genetic relationship between regional tungsten skarns and granitic intrusions (Kwak 1985). In particular the large distance to any intrusive plutonic rocks and the stratabound character of the mineralizations seems inconsistent with a magmatic origin. Ore-forming fluids composed of  $\text{CO}_2$  + minor  $\text{CH}_4$  additionally points away from a magmatic origin, since the fluids exsolved from a calcalkaline magma normally would contain considerable amounts of water.

A volcanic-exhalative origin is favoured for the tungsten mineralizations in Felbertal (Austria) (Maucher 1972, 1976; Höll 1971, 1977); a theory which recently has been supported by the discovery of a scheelite mineralized hydrothermal eruption breccia, which, in a strati-form fashion, can be followed along the strike for 100 m (Höll and Schenk 1988). Skaarup (1974) also ascribed the stratabound tungsten skarn from Bindal (Norway) to secondary volcanic processes. In particular, the presence of sulfides (arsenopyrite, pyrrhotite, chalcopyrite, etc.) together with scheelite, indicates that the deposits may be attributed to volcanic emanations, and later on were remobilized during regional metamorphism.

Though the tungsten skarns in the Bjellatind area have much in common with the tungsten skarns in Bindal, they do not show any features consistent with former volcanic-exhalative processes. There are no major metavolcanic units in the region and the only important sulfide is pyrrhotite, which is a relatively common sulfide in regional metamorphic terrains.

The close spatial relationship between ore bearing skarns and formations of the large-scale dome-shaped fold, and the relatively high pressure apparent during ore-skarn formation, indicates that metamorphic processes played an important role in the ore-forming process. Metamorphism and decomposition of the impure marble horizons in the WMZ must have released a huge

amount of  $\text{CO}_2$  that could evolve as an ore forming fluid. If tremolite, calcite and biotite were produced by the following two reactions proposed by Winkler (1979):



The overall dominating constituent in the fluid phase is  $\text{CO}_2$ .

None of the analyzed rockunits from the WMZ or elsewhere in the studied area were anomalous with respect to tungsten and molybdenum, so although it is possible to create an ore-forming fluid it is difficult to find a source rock. A distant unexposed source can neither be ruled out nor proved.

#### **Conclusions**

Ore forming  $\text{CO}_2$ - $\text{CH}_4$  fluids were possibly released during metamorphism and decomposition of impure marbles simultaneously with large-scale folding at the end of the Caledonian orogenesis.

The ore-forming fluids migrated through a fracture system in the boudinage zone (Fig. 5) towards lower pressures and temperatures in the hinge of the dome-shaped culmination (Fig. 4).

Tungsten was transported in  $\text{CO}_2$ - $\text{CH}_4$  fluids to sites where hornblende gneiss and relicts of impure marble acted as chemical barriers causing scapolite to grow while plagioclase started to precipitate in fissures and cavities where marble was absent.

Scapolite and plagioclase continued to form while the temperature was above  $\sim 550^\circ\text{C}$ , and thus prepared the ground for scheelite (and molybdenite) which started to nucleate on the scapolite/plagioclase faces while scapolite and plagioclase ceased to grow.

The ore-forming process took place under reducing conditions between 350 and  $800^\circ\text{C}$  and above 2 Kbar pressure.

It is finally concluded that the skarn deposits in the Bjellatind area seem to lack any relation to intrusive igneous rocks, but rather must be ascribed to metamorphic processes and so can be regarded as a metamorphic ore deposit.

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#### **References**

- Ackermann, J., Walton, B.J.: (1960) Mineral development and deformation in metasedimentary rocks in the Glomfjord region, Northern Norway. *Int. Geol. Congr.* 21: 33–42

- Aitken, G.B. (1983) T-X<sub>CO<sub>2</sub></sub> stability relations and phase equilibria of calcic carbonate scapolite. *Geoch. et Cosmoch. Acta.* 47: 351–362
- Barabanov, V.F. (1971) Geochemistry of tungsten. *Int. Geol. Rev.* 13: 332–344
- Busch, K. (1989) Tungsten deposits related to solution-remobilization during regional metamorphism in the Bjellåtind area, Nordland, Norway (Danish). M. Sc. Thesis University of Copenhagen
- Crawford, M.L., Nichols, J. (1985) FORTRAN programs for calculations of fluid properties from microthermometric data on fluid inclusions. *Comp. and Geosci.* 11: 619–645
- Einaudi, T.M., Meinert, L.D., Newberry R.J. (1981) Skarn deposits. *Econ. Geol.* 75th Anniv. Vol. 317–391
- Einaudi, T.M., Burt, D.M. (1982) Introduction-terminology, classification and composition of skarn deposits. *Econ. Geol.* 77: 745–754
- Foster, R.P., Mann, A.G., Armin, A., Burmeister, B.B. (1977) Solubility of scheelite in hydrothermal chloride solution. *Chem. Geol.* 20: 27–45
- Goldschmidt, J.R. (1976) Scapolites, granulites and volatiles in the lower crust. *Geol. Soc. Amer. Bull.* 87: 161–168
- Goldschmidt, J.R., Newton, R.C. (1977) Scapolite-plagioclase stability at high pressures and temperatures in the system NaAlSi<sub>3</sub>O<sub>8</sub>-CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>-CaCO<sub>3</sub>-CaSO<sub>4</sub>. *Amer. Min.* 62: 1063–1081
- Holmes, M. (1965) Structures of the area north of Ørnes, Nordland, Norway. *Geol. Surv. Norw.* 242: 63–87
- Höll, R. (1971) Scheelitvorkommen in Österreich. *Erzmetall* 24: 273–282
- Høll, R. (1977) Early Paleozoic ore deposits of the Sb-U-Hg formation in the eastern Alps and their genetic interpretation, in: *Time and Stratabound Ore Deposits*. Klemm, D.D. and Schneider, H.J. (eds.) pp. 169–199. Springer: Berlin, Heidelberg, New York
- Høll, R., Schenk, P. (1988) Metamorphosed hydrothermal eruption breccia (conglomerate) in the Felbertall Scheelite deposit, eastern Alps, Austria. *Mar. Geol.* 84: 273–282
- Kwak, T.A.P. (1987) Sn-W skarn deposits. Elsevier, Amsterdam, pp. 415
- Larsen, R.B. (1988) Tungsten-deposits in the Bjellåtind area Nordland, Norway (Danish). M. Sc. thesis University of Copenhagen, pp. 110
- Larsen, R.B. (1989) Evolution of the fluid phase in regional tungsten skarn from the Norwegian Caledonides: a fluid inclusion study. *Geological Society of America Abstracts with programs* 21: A286
- Maucher, A. (1972) Time and stratabound ore deposits and the evolution of the Earth. 24th Geol. Congr. Can., pp. 83–88
- Maucher, A. (1976) The stratabound cinnabar-stibnite-scheelite deposits. In: Wolf, K.H. (ed.) *Handbook of Stratabound and Stratiform Ore Deposits*, pp. 477–501
- Manning, D.A.C., Henderson, P. (1984) The behavior of tungsten in granitic-melt-vapour systems. *Contr. Min. Petr.* 86: 286–293
- Oterdoom, W.H., Gunter, W.D. (1983) Activity models for plagioclase and CO<sub>2</sub>-scapolites: an analysis of field and laboratory data. *Am. J. Sci.* 283-A: 255–283
- Rutland, R.W.R., Nichollson, R. (1965) Tectonics in the Caledonides in part of Nordland, Norway. *Jour. Geol. Soc. Lond.* 121: 73–109
- Rutland, R.W.R., Sutherland, D.S. (1967) The chemical composition of granitic gneisses and sparagmitic metasediments in the Glomfjord region, Northern Norway. *Geol. Surv. Norw.* 47: 359–374
- Skaarup, P. (1974) Stratabound scheelite mineralizations in skarn and gneisses from the Bindal area, Northern Norway. *Min. Dep.* 9: 299–308
- Stemprok, M., Voldan, J. (1982) Solubility of tungstic oxide in granitic melts. *Vestnik* 6: 321–384
- Stephens, M.B., Gustavson, M., Ramberg, I.B., Zachrisson, E. (1985) The Caledonides of central north Scandinavia – a tectonostratigraphic overview, in: *The Caledonide Orogen – Scandinavia and related areas*. Gee, D.G., Stuart, B.A. (eds.) pp. 135–162. John Wiley, New York
- Wilson, M.R., Nichollson, R. (1973) The structural setting and geochronology of the basal granitic gneisses in the Caledonide part of Nordland Norway. *Jour. Geol. Soc. Lond.* 129: 365–387
- Winkler, G.F.H. (1979) *Petrogenesis of metamorphic rocks*, 5th. ed. p. 269. Berlin-Heidelberg-New York: Springer