Geology and K/Ar chronology of the Målvika scheelite skarns, Central Norwegian Caledonides

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Skarns present on the northern shore of Tosenfjord overprint the S2 fabric of the adjacent gneiss (which formed during peak regional metamorphism). Together with petrographic evidence of the late crystallization of scheelite, this indicates that mineralization was post-metamorphic and epigenetic. K/Ar apparent ages of nine mineral separates (four post-scheelite amphiboles from skarn, two muscovites and three biotites from intrusions) are concordant at the 1σ level, giving an Inverse Variance Weighted Mean (IVWM) age of 402 ± 2 Ma. The close agreement of results from different minerals points to rapid post-orogenic uplift in the Central Scandinavian Caledonides. Two other post-scheelite amphibole skarn samples gave indistinguishable (at 1σ) apparent ages whose mean is 472 Ma. If valid, this age would substantially constrain the timing of regional metamorphism and mineralization. However, the possibility that the ages are spurious, due to the presence of excess argon, cannot be excluded.

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Introduction

Scheelite was first discovered within the Helgeland Nappe Complex (HNC) in 1969. It was located in skarns and quartz veins, associated with marble (Nissen 1969), near Mosjøen (Fig. 1). Subsequently, scheelite was detected in the gold-arsenopyrite deposits of the Kolsvik area (Skaarup 1974). A reconnaissance exploration programme for scheelite, in 1970, led to the discovery of several additional occurrences on either side of Tosenfjord. Brief descriptions of the geology and petrography of these prospects were provided by Skaarup (1974), who considered them to have a syngenetic origin. Syngenetic tungsten deposits are believed to form by the accumulation on the sea-floor of tungsten-rich precipitates, which crystallize as a result of the mixing of tungsten-bearing solutions (emitted from sea-floor smokers after percolating through rock with a high basic igneous component) with colder sea water (Maucher 1965).

Four principal hypotheses may be postulated for the tungsten (scheelite) mineralization at Målvika:

a) Scheelite was syngenetic with the accumulation of the host lithologies.
b) Scheelite precipitated from tungsten-bearing hydrothermal fluids which were mobilised by regional metamorphism.
c) Scheelite precipitated from tungsten-bearing hydrothermal fluids of a magmatic origin, or tungsten was leached from the country-rocks by fluids circulating around a granitic pluton.
d) Scheelite precipitated after the cessation of magmatic activity, from tungsten-bearing hydrothermal fluids.

The aim of the present study was to establish constraints on the relative and absolute timing of mineralization, and hence test the validity of the above hypotheses. The K/Ar radiometric ages presented here may also have incidental value in clarifying the tectonometamorphic evolution of the Helgeland Nappe Complex.

Regional Geology

The Helgeland Nappe Complex is the structurally highest unit of the Uppermost Allochthon (Gee et al. 1985). The HNC is considered to consist of at least two tectono-stratigraphic units (Nordgulen & Schouenborg 1990, Thorsnes & Løseth 1991):

1. Mafic and ultramafic lithologies occur in the western part of the HNC (Nordgulen & Schouenborg 1990). These rocks have been interpreted as the remnants of a dismembered ophiolite (Husmo & Nordgulen 1988, Thorsnes & Løseth 1991).

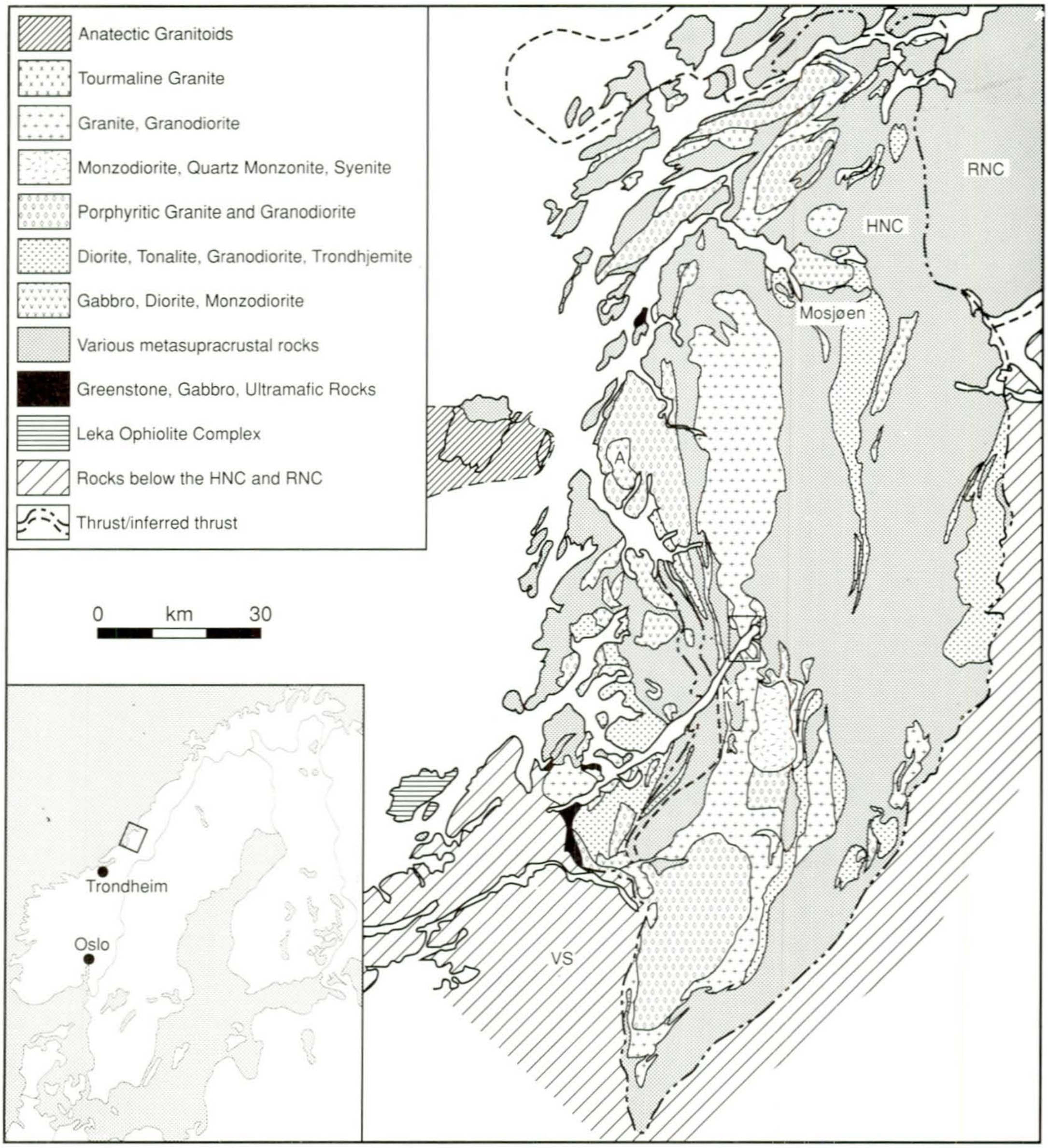

Fig. 1. Geological map of the Helgeland Nappe Complex. HNC = Helgeland Nappe Complex; RNC = Rödingsfjället Nappe Complex; VS = Vestranden; K = Kolsvik; A = Andalshatten Pluton; rectangle encloses area of Fig. 2. Modified from Nordgulen & Sundvoll 1992.

2. A supracrustal sequence of continental derivation has also been identified. It is composed of strongly deformed, high-grade pelitic to semi-pelitic gneisses (partly migmatitic) and calcareous metasedimentary rocks.

A calc-alkaline intrusive complex, the Bindal Batholith, constitutes a substantial proportion of the HNC (Nordgulen & Schouenborg 1990). Medium- to coarse-grained and megacrystic granites and granodiorites typify the batholith (Nordgulen & Mitchell 1988, Nordgulen et al. 1993). Radiometric age determinations indicate that intrusive activity was syn-orogenic, spanning the period from the Middle/Late Ordovician to the Late Silurian (Nordgulen et al. 1993).

Kollung (1967) and Myrland (1972) indicated that peak metamorphism reached almandineamphibolite facies throughout much of the HNC. The formation of the dominant (S2) foliation coincided with the peak of metamorphism (Thorsnes & Løseth 1991). Later deformational events (D3 and D4) produced open, large-scale folds (Myrland 1972, Tørudbakken & Mickelson 1986, Gustavson 1988). These events are responsible for the present attitude (c.60° dip to ENE) of the rocks in the vicinity of the study area (Thorsnes & Løseth 1991).

As S2 structures are present in inclusions cut by the megacrystic Andalshatten pluton (dated at 447±7 Ma; Nordgulen et al. 1993), the foliation must have formed prior to or during the Late Ordovician. There is therefore evidence from the HNC, as from the granitoid terrane of Smøla-Hitra (Roberts 1980, Gautneb & Roberts 1989) and elsewhere in the Upper Allochthon (Kullerud et al. 1988) and Uppermost Allochthon (Claesson 1979), that a major tectono-magmatic event occurred during the Ordovician (Nordgulen & Schouenborg 1990). Nevertheless, the final eastward thrusting of the HNC probably took place during the Scandian continent-to-continent collision.

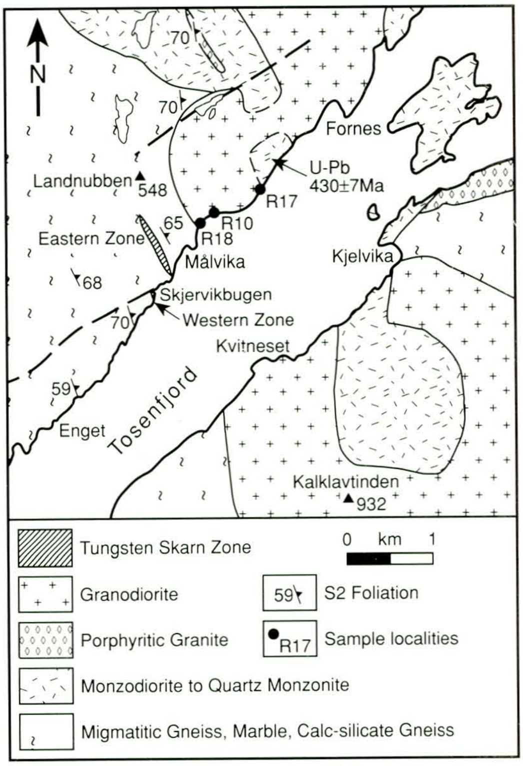

Fig. 2. Geological map of the area surrounding the scheelite skarns of Målvika.

Geology and Petrography of the Målvika skarns

Tungsten-bearing skarns occur in two zones in the vicinity of Målvika, which is situated on the northern side of Tosenfjord (Figs. 1 & 2). The southern tip of the 100 metre-wide main zone (Skaarup 1974) lies 100 m southwest of Målvika and extends NNW for 700 m inland, to a height of 400 metres. The second (western) zone is exposed in a road-cut 200 m to the southwest, near Skjervikbugen. This 10 m wide zone extends for 70 m northwards, where it terminates against a prominent, ENE-WSW trending fault.

The skarns occur as heterogeneous horizons not exceeding 1.5 metres in width. They are enclosed by leucocratic biotite gneiss or melanocratic, weakly foliated, amphibole-biotite gneiss. The two zones differ in the abundance of marble. The marble in the eastern zone occurs as widely scattered inclusions, whereas it is present as continuous horizons enclosed by <30 cm wide skarn horizons in the western zone. Anastomosing vein networks and assemblages formed by the replacement of the first-formed skarn assemblages occur extensively in the skarns of the eastern zone, whereas in the western zone veins and replacement assemblages are volumetrically minor.

Fig. 3 illustrates the relationship between skarn, marble and gneiss, in the western zone. Each skarn horizon consists predominantly of two primary (i.e. first-formed) lithologies, one consisting largely of pyroxene and plagioclase whereas the other is composed mainly of garnet and pyroxene. The former occurs as a continuous horizon up to 15 cm in width, adjacent to gneiss. The garnet skarn, in contrast, generally occurs as disparate lenses (up to 5cm wide) along the marble-skarn contact (Fig. 3). Fig. 4 shows that garnet skarn probably formed by replacement of marble. The garnet skarn was, in turn, partially replaced by an epidote + quartz (+ residual pyroxene) assemblage. This accounts for the erratic distribution of garnet skarn lenses, as in Fig. 3. A <5mm wide selvage of wollastonite (+ pyroxene) skarn is typically developed at the contact between the garnet skarn and marble. A zone of amphibole + plagioclase skarn

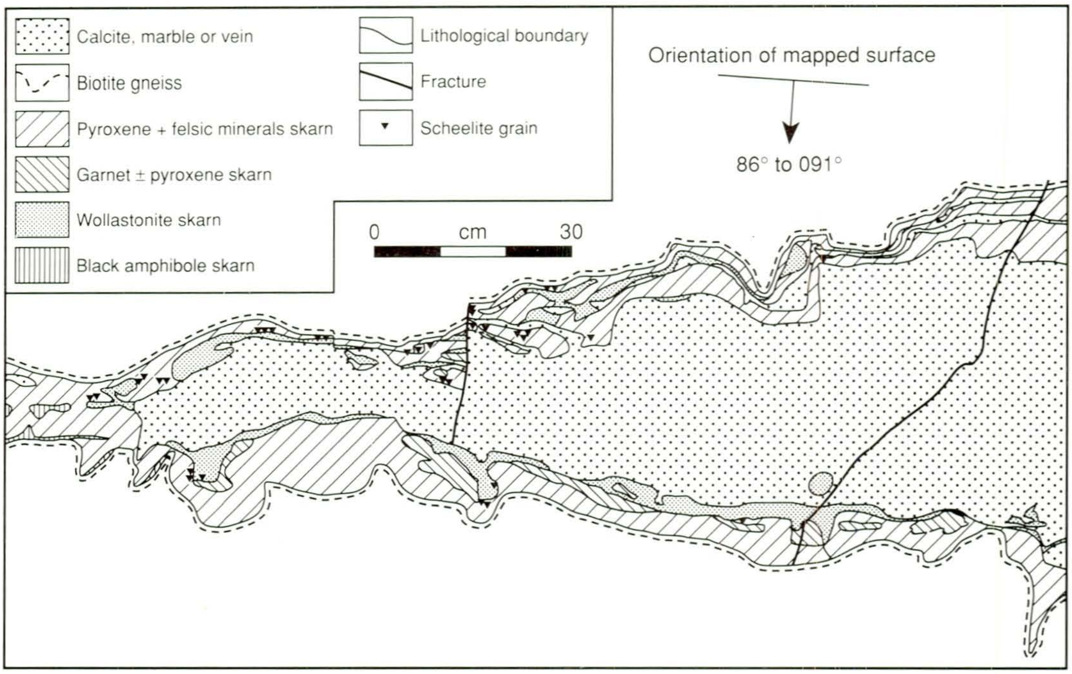

Fig. 3. Detailed sketch map of a typical skarn horizon of the Skjervikbugen (western) zone.

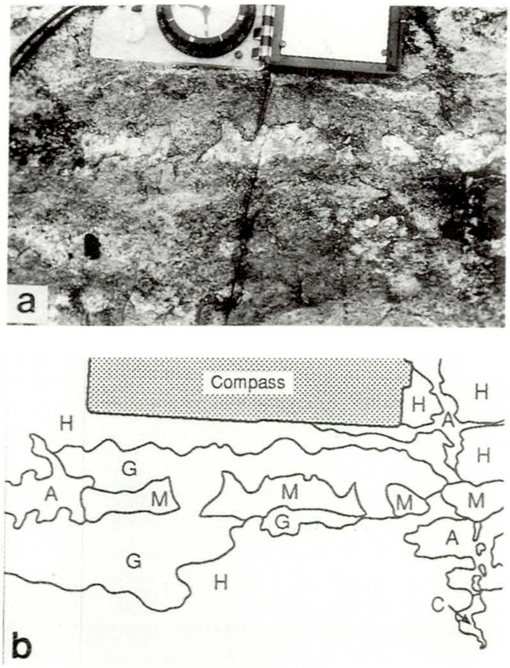

Fig. 4. Garnet skarn (G) replacing marble (M). A = Amphibole wall-rock skarn enclosing calcite vein (C). H = Hydrous replacement assemblage (after garnet skarn) consisting mainly of epidote and quartz (with minor scheelite). Boulder, roadside, western zone.

(<5mm wide) is found at the contact of the pyroxene + plaagioclase skarn with the gneiss. Idocrase (+ pyroxene) is rarely developed in place of the garnet skarn.

A hydrous assemblage consisting mainly of epidote + quartz + amphibole is extensively developed at the expense of the garnet skarn. Scheelite is locally a significant component, accounting for up to 20% of the assemblage. To a lesser extent hydrous mineral skarn (without scheelite) replaced the pyroxene + plagioclase skarn. In places it is spatially associated with cross-cutting fractures or veins. However, the replacement skarn generally occurs more extensively, with preferential development along the contacts between the primary skarn assemblages. Another type of hydrous mineral replacement is developed exclusively at the peripheries of quartz-calcite veins. It consists primarily of blades of ferro-pargasitic amphibole and cubes of almandine-spessartine-rich garnet (James 1991). Variable proportions of pyrrhotite, calcite, quartz and epidote occupy the interstices between amphibole and garnet crystals. Coeval scheelite is absent from this wall-rock assemblage. Biotite is a minor constituent of the quartz-calcite veins and scheelite is rarely present. The veins are pla-

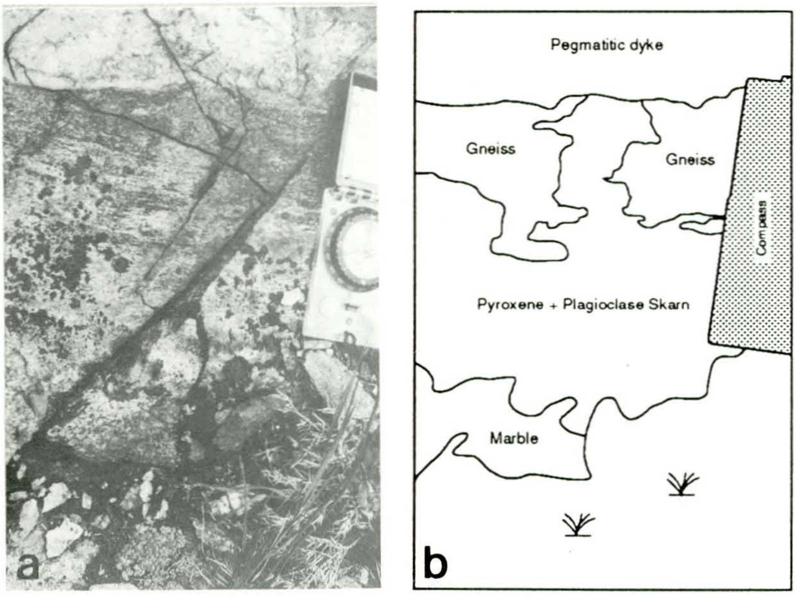

Fig. 5. Pyroxene skarn projecting irregularly across the foliation of the adjacent amphibole-biotite gneiss. Western zone.

nar, exhibit preferential orientation and are restricted to the skarn.

Skaarup (1974) implied that the scheelite-bearing skarns were formed by isochemical transformation of tungsten-rich marl protoliths, during regional metamorphism. However, Fig. 5 shows pyroxene + plagioclase skarn cross-cutting the foliation of the adjacent gneiss at a high angle. This indicates that this type of skarn post-dated the S2 fabric in the gneiss; hence the skarn formed after the peak of regional metamorphism.

The character of the ore at Målvika is also inconsistent with Skaarup's (1974) conclusions. Investigation of tungsten skarns worldwide have shown that scheelite comprises at least 95% of all skarn tungsten minerals (Kwak 1987). This is due to the very high negative free energy of formation of scheelite:

$CaO + WO_3 = CaWO_4$ $\triangle G^{2000}_{800} = -52,320$ Cal/Mole (Hsu & Galli 1973)

Only if the Ca activity is low, or under supergene conditions, do other tungsten minerals (mainly wolframite) form. Hence, it is reasonable to assume that any tungsten present in skarn and Ca-rich precursors to skarn would occur in scheelite. The earliest generation of scheelite in the Målvika skarns crystallized late in the primary paragenesis (minor scheelite occurs as a late-stage infill of the interstices between the well-formed primary garnet crystals; see Fig. 6 for the complete paragenesis). This points to the introduction of tungsten

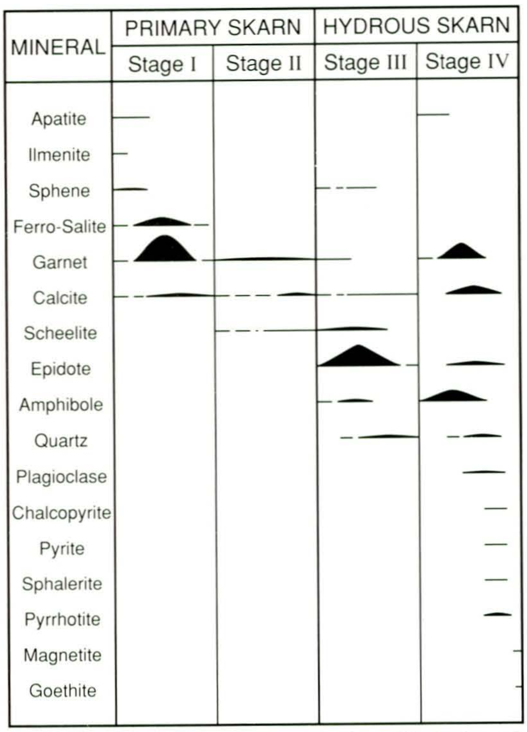

Fig. 6. Mineral paragenesis of garnet skarn. The horizontal axis represents the relative timing of crystallisation, with time increasing from left to right. The size of each shaded area is indicative of the approximate volumetric abundance of the phase. Apatite of Stage IV is fluor-apatite. Garnet of Stage ! is grossular, Garnet of Stages II and III is Gross-Alm-Spess. Garnet of Stage IV is Alm-Spess. Scheelite is Mo-free. Epidote composition spans the epidote-clinozoisite divide and Stage IV amphibole is ferro-pargasitic (analyses reported in James 1991).

by epigenetic hydrothermal fluids. Furthermore, the most intensive phase of scheelite mineralization occurred later in the evolution of the skarn, during the replacement of the primary garnet skarn by the hydrous mineral skarn. The concentration of scheelite present in the primary skarn is far too small for the scheelite in the replacement skarn to have been derived solely by re-distribution of primary skarn scheelite. Considering this together with the evidence of a post-regional metamorphic origin for the primary pyroxene + plagioclase skarn, it is concluded that it is highly improbable that tungsten mineralization in the Målvika area was syngenetic with the deposition of the host-lithologies.

In order to constrain the timing of mineralization, and thereby test the afore-mentioned hypotheses, a K/Ar geochronological investigation was undertaken.

K/Ar isotopic age determinations

The amphiboles (Table 1) were chipped directly from fresh roadside exposures of the vein wall-rock skarn. Biotite chip samples R11 and R12 were obtained from pegmatitic two-mica granitic dykes located in the western zone. The dykes post-date the adjacent primary skarn, since xenoliths of skarn were present within the dykes and an amphibole reaction skarn was developed at the dyke-skarn contact. Three whole-rock samples were obtained from fresh roadside exposures of the two-mica granodiorite pluton located 500 m northeast from the eastern zone.

Chip samples were purified by crushing the sample in a pestle and mortar and then progressively removing the relatively magnetic amphibole or biotite with an electromagnetic separator. Purities in excess of 99 percent were attained.

Whole-rock samples of the two-mica granodiorite were crushed and sieved to obtain an optimal size fraction of 90 to 150 μm. Purities greater than 99% were attained for biotite. Weakly paramagnetic muscovite proved difficult to separate from compound grains which consisted of non-magnetic quartz or feldspar in combination with magnetic biotite or ilmenite. This resulted in a purity of 95% for muscovite separates.

Potassium analyses were carried out using a Corning 450 flame photometer with a lithium internal standard. Argon isotopic analyses

Table 1. K/Ar determinations of biotite, muscovite and amphibole separates from the Målvika area (see map-sheet 1825-I Tosbotn for sample localities).

Sample number	UTM co-ordinates	K_2O* (wt.%)	Radiogenic** ^{40}Ar (mm^3g^{-1})	Atmospheric*** contamination (%)	Age (Ma ± 1σ)
Two-mica granodiorite. Muscovite					
R10	40125-724430	9.90 ± 0.14	(1.445 ± 0.013) x 10^{-1}	3.3	404 ± 7
R18	40105-724420	9.51 ± 0.03	(1.358 ± 0.012) x 10^{-1}	2.8	396 ± 4
R17	40175-724455	8.32 ± 0.09	(1.194 ± 0.011) x 10^{-1}	2.8	398 ± 6
Two-mica granodiorite. Biotite					
R17	40175-724455	9.24 ± 0.20	(1.327 ± 0.012) x 10^{-1}	1.4	398 ± 9
Two-mica granitic dykes. Biotite					
R11	40050-724330	9.80 ± 0.15	(1.400 ± 0.016) x 10^{-1}	3.3	396 ± 8
R12	40050-724330	9.82 ± 0.10	(1.420 ± 0.016) x 10^{-1}	4.0	400 ± 6
Wall-rock skarn. Amphibole					
R2	40070-724355	1.206 ± 0.010	(1.720 ± 0.020) x 10^{-2}	5.8	395 ± 6
R14	40050-724330	1.046 ± 0.018	(1.514 ± 0.019) x 10^{-2}	14.2	401 ± 9
R9	40070-724355	1.207 ± 0.007	(1.755 ± 0.020) x 10^{-2}	7.5	402 ± 5
R6	40070-724355	1.490 ± 0.014	(2.202 ± 0.024) x 10^{-2}	4.2	408 ± 6
R4	40070-724355	1.084 ± 0.015	(1.610 ± 0.020) x 10^{-2}	7.3	410 ± 8
R7	40070-724355	1.403 ± 0.017	(2.115 ± 0.028) x 10^{-2}	6.3	415 ± 7
R8	40070-724355	1.150 ± 0.020	(1.990 ± 0.020) x 10^{-2}	4.5	470 ± 9
R3	40070-724355	1.310 ± 0.010	(2.290 ± 0.020) x 10^{-2}	7.2	474 ± 5

*Mean of three analyses, **Mean of two analyses,
***Higher of two recorded atmospheric contamination values.
$^{40}K/K$ = 1.167 x 10^{-2} atom per cent, λ_e = 0.581 x $10^{-10}a^{-1}$, λ_β = 4.962 x $10^{-10}a^{-1}$.
Constants after Steiger & Jäger (1977).

were performed by the isotope dilution method on a modified Kratos MS10 mass spectrometer (Wilkinson et al. 1986).

Nine of the fourteen apparent ages (Table 1) are concordant at the 1σ level. This group comprises the two muscovites (R10 and R17), the three biotites (R11, R12 and R17) and four of the amphiboles (R4, R6, R9 and R14). The Inverse Variance Weighted Mean (IVWM) of the nine ages is 402 ± 2 Ma. At the 2σ confidence level, twelve of the fourteen ages are concordant with an IVWM of 399 ± 2 Ma (excluding only amphiboles R3 and R8). Such concordancy in apparent age among different minerals, and among samples of the same mineral (with varying chemistries), indicates that the age obtained has not been perturbed by factors such as the incorporation of initial argon into the crystal lattices or the loss or gain of variable argon/potassium caused by weathering or metasomatism (Dalrymple & Lanphere 1969). The age obtained may thus be regarded as representative of an event in the tectono-thermal history of the host lithologies which led to setting (or total resetting) of the K/Ar isotopic system in the micas and amphiboles.

The c.400 Ma age accords with other K/Ar ages of micas from the Central Scandinavian Caledonides. Lux (1985) reported K/Ar ages from the Western Gneiss Region in the range 410 to 370 Ma and a whole-rock sample of kentallenite from the Bindal area (c.30 km southwest of Målvika) gave an age of 399±10 Ma (Nordgulen & Mitchell 1988). Ages within the range 420-380 Ma have been interpreted as timing uplift and cooling at the end of the Caledonian Orogeny (e.g. Sturt et al. 1967). Hence, the ages obtained from the minerals we have studied are regarded as having an equivalent significance for the Helgeland Nappe Complex.

The concordancy of the ages is highly significant, given that muscovite has a somewhat higher blocking temperature than biotite and that amphibole has a significantly higher blocking temperature than muscovite (Dalrymple & Lanphere 1969). This implies that cooling through the respective thresholds for argon retention in each of these minerals must have occurred within a time scale of less than 5 Ma. In the context of a regional metamorphic terrain this implies a process of rapid uplift. This inference accords with the views of Tucker et al. (1987), who obtained U/Pb ages from the area to the southwest of Trondheimsfjord that pointed to a "... very short period of burial and uplift in the Western Gneiss Region". This occurred at about 395 Ma (the timing of cooling through the c.500°C threshold for isotopic diffusion of lead in titanite), virtually contemporaneous with cooling in the Målvika area. Further evidence of rapid uplift is provided by Johansson et al. (1990) from their study of the metamorphic evolution of the Roan area of Central Vestranden, also in the Western Gneiss Region. ^{40}Ar-^{39}Ar ages for six hornblende separates give plateau ages around 400 Ma (indicating the timing of cooling through about 500°C). ^{40}Ar-^{39}Ar ages of six muscovite separates indicate subsequent cooling through their c.350°C blocking temperature at 390-395 Ma. This rapid cooling is alleged to have been accompanied by minimal uplift (Johansson et al. 1990). However, in a regional metamorphic environment, it is difficult to envisage by what process rapid cooling could occur other than by rapid uplift to high crustal levels. Rb-Sr dating by Piasecki & Cliff (1988) on muscovite books from shear-zone pegmatites from the Bjugn area of Central Vestranden gave ages of 389 ± 6 and 386 ± 6 Ma. Small, matrix-size muscovite and biotite from the same mylonite zones, on the other hand, yielded ages of 378 ± 5 and 365 ± 5 Ma; these younger ages were interpreted by Piasecki & Cliff to relate to post-shearing uplift and cooling.

In the present study, among the eight amphiboles dated one gave an age significantly older than that of the main group at the 1σ confidence level (415 ± 7 Ma). Two other samples gave indistinguishable (at 1σ) apparent ages whose mean is 472 Ma, which is distinguishably older than the remaining amphiboles.

If the c.472 Ma age accurately records a tectono-thermal (or crystallization) event then the timing of amphibolite facies metamorphism in the HNC would also be constrained. The high-grade metamorphic event must have preceded the crystallization of the undeformed, unmetamorphosed, amphibole wall-rock skarn. Amphibolite facies metamorphism and the development of the S2 fabric, (which coincided with the peak of metamorphism (Gustavson 1988, Thorsnes & Løseth 1991) would therefore have to be related to tectonism of Early Ordovician age, or earlier.

If the c.472 Ma age is valid then this would also constrain the timing and mechanism of mineralization. As scheelite pre-dated the formation of the amphibole wall-rocks, the main mineralization event could not be associated with the adjacent two-mica granodiorite pluton. This is because the pluton is known to be younger than 430 Ma since it cuts the adjacent monzodiorite (Fig. 2), which has given a U/Pb age of 430 ± 7 Ma (Nordgulen et al. 1993). The c.472 Ma age would also imply that scheelite mineralization pre-dates known igneous activity by about 25 Ma (ignoring the Rb/Sr Cambrian dates obtained by Nissen (1986) which have recently been supplanted by more reliable, younger U/Pb ages (Nordgulen et al. 1993). Furthermore, the earliest scheelite mineralization at Målvika could not then be related to the Kolsvik gold mineralization, since the latter is linked to Early Devonian brittle deformation (P. Ihlen, pers. comm. 1991).

These inferences are dependant on the assumption that the c.472 Ma apparent age is geologically significant. However, previous K/Ar investigations of the Uppermost Allochthon have encountered problems with excess argon (Wilson 1972, Wilson & Nicholson 1973). Wilson (1972) was of the opinion that the excess argon in the Sulitjelma region was inherited as a result of argon outgassing from the 1700-1800 Ma basement during regional metamorphism. Given the proximity of the Sulitjelma region it is a possibility that radiogenic argon, released from basement rocks, was present in fluids circulating through the Målvika area at the time of cooling through the argon blocking temperature of amphibole (at a time later than 472 Ma). However, since the total radiogenic argon and potassium contents of the two samples with the oldest apparent ages differ by about 15% it would be an improbable coincidence that excess argon resulted in their indistinguishable apparent ages. The difference (c.55 Ma) between the two oldest concordant ages and the next oldest age is also inconsistent with the randomizing effect of excess argon on apparent ages.

In view of the contradictory evidence described above, further radiometric ages would need to be obtained, utilising other isotopic methods (e.g ^{40}Ar - ^{39}Ar or Sm/Nd - see Bell et al. 1989), before the two oldest K/Ar amphibole ages obtained can be confidently regarded as having chronological significance.

Conclusions

Geological evidence shows that pyroxene + plagioclase skarn, at Målvika, post-dated the S2 fabric in the gneiss, indicating that the skarn formed after the peak of regional metamorphism. This and the petrographic evidence of scheelite crystallizing late in the skarn paragenesis demonstrate that tungsten was deposited from epigenetic hydrothermal fluids. This refutes Skaarup's (1974) suggestion that the tungsten was deposited contemporaneously with the accumulation of the host lithologies.

K/Ar apparent ages of biotite, muscovite and three amphibole separates define the cooling history of the Helgeland Nappe Complex at the end of the Caledonian orogeny. The indistinguishability (at 1σ) of apparent ages from these minerals implies that rapid uplift was responsible for the cooling, a conclusion which is consistent with the findings of two geochronological investigations of the Western Gneiss Region (Tucker et al. 1987, Johannson et al. 1990).

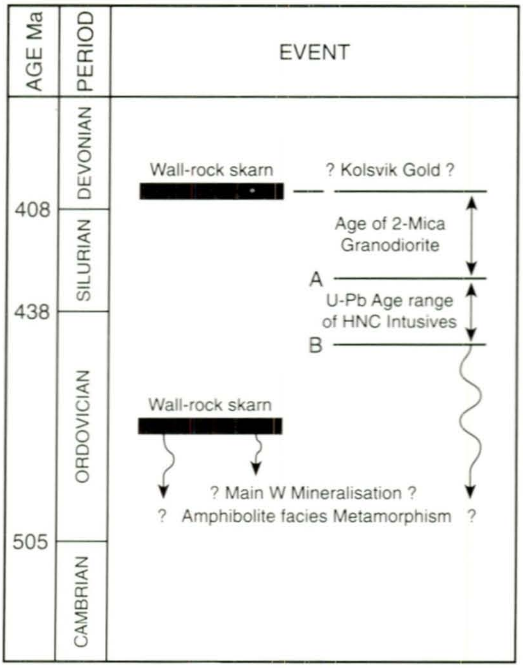

Fig. 7. Chronological context of scheelite mineralisation. The upper black rectangle show the IVWM (with 1σ error bar) of the two oldest (amphibole wall-rock skarn) K/Ar ages. A and B indicate the timing of crystallization of the monzodiorite pluton north-east of Målvika (see Fig. 2) and Andalshatten pluton respectively (U-Pb on zircon; Nordgulen et al. in press.) 'Age of 2-mica Granodiorite' indicates the possible time-span of intrusion of the cross-cutting granodiorite that lies adjacent to the U-Pb dated monzodiorite pluton.

Two oldest amphibole samples gave indistinguishable (at 1σ) apparent ages whose mean is 472 Ma. These apparent ages may record the timing of a tectono-thermal event or crystallization. It follows that the amphibolite facies metamorphism of the host-rocks would have occurred during the Early Ordovician, or earlier. In addition, the earliest scheelite mineralization would pre-date intrusive activity in the HNC (Fig. 7) and would be unrelated to the Early Devonian gold/arsenopyrite mineralization at Kolsvik. An alternative explanation for these two apparent ages is that they are a result of the incorporation of excess argon from circulating fluids, at about 400 Ma.

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