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ORIGINAL PAPER

Variscan ore formation and metamorphism at the Felbertal scheelite deposit (Austria): constraining tungsten mineralisation from Re–Os dating of molybdenite

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Abstract The Felbertal scheelite deposit in the Eastern Alps has been regarded as the type locality for stratabound scheelite deposits. It is hosted by a Cambro-Ordovician metavolcanic arc sequence with minor Variscan granitoids (~ 340 Ma) in the central Tauern Window. Re–Os model ages for molybdenite from the Felbertal tungsten deposit range between ~ 358 and ~ 336 Ma and record several pulses of magmatic-hydrothermal-metamorphic molybdenite formation. Molybdenite ages from the K2 orebody, a scheelite-rich quartz mylonite in the Western ore field, indicate that both mineralisation and mylonite are Variscan in age and suggest that the shear zone was active for ~ 20 million years. Early stage tungsten mineralisation (*Scheelite 1*) in quartzitic ores in the Eastern ore field, which is free of molybdenite, yielded very low to near blank levels of Re and Os and thus could not be dated. However, molybdenite from scheelite–quartz stringers, previously interpreted as a feeder stockwork to quartzitic scheelite ore of presumed Cambrian age, yielded Variscan Re–Os ages of ~ 342 and ~ 337 Ma. Dating of molybdenite contained in scheelite ores thus far provides no indication of a Cambrian component to the tungsten mineralisation. Our data are consistent with a model of either granite intrusion-related ore formation and coeval metamorphic overprint during the Early Carboniferous or, alternatively, molybdenite formation may be exclusively attributed to Variscan metamorphism (see Stein 2006).

Keywords Felbertal · Scheelite · Tungsten · Molybdenite · Re–Os dating · Variscan

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Introduction

The concept of stratiform and stratabound tungsten deposits was formulated 40–50 years ago (Höll and Maucher 1967; Maucher 1965, 1976). Subsequent discovery of the Felbertal scheelite deposit (Höll 1975) in Austria stimulated exploration interest worldwide for this previously unrecognised ore deposit type.

Stratabound tungsten deposits occur in tectonically complex and often polymetamorphic Archaen to Phanerozoic terranes, and are mainly hosted in volcano-sedimentary sequences (metabasites, calc-silicate and metacarbonate rocks, tourmalinites, Plimer 1987). In contrast to other types of W–Mo–(Cu) deposits showing indisputable genetic association with intrusive magmatic systems (e.g., Kwak 1987) the genesis of stratabound W mineralisation is still debated, and various source(s) and processes of metal concentration have been proposed (Cheilletz 1988).

The active Felbertal mine in Salzburg Province (Austria), the type locality of strata-bound tungsten deposits, is one of the largest tungsten producers in the world (annual production in 2003 was ~ 450,800 tons of ore at 0.44 wt% WO_3, Bundesministerium für Wirtschaft und Arbeit 2004). Felbertal provides a prime example of on-going debate between syngenetic stratabound and epigenetic granite-related ore genesis models. What is not covered in this debate is the added possibility of a metamorphic origin for W–(Mo) mineralisation whereby scheelite–(molybdenite) forms in association with leucocratic orthogneiss (leucosomes), due to dehydration melting during high-grade metamorphism, rather than an emplaced Variscan intrusion (Stein 2006). In this dehydration melting model, ore may be concentrated in the vicinity of leucosome–melanosome boundaries which may be quartz-rich (Stein 2006). This paper highlights an intrusion-related model for scheelite, with most of the molybdenite being a product of recrystallisation of Mo-bearing scheelite. The model presented here, however, does not preclude formation of molybdenite in the Felbertal W deposit by metamorphic means (rather than an emplaced intrusion) as described in Stein (2006).

When mining of the Eastern ore field at Felbertal commenced, the mineralisation was interpreted as a novel stratiform-stratabound scheelite deposit of exhalative-hydrothermal origin (Höll 1975). According to this model, tungsten mineralisation is the same age as the Early Cambrian mafic to felsic volcanic protoliths hosting the deposit (metabasites, felsic gneisses, and quartz-rich rocks now dated at ~ 520–540 Ma, Höll and Eichhorn 2000).

Subsequent discovery of economic scheelite ores in the Western ore field, associated with a highly fractionated orthogneiss body (K1–K3 orthogneiss) in the underground part of the mine, and recognition and confirmation of its Lower Carboniferous age (Pestal 1983; ~ 340 Ma, Eichhorn et al. 1997), led some researchers to argue that Felbertal is a metamorphosed granite-related tungsten deposit of Variscan age (Brigleb et al. 1985; Brigleb 1991; Trudu and Clark 1986). A strong argument for this epigenetic model was the discovery of an orthogneiss body (K1–K3 orthogneiss) in the then newly opened western ore field, recognition of its anomalous (A-type) geochemistry (Finger et al. 1985) and its close spatial association with economic grade scheelite ores. More recently, a more complex polystage genetic model embracing both Cambrian (~ 520 Ma) and Early Carboniferous (~ 340 Ma) scheelite mineralisation has been proposed (Eichhorn et al. 1997; Eichhorn et al. 1999a).

Re–Os dating of molybdenite has been used to date W–Mo mineralisation in the context of a dehydration melting model (Bingen and Stein 2003; Stein 2006). In addition, Re–Os dating of molybdenite has been used to determine the time of ductile and brittle deformation (Stein and Bingen 2002; Stein et al. 2004), and to elucidate unroofing of orogenic terranes (Bingen et al. 2006). The robustness of Re–Os systematics in molybdenite through high-grade metamorphic overprints has been amply documented (e.g., Langthaler et al. 2004; Stein et al. 2004; Kohút and Stein 2005).

In this paper we present Re–Os molybdenite ages from the Felbertal W–(Mo) deposit and document our attempt to date scheelite using the Re–Os method. We discuss the meaning of these ages in the context of the genetic debate and geologic evolution of this major and economically important scheelite deposit. Several pulses of Variscan orogenic activity (thermal and deformational) figure prominently in the formation of W–(Mo) ore at Felbertal.

Geological setting

The Felbertal scheelite deposit is situated in the central part of the Tauern Window, a major tectonic window in the Eastern Alps where rocks of the Penninic and Helvetic units tectonically underlying Austroalpine units are exposed (Fig. 1). Based on the pioneering studies by (Frasl 1958; Frasl and Frank 1966) three major geologic units are distinguished in the Tauern Window, which were all deformed and metamorphosed during the Alpine orogeny: (1) pre-Variscan basement, (2) magmatic rocks of Variscan age (ca. 360–270 Ma); the metagranitoids are referred to as "Central Gneiss", and (3) Permian to Mesozoic auto- to allochthonous volcano-sedimentary cover rocks (for review see Ebner 1997).

In the central Tauern Window the basement rocks and metagranitoids constitute the Habach terrane, which is characterised by oceanic crust, magmatic arc systems and granitoid intrusions. In the Felbertal area the Habach terrane is composed of several tectonic subunits (from bottom to top): the Basal Amphibolite, the Basal Schist, the Lower Magmatic Series, and the Upper Magmatic Series (Höck et al. 1993; Höll 1975; Kraiger 1989). Economic scheelite mineralisation is restricted to the Lower Magmatic Series (Höll 1975; Höll and Eichhorn 2000).

The Basal Amphibolite (metabasites, hornblende-plagioclase gneisses, epi- to pyroclastic metasedimentary rocks, meta-ultramafic rocks) is interpreted as part of an ophiolite complex formed in a back-arc/supra-

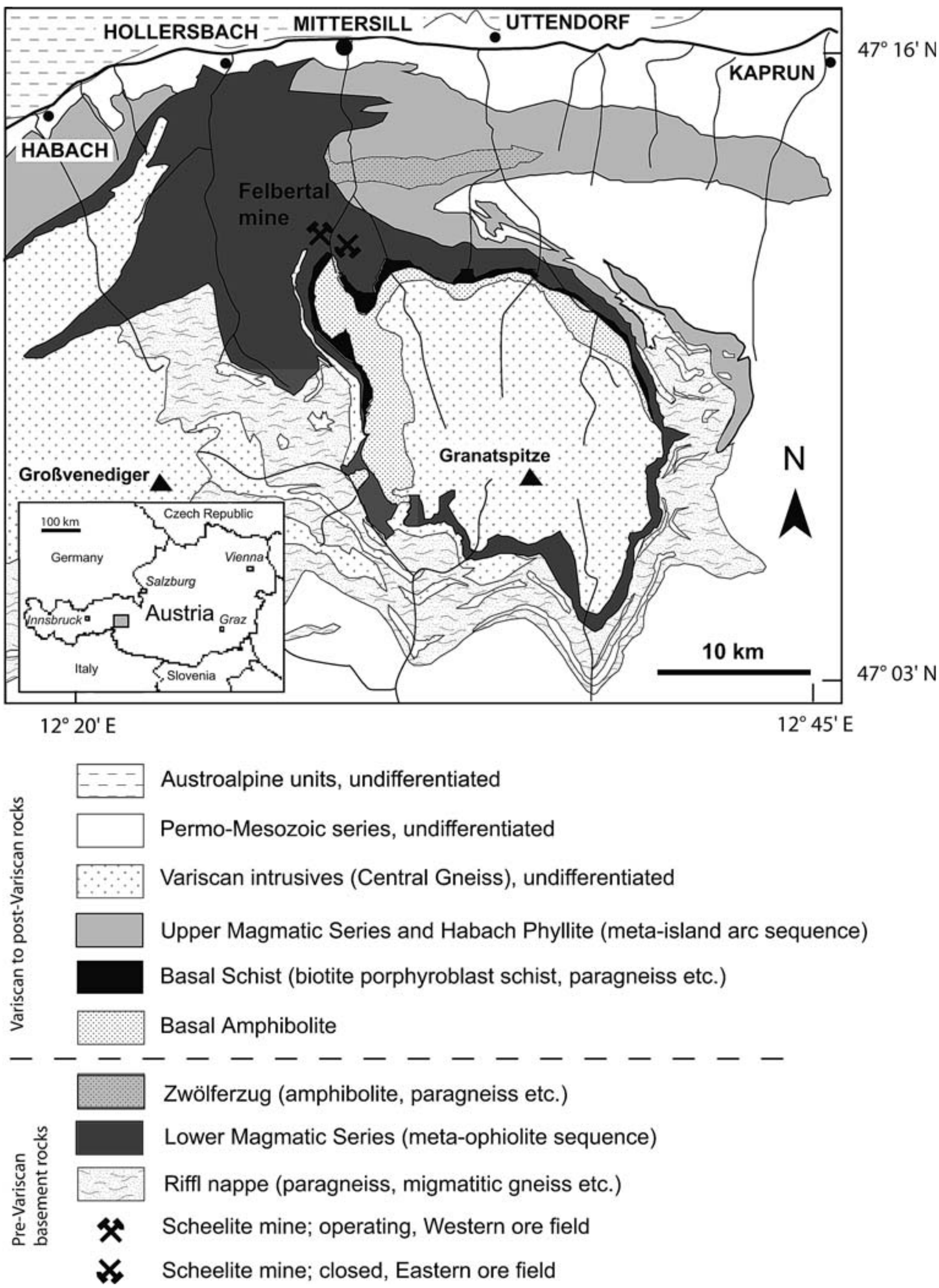


Fig. 1 Simplified geological map showing the central Tauern Window in the Eastern Alps and location of the Felbertal scheelite mine (modified from Höll and Eichhorn 2000; Kebede et al. 2005)

subduction setting recently dated as Early Carboniferous (Kebede et al. 2005; Kebede et al. 2003). However, some rocks of this unit were also dated as Late Pre-Cambrian/Early Palaeozoic (Eichhorn et al. 2001; von Quadt 1992). The transgressive Basal Schist is composed of metasedimentary rocks (mica schists, paragneisses etc.), amphibolites and minor orthogneisses formed in an island arc setting (Gilg et al. 1989). Recent U–Pb zircon dating of detrital zircons from these flysch-like sequences by Kebede et al. (2005) demonstrates that metasedimentary protoliths have a maximum Late Devonian/Early Carboniferous sedimentation age. Thus, at least parts of these two basal units cannot be part of the pre-Varsican basement of the Habach terrane as previously thought.

In contrast, the Felbertal scheelite deposit is located in the older pre-Variscan parts of the Habach terrane, in the Lower Magmatic Series (Höck et al. 1993; Höll 1975). The Lower Magmatic Series is dominated by mafic and felsic meta-igneous rocks (Höck et al. 1993) of mainly Cambrian age (Eichhorn et al. 1999a, b; Eichhorn et al. 2000). Metabasites in this up to 4,000 m thick sequence include fine-grained amphibolites (547 ± 27 Ma) as well as coarse-grained amphibolites (482 ± 5 Ma, Eichhorn et al. 2000) and hornblendites (496 ± 2 Ma, von Quadt 1985). The protoliths were dismembered ophiolites (Höck et al. 1993) as well as volcanic arc basalts, gabbros and pyroxenites, which formed in an arc environment along an active continental margin (Höll and Eichhorn 2000).

Leucocratic gneisses, poor in alkali feldspar, are associated with these metabasites. These Early Palaeozoic gneisses, formerly interpreted as metamorphosed rhyolites and rhyodacites (Eichhorn et al. 1995; Thalhammer et al. 1989; von Quadt 1985) are now recognised as two types of calc-alkaline I-type metagranitoids both showing volcanic arc characteristics (Höll and Eichhorn 2000). The emplacement ages of the older gneisses ("older K2 gneiss") range between 547 and 529 Ma, with the younger ones ("younger K2 gneiss") dated at 519 ± 14 Ma (Eichhorn et al. 1999a). A gneiss sample ("EOZ gneiss") underlying the scheelite-rich quartzite in the Eastern ore field (Fig. 2, and see below) yielded 529 ± 17 Ma (Eichhorn et al. 1999a). These newer in-situ U–Pb SHRIMP zircon ages confirm earlier conventional Pb–Pb zircon ages of 541 ± 53 and 537 ± 40 Ma for these gneisses (von Quadt 1985), but neither SHRIMP nor conventional dating yields precise U–Pb age results.

The Habach Phyllites are the most prominent member of the arc-type Upper Magmatic Series (mafic to felsic metavolcanics, dark phyllites, micaschists, and serpentinites) and are interpreted to represent forearc basin development in the Habach terrane (Eichhorn et al. 2001). Zircons from gabbro clasts and detrital zircons from meta-agglomerates yield ages of 536 ± 8 and 506 ± 9 Ma for this series. It is now recognised that the Habach terrane in the central Tauern Window includes tectonically interleaved Variscan metavolcano-sedimentary units in addition to pre-Variscan units (Fig. 1, Kebede et al. 2005).

During the Variscan orogeny, granitoids (orthogneisses constituting the Central Gneiss, Fig. 1), classified as I-type and to a minor extent as S- and A-type granitoids (Finger et al. 1993; Finger and Steyrer 1988) intruded these Early Palaeozoic sequences. In the

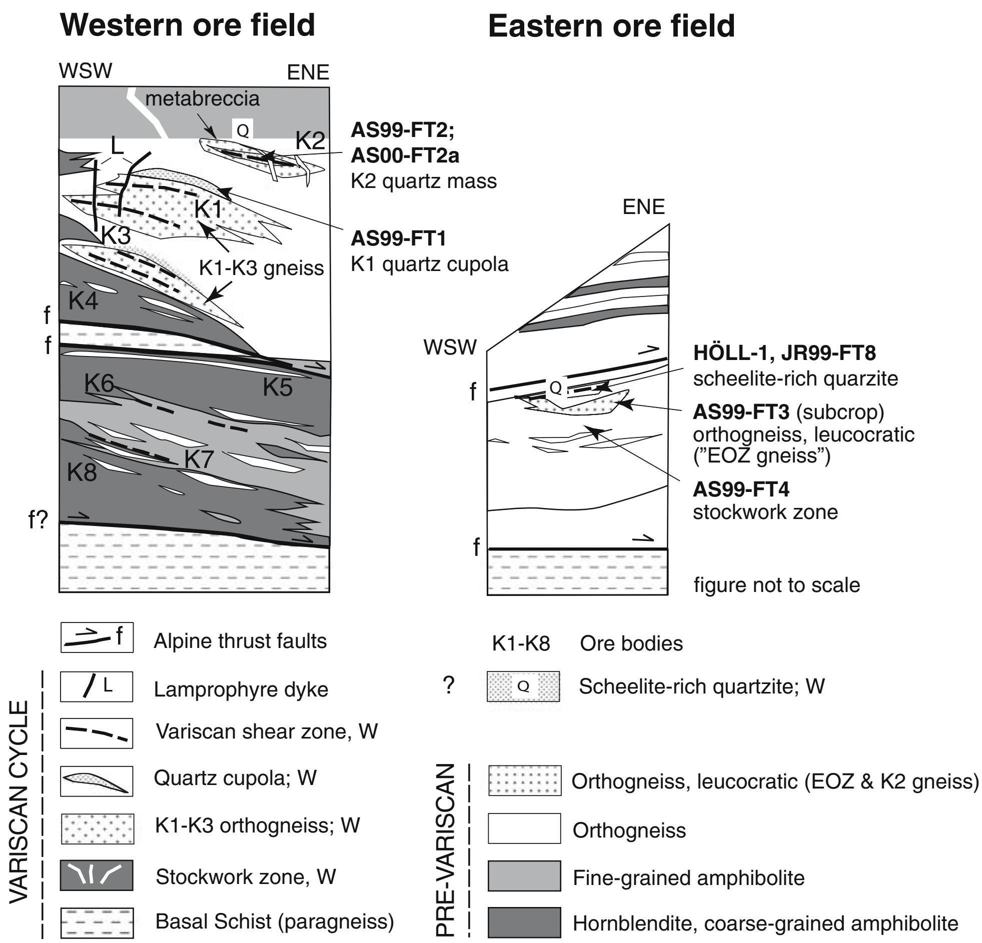


Fig. 2 Schematic cross sections (not to scale) through the Western and Eastern ore fields of the Felbertal scheelite deposit and sample locations; K1–K8 refer to major ore bodies in the operating underground mine; modified from Höll and Eichhorn (2000). Tungsten-bearing units and structures are marked with a *W* in legend. Based on our Re–Os data, the K1–K3 and K2 ores in the Western ore field as well as the stockwork ores from the Eastern ore field are interpreted to have formed during the Variscan orogenic cycle. The age of mineralisation from the scheelite-rich quartzite from the Eastern ore field is still unconstrained

Tauern Window the emplacement ages of these igneous rocks range from the Upper Devonian to Permian (Eichhorn et al. 2000). Most widespread are high-K I-type metagranitoids falling into two age groups: Early (~ 340 Ma) and Late Carboniferous (~ 310 Ma). Minor S-type granites at Granatspitze (Fig. 1) of debated Permian (Eichhorn et al. 2000) or Upper Carboniferous age (Kebede et al. 2005) are also present. Permian granites with A-type affinities are rare and have been equated to post orogenic crustal extension (von Quadt et al. 1999). Metagranitoids in the Felbertal area mostly belong to the Early Carboniferous group, interpreted to represent Variscan collision and amalgamation of northern Gondwana with Laurasia–Avalonia (Eichhorn et al. 2001).

At Felbertal, a several hundred meter long and several tens of meters wide orthogneiss body of Early Carboniferous age is exposed in the active underground mine. This so-called K1–K3 orthogneiss is a geochemically anomalous (high Be, Li, Sn, W etc.) muscovite-microcline gneiss (Finger et al. 1985), dated at 336 ± 15 Ma (conventional U–Pb zircon, Eichhorn et al. 1995). It is associated with major economic scheelite mineralisation.

The dominant Barrovian-type regional metamorphism in the Tauern Window is of Young Alpine age (~ 30–40 Ma, e.g., Eichhorn et al. 1995; Grundmann 1989; Inger and Cliff 1994), which in the Tauern Window reached upper greenschist to lower amphibolite facies conditions. At the northern margin of the Tauern Window in the Felbertal area (near Hintersee) metamorphic temperatures were ~ 600°C (Hoernes and Friedrichsen 1974). High-P metamorphism is also of Oligocene age as recently confirmed by Glodny et al. (2005) but is restricted to the eclogite zone at the southern margin of the Tauern Window.

The extent and timing of pre-Alpine metamorphic events in the Habach terrane and related basement units in the Tauern Window is still debated. First clear petrographic evidence for polyphase metamorphism in the Habach terrane was provided by Grundmann and Morteani (1982). *P*–*T* conditions of 420°C and 2 kbar were estimated for this low-P regional metamorphic event (Koller and Richter 1984). A Sm–Nd isochron age of 336 ± 32 for rocks from the Zwölferzug provides geochronological evidence for Variscan metamorphism in the Tauern Window (von Quadt 1992). A monazite age of 373 ± 15 Ma (Finger and Bankhammer 2003) was interpreted as possible evidence for Devonian high-grade metamorphism.

A Sm–Nd isochron age of 319 ± 34 (Eichhorn et al. 1997) for one of the four scheelite generations at Felbertal (see below) was also attributed to Variscan regional metamorphism. Even ages as young as 282 ± 2 Ma (conventional U–Pb dating on titanite, Eichhorn et al. 1995) were ascribed to the Variscan orogeny.

High-P metamorphism of Silurian age (~ 420 Ma) has been proposed by von Quadt et al. (1997). Re–Os molybdenite ages of 414.3 ± 1.6 and 417.3 ± 1.6 Ma could correspond with this Silurian metamorphic event (Raith et al. 2003). Migmatitic leucosomes yielding ages of 449 ± 7 Ma (Eichhorn et al. 2001) and 458 ± 11 Ma (Eichhorn et al. 1999b) likely date anatexis related to Caledonian high-grade metamorphism in the Habach terrane. In the same study the authors argue for widespread amphibolite facies Alpine as well as Variscan regional metamorphism. The dominant penetrative fabrics and folding of scheelite–quartz veins at Felbertal previously interpreted as Alpine age are now mostly regarded as Variscan (Eichhorn et al. 1995). Structures of clear Alpine age are discrete shear zones separating the ore deposit into several tectonic slices (Höll and Eichhorn 2000). These Alpine shear zones are characterised by retrograde greenschist facies assemblages. In the Eastern ore field up to a few meters-thick pyrite-rich chlorite schists are retrograde products of amphibolites and hornblendites.

Scheelite generations and their postulated ages

Studies by Schenk (1990) and continued by Höll and Eichhorn (2000) suggest four generations of scheelite at Felbertal. Since we will refer repeatedly to their nomenclature in our paper, the major aspects distinguishing scheelite generations are summarized briefly below.

Scheelite 1 is fine-grained (up to 0.4 mm), white with yellowish-white fluorescence and sometimes preserves excellent primary growth zoning. It has been reported from the scheelite-rich quartzite ore underlying stockwork mineralisation in the Eastern ore field. In the Western ore field laminated scheelite-quartz ores from the K2 ore body are possible equivalents. Chemically, *Scheelite 1* is distinguished from the other generations by higher $^{206}Pb/^{204}Pb$ and higher U contents reaching up to several tens of ppm U (Höll and Eichhorn 2000). *Scheelite 1* has so far not been successfully dated (see below).

Scheelite 2 is fine- to coarse-grained (up to cm scale), grey with greasy lustre, yellow fluorescent with 0.1–1.7 wt% Mo substitution. It is widespread in the Western ore field and less common in the Eastern. It often exhibits brittle deformation with cracks containing exsolutions of molybdenite and tungstenite (Schenk 1990). *Scheelite 2* was previously thought to be (at least in part) Cambrian age but is now accepted to be of Early Carboniferous age (e.g., compare Fig. 10 in Eichhorn et al. 1997 with Fig. 12 in Höll and Eichhorn 2000).

Scheelite 3 commonly forms rims around and fracture fillings within *Scheelites 1* and *2*. It is grey to white with blue fluorescence reflecting its low Mo content. It is commonly associated with fine-grained molybdenite. The Sm–Nd isochron age of 319 ± 34 Ma calculated for *Scheelite 3* is interpreted as the age of recrystallisation of older scheelite generations during Variscan regional metamorphism (Eichhorn et al. 1997).

Scheelite 4 is rare and forms isolated porphyroblasts with white to pale blue fluorescence reflecting its extremely low Mo concentrations. It occurs in Alpine metamorphic quartz veins or as overgrowths on older scheelite generations. It has been interpreted as scheelite mobilised during Alpine regional metamorphism. The Alpine age of *Scheelite 4* is suggested by an imprecise Sm–Nd isochron age of 29 ± 17 Ma (Eichhorn et al. 1997).

Methods

Principles of Re–Os molybdenite chronometry are well established (Stein et al. 2001; Stein et al. 2003; Selby and Creaser 2004). This study afforded the opportunity to compare Re–Os ages obtained using the single Os (Markey et al. 1998) and the newer double Os spike (Markey et al. 2003) approaches. The two methods have been previously compared and produce identical age results (e.g., Stein 2006). Re–Os model ages and their reported uncertainties are based on propagation of all analytical errors. These errors include a comprehensive treatment of blank (Re and Os concentrations and Os isotopic composition) and blank uncertainty, important to the data reported in this study. Re–Os isochron ages were calculated using Isoplot 3.0 (Ludwig 2003).

During the course of this study (1999–2003) it became evident that consistent scatter in the Re–Os molybdenite ages must reflect real temporal (geologic) differences, even in some samples consisting of several pieces taken from the same general locality. This is clearly proven in replicate runs using multiple mineral separates, taken from different hand samples collected at a single locality (see discussion in Stein 2006). This complexity, present at the hand-specimen scale, led us to limit our sampling to molybdenite flakes from single foliation surfaces in some of the deformed quartz-rich bands or from small regions of a sample, rather than combining molybdenite flakes from multiple hand specimens from the same general locality. This approach helped limit potential for mixing of multiple generations of molybdenite that formed over several tens of millions of years. Still, some variability in reproducibility suggests mixing of molybdenite that may have been deposited over an interval of time, or as temporally closely spaced generations.

This paper also explores the Re–Os potential for scheelite ($CaWO_4$), a mineral that is named powellite when Mo substitution for W is substantial. The premise for testing the Re–Os chronometer on scheelite was that for Mo-bearing scheelite, Re might also be present in measurable amounts if molybdenite was not directly precipitating with the scheelite. Considerable effort including laborious handpicking of grains from two samples was spent in mechanical separation of the two scheelite generations, which form intimate intergrowths in all samples. Even though these samples provided excellent examples of first stage yellow fluorescent *Scheelite 1*, crushing, sieving, and gravity separation of the 120–140 mesh fraction produced a mineral separate of yellow fluorescent Mo-rich scheelite, but not without some blue *Scheelite 3* present. In the end, it was not possible to fully separate the two scheelite generations, even by handpicking of a fine-grained fraction under a UV lamp.

Back scattered electron (BSE) and cathodoluminescence (CL) imaging was done at Technische Universität Bergakademie Freiberg using a JEOL JSM 6400 scanning electron microscope equipped with an Oxford MonoCL system (accelerating voltage, 20 kV, beam current, 0.8 nA) on carbon-coated polished sections. Mo concentrations in scheelite were analysed using an ARL SEMQ electron microprobe at the University of Leoben (wave length dispersive spectrometry (WDS) mode; MoL_α line; 25 kV, 15 nA; pure Mo standard; data correction according to Bastin and Heijligers 1991).

Results

Samples, petrography, and textural relationships of molybdenite and scheelite

Molybdenite-bearing samples, most of them containing scheelite, were sampled from various ore bodies within the Felbertal W deposits from both the active underground mine (Western ore field) and the abandoned open pit area (Eastern ore field). Their locations are schematically illustrated on Fig. 2. Microtextural relationships between scheelite and molybdenite are documented in Fig. 4a–f.

AS99-FT1 (JR99-FT3/3): Western ore field, upper part of K1 ore body, 1,152 m level

Molybdenite was sampled from a massive, up to 2 m thick, quartz body immediately above the Early Carboniferous K1–K3 orthogneiss. This quartz mass has been interpreted as a quartz cupola developed in the apical parts of this granite (Höll and Eichhorn 2000) and is locally rich in scheelite. The quartz body and its contact to the gneiss are highly sheared and deformed. In nearby galleries, scheelite–quartz veins are exposed. They clearly crosscut the K1–K3 orthogneiss, but are deformed (Fig. 3a). *Scheelite 2* porphyroclasts, up to several cm in size, recrystallised to *Scheelite 3* during this deformation event.

Molybdenite in this sample is very fine-grained and forms clots and millimeter size patches in milky and sheared sucrosic quartz. The molybdenite-rich parts of the sample used for Re–Os dating were scheelite-free. The patches and plates of molybdenite are aligned parallel to the foliation defined by sparse mica-richer layers in the quartz mass but also cut across the well-developed shear fabric in the quartz. Minor pyrrhotite, chalcopyrite and Cu–Pb–Bi sulphosalts (for details on these phases see Topa et al. 2002) are associated with molybdenite.

AS99-FT2, AS00-FT2a (JR99-FT4/1): Western ore field, K2 ore body, 1,164 m level

The K2 orebody, above the K1–K3 ore bodies in the Western ore field (Fig. 2), is an elongate lens-shaped (~ 40 m long, ~ 4–5 m thick) and strongly sheared quartz mass (Fig. 3b) associated with gneisses, schists and fine-grained amphibolites. It is topped by a presently inaccessible metabreccia, interpreted as a metamorphosed hydrothermal eruption breccia (Höll and Schenk 1988; Schenk and Höll 1988). According to a personal communication by R. Höll (1999), leucocratic gneisses (younger K2 gneiss, 519 ± 14, Eichhorn et al. 1999a) were reported to crosscut the quartz mass and the breccia; (e.g., see Fig. 4 in Höll and Eichhorn 2000). The laminated K2 scheelite–quartz ores in the Western ore field are similar to the scheelite-rich quartzitic ores in the Eastern ore field and both were interpreted as part of an early, pre-Variscan mineralisation stage (Eichhorn et al. 1999a; Höll and Schenk 1988).

A mylonitic fabric characterises this sample (Fig. 3b). Molybdenite, scheelite and minor other sulphides (Cu–Pb–Bi sulphosalts) are aligned in the penetrative foliation. The sample contains minor calcite. Scheelite is concentrated in laminated bands within quartz. In these bands two types of scheelite are distinguished. *Scheelite 1* occurs as up to 5 mm, grey and yellowish fluorescent porphyroclasts that have been synkinematically deformed. *Scheelite 3* is a recrystallised and finer-grained white and bluish fluorescent variety, occurring as overgrowths on *Scheelite 1*. Several millimetre-sized flakes of molybdenite occur along shear planes paralleling scheelite bands. The molybdenite records deformation such as microfolding and kinking (Fig. 4d, e) and has grain contacts with both types of scheelite (Fig. 4d, f). Parts of some deformed molybdenite grains exhibit a porous texture with development of variably oriented and discontinuous microcracks (Fig. 4e).

AS99-FT3 (JR99-FT6): Eastern ore field, 1,860 m, "Kehre 13"

Scheelite and sparse, fine-grained molybdenite were sampled from a meter-sized block in a large boulder field of leucocratic granite gneiss. This Cambrian gneiss (EOZ gneiss, Fig. 2) is comparable to K2 orthogneiss in the Western ore field. It is highly foliated and contains abundant foliation-parallel biotite and muscovite. Scheelite is aligned and elongated parallel to the foliation and exhibits intense synkinematic recrystallisation. Mo-bearing *Scheelite 2* is only locally preserved as relicts. Most *Scheelite 2* has been recrystallised to bluish fluorescent Mo-poor *Scheelite 3*. Euhedral crystals of molybdenite of variable size (up to hundreds of μm) are intimately intergrown with *Scheelite 3*.

AS99-FT4 (JR99-FT7): Eastern ore field, 1,920 m, "Kehre 15"

Molybdenite was sampled from a large outcrop (subcrop) of amphibolite cut by deformed quartz–scheelite stringers. The molybdenite is associated with the margin of a ~ 1 cm thick quartz veinlet cutting a coarse-grained amphibolite. This type of stringer ore in the Eastern ore field was interpreted as a stockwork-feeder zone underlying the scheelite-rich quartzite ore body (e.g., Höll and Schenk 1988).

Most molybdenite in this sample is relatively coarse-grained and associated with *Scheelite 2* porphyroclasts that recrystallised to *Scheelite 3*, the latter characterised by much brighter cathodoluminescence intensity (Fig. 4c). Tiny molybdenite crystals are abundant in boundary regions between *Scheelite 2* and *3*. They are never found in the cores of larger *Scheelite 2* porphyroclasts but are concentrated in the transition zone and in the reaction rims between *Scheelite 2* and *Scheelite 3*. Molybdenite crystals may be present along microcracks within larger scheelite porphyroclasts, however. In transmitted light, semi-transparent platy inclusions of intensely brown biotite, sometimes with a pseudohexagonal crystal shape, are commonly associated with molybdenite (Fig. 4a, b). Schenk (1990) also reports inclusions of tungstenite (WS_2) in scheelite. In accordance with Schenk (1990) and later studies (e.g., Höll and Eichhorn 2000) we interpret molybdenite associated with Mo-poor *Scheelite 3* that developed around porphyroclasts or within microfractures of Mo-rich *Scheelite 2* as a metamorphic reaction product.

Höll-1, JR99-FT8

These two samples are representative of scheelite-rich quartzite ore from the Eastern ore field. Because these

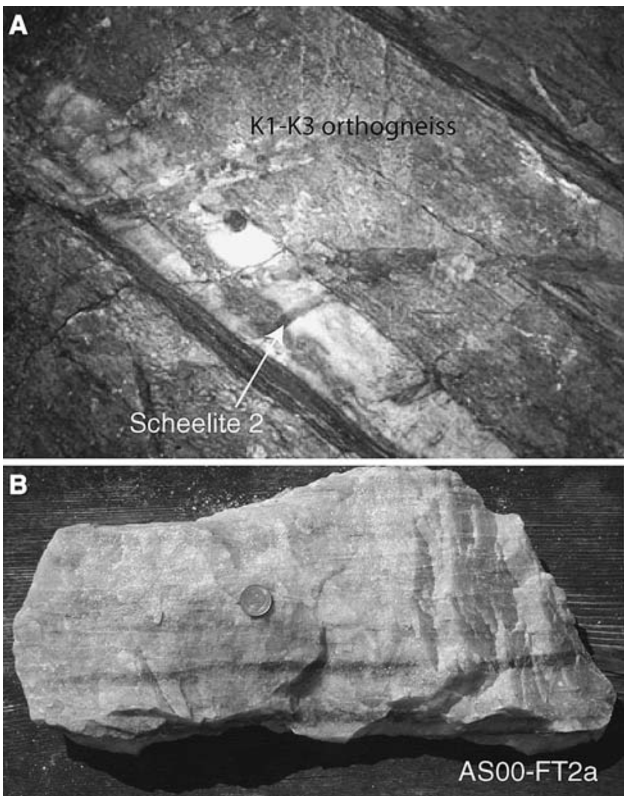


Fig. 3 **a** A ~ 10 cm thick deformed quartz vein containing elongate scheelite (*grey* mostly *Scheelite 2*) in K1–K3 orthogneiss. The mineralised vein crosscuts Early Carboniferous granite gneiss (336 ± 19 Ma, Eichhorn et al. 1995) but shows penetrative foliation. Western ore field, upper part of K1 ore body, 1,152 m level. **b** Laminated scheelite–quartz ore interpreted as a quartz–scheelite mylonite. The darker bands contain molybdenite and other minor sulphides. Dated sample AS00-FT2a (JR99-FT4/1), Western ore field, K2 ore body, 1,164 m level

high-grade tungsten ores have been completely mined out, we utilised well-defined sample material from R. Höll's collection (sample Höll 1). The second sample JR99-FT8 is from a large meter-sized block now used as armour stone in a rock wall close to the main entrance to the Western ore field galleries. R. Höll assured us that this sample is representative scheelite-rich quartzite ore taken directly from the Eastern ore field.

Scheelite-rich quartzite from the Eastern ore field is a fine-grained and laminated quartz rock composed of quartz and scheelite, with minor amounts of feldspar, muscovite and carbonate. Sub-mm to mm-scale layering in the polygonal quartz fabric is defined by oriented muscovite and especially by elongate fine-grained scheelite aggregates. Quartz has a tendency to develop straight grain boundaries and polygonal mosaic fabric. It displays ~ 3–5 times larger grain size than scheelite. There are always two generations of scheelite present. *Scheelite 1* is whitish-yellow fluorescent, averages ~ 1 wt% Mo and rarely preserves primary growth zoning (Schenk 1990). It is intimately intergrown with or overgrown by bluish fluorescent euhedral *Scheelite 3* carrying < 0.1 wt% Mo. As with previously described samples, *Scheelite 3* is clearly the recrystallisation product of *Scheelite 1*. It is noteworthy that *no* molybdenite is associated with scheelite in this type of ore, even at the *Scheelite 1* to *Scheelite 3* transition.

Re–Os dating of molybdenite

Re–Os dating was carried out on four samples, three from the Western and one from the Eastern ore field. Replicate analyses, utilising different mineral separates, provide a total of 12 ^{187}Re–^{187}Os model ages for Felbertal (Table 1). As discussed earlier, care was taken to extract what appeared to be single generation occurrences from hand specimens. Further, gleaming and pristine millimeter-size molybdenite platelets occur as isolated grains in exceedingly fresh, nearly white felsic gneiss or quartz-rich rocks. This removes the possibility for exchange, gain, or loss of Re and Os as the surrounding medium is silicate that has no affinity for either of these chalcophile-siderophile elements. Significantly, the Re–Os analyses were carried out using both a single and a double Os spike (Markey et al. 2003), and both methods are in good agreement. Analytical details and blank corrections are provided as footnotes in Table 1. Re concentrations are relatively low, ranging from 3.3 to 20.5 ppm. Most mineral separations were minimally diluted by silicate and therefore the Re concentrations directly reflect Re content in molybdenite.

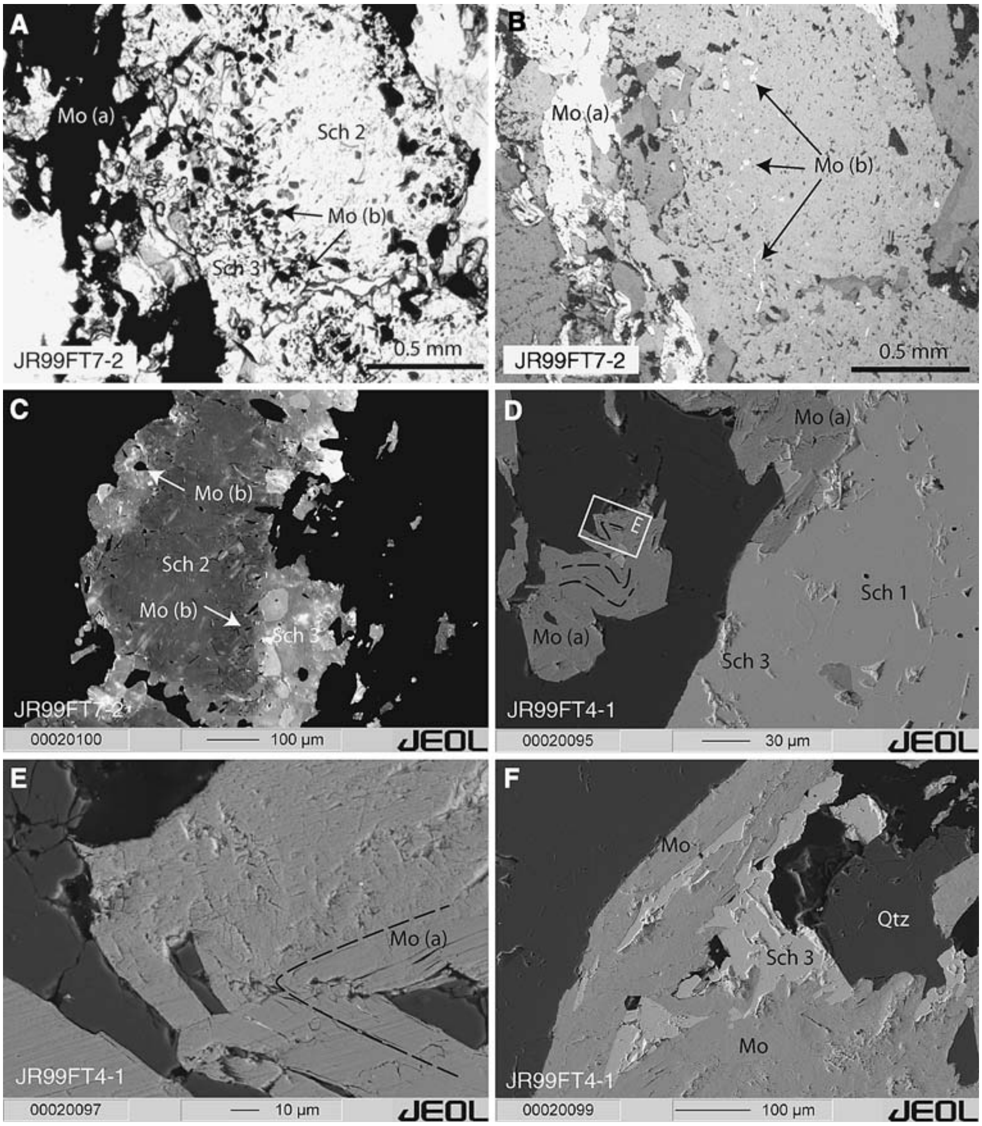


Fig. 4 Microtextural relationships between scheelite and molybdenite. **a, b** Microscopic images showing two types of scheelite and molybdenite: Type a molybdenite [Mo (a)] is coarse-grained, type b is fine-grained [Mo (b)]. The latter occurs as a reaction product from breakdown of Mo-rich scheelite (*Scheelite 2*) to Mo-poor scheelite (*Scheelite 3*) and it is concentrated within the reaction rim of *Scheelite 2*; semi-opaque inclusions in (**a**) are mostly biotite. Transmitted light (**a**) and reflected light with normal polars (**b**). Width of each photo is ~ 2 mm. Sample JR99FT7-2, Eastern ore field, ''Kehre 15'', 1,920 m. **c** Cathodoluminescence (*CL*) image of corroded *Scheelite 2* (*Sch 2*) porphyroclast, which is recrystallised to CL-brighter *Scheelite 3* (*Sch 3*) at the margins. The *Scheelite 3* rim and the transition zone between *Scheelite 2* and *3* are rich in tiny molybdenite crystals (*white arrow*, *black* in CL). Sample JR99FT7-2, Eastern ore field, ''Kehre 15'', 1,920 m. **d**, **e** Backscattered electron (*BSE*) images showing the association of molybdenite Mo (a) with Sch1 and Sch 3 from banded K2 ores (see Fig. 3b). Molybdenite is deformed and folded. **e** shows detail of **d**; *dashed line* highlights kinked molybdenite; *upper part* of this grain shows poorly polished porous surface and small discontinuous microcracks. Sample JR99FT4-1, Western ore field, banded ore of K2 ore body, level 1,164 m. **f** BSE image of *Scheelite 3* intergrown with molybdenite. Sample JR99FT4-1, Western ore field, banded ore of K2 ore body, level 1,164 m. Images **c–f** courtesy U. Kempe, Freiberg

There are two general periods of molybdenite deposition, an earlier suggestion of ore formation at 360–355 Ma (two runs) and a younger period of ore formation at 345–335 Ma (ten runs). Neither is well-defined, and some mixing between generations is possible. Alternatively, molybdenite deposition could have taken place episodically over an interval of time (e.g., Bingen et al. 2006; Stein 2006). These Re–Os data nonetheless unequivocally provide a Variscan age for the dated samples, and the scatter seen in the age results is geologic, and not analytical.

Re–Os model ages for Felbertal molybdenites provide a calculated weighted mean age of 340.2 ± 2.2 Ma with an MSWD of 33 indicating excess scatter (Fig. 5a).

Table 1 Re–Os data for molybdenites from the Felbertal W–(Mo) deposit, Austria

AIRIE run	Sample name	Scheelite, association	Re (ppm)	^{187}Os (ppb)	Age (Ma)
K1 orebody, Western ore field					
CT-288A	AS99-FT1	None	15.92 (1)	57.62 (3)	344.7 ± 1.1
MDID-107	AS99-FT1	None	14.224 (2)	50.84 (4)	340.4 ± 1.1
MDID-123	AS99-FT1	None	12.925 (3)	46.71 (2)	344.1 ± 1.1
K2 orebody, Western ore field					
CT-296A	AS99-FT2	Scheelite 1, 3	16.21 (1)	60.99 (3)	358.3 ± 1.2
CT-300A	AS99-FT2	Scheelite 1, 3	18.27 (1)	65.13 (4)	339.5 ± 1.1
CT-311A	AS99-FT2	Scheelite 1, 3	20.47 (1)	72.64 (4)	337.9 ± 1.1
MDID-108	AS99-FT2	Scheelite 1, 3	7.415 (2)	26.71 (2)	343.0 ± 1.1
CT-541A	AS00-FT2a	Scheelite 1, 3	12.18 (1)	45.36 (4)	354.5 ± 1.2
MDID-111	AS00-FT2a	Scheelite 1, 3	14.478 (3)	51.05 (4)	335.8 ± 1.1
MDID-125	AS00-FT2a	Scheelite 1, 3	14.291 (2)	50.75 (2)	338.2 ± 1.1
Stockwork zone, Eastern ore field					
CT-289A	AS99-FT4	Scheelite 2, 3	3.429 (4)	12.33 (1)	342.4 ± 1.2
MDID-109	AS99-FT4	Scheelite 2, 3	3.309 (1)	11.71 (1)	336.9 ± 1.1

Assumed initial ^{187}Os/^{188}Os for age calculation = 0.2 ± 0.1. Absolute uncertainties shown, all at 2-sigma level, for last digit indicated. Decay constant used for ^{187}Re is 1.666×10^{-11} year^{-1} (Smoliar et al. 1996). Carius tube dissolution with single Os (CT) or double Os (MDID) spiking on 16–80 mg samples. Ages corrected for Re blank = 1.16 ± 0.03 pg, total Os = 1.9 ± 0.1 pg, ^{187}Os/^{188}Os = 0.24 ± 0.01. Ages calculated using ^{187}Os = ^{187}Re ($e^{\lambda t}$ – 1) include analytical and ^{187}Re decay constant uncertainties

Furthermore, the stated uncertainty for the weighted mean age is an underestimate, as the uncertainty in the decay constant is included in each analysis. Employment of the more rigorous isochron method based on a division of samples into 345–340 and 338–336 Ma model age groups, yields ages of 340.8 ± 7.9 and 337.9 ± 6.8 Ma (Fig. 5b, c). The isochrons do not make use of a zero point anchor (Stein et al. 2001), but are a regression through sample Re and Os concentration data alone. The isochron ^{187}Os initial is zero, as expected for molybdenite (Fig. 5b, c). The Model 3 isochron ages are indistinguishable within their two-sigma uncertainties, but the high MSWD values of 340 and 102 for the isochrons affirm geologic scatter in the data.

Re–Os analyses of scheelite

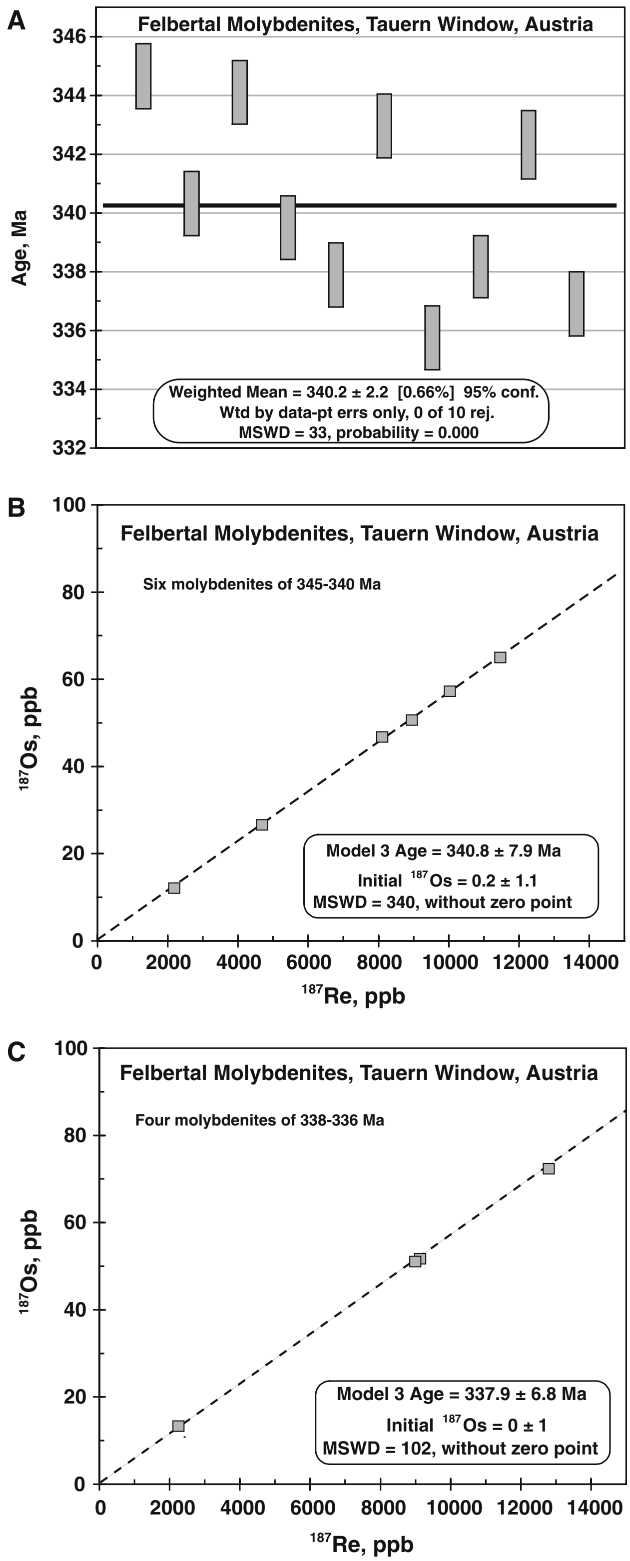
Two samples of scheelite from the Eastern ore field were prepared for Re–Os dating. *Scheelite 1* is represented by sample Höll-1, *Scheelite 2* by AS99-FT3. Time-intensive hand-picking of grains under a UV lamp provided a pure scheelite mineral separate, but it was impossible to fully separate the dominantly yellowish scheelite from intergrown blue florescent scheelite, even at the 120–140 mesh level, because of the fine-scale intergrowth of these two scheelite generations. Both samples yielded extremely low to near blank levels for Re and Os concentrations, precluding derivation of any meaningful age information. Sample AS99-FT3 was spiked using a *single Os spike* on the presumption that its isotopic composition would mimic a molybdenite and that the sample could be classified as LLHR (i.e., low-level highly radiogenic, Stein et al. 2000). This sample run (CT-297) had only 0.0086(1) ppm Re and 0.0117(1) ppb ^{187}Os. Sample Höll-1 was spiked for near blank level Re and Os, with normal Os isotopic composition, using a *double Os spike*. This scheelite run (LL-17) registered < 200 ppt Re, total Os = 1.5 ± 2 ppt, and ^{187}Os/^{188}Os = 9 ± 24. For run LL-17, the Re blank was 4.6 ± 0.01 pg and the Os blank was 5 ± 1 pg with ^{187}Os/^{188}Os = 0.190 ± 0.002. To summarize, this Os measurement is composed of 75% blank, and thus scheelite, in this particular setting, holds no promise for obtaining age information, even though we targeted our dating at the Mo-rich yellow florescent scheelite. Mo-rich scheelite does not translate to Re-rich scheelite, as we had hoped.

Discussion

Ages of the scheelite generations

Previous attempts to date scheelite from Felbertal with the Sm–Nd and U–Pb methods (Eichhorn et al. 1997; Eichhorn et al. 1995) were only partly successful; only Mo-poor *Scheelite 3* and *4* could be dated. Two published and highly imprecise Sm–Nd ages of 319 ± 34 Ma for *Scheelite 3* and 29 ± 17 Ma for *Scheelite 4* were interpreted to date metamorphic recrystallisation and scheelite mobilisation during Variscan and Alpine regional metamorphism (Eichhorn et al. 1997).

Both of these metamorphic events (Variscan and Alpine) overprint a presumed older scheelite



◀ **Fig. 5** Re–Os data for Felbertal molybdenites. **a** Weighted average of all Re–Os ages except CT-296A and CT-541A (discussed in text). High MSWD for these ten samples points to real temporal differences for formation of molybdenites. **b** Re–Os isochron for ''older'' molybdenites (six of the ten samples). Very high MSWD signals geologic differences in ages that are beyond analytical uncertainty. **c** Re–Os isochron for ''younger'' molybdenites (four of the ten samples). High MSWD again indicates geologic scatter. The uncertainties for isochron ages in **b** and **c** overlap at two-sigma precluding assignment of ages to two distinct, closely spaced episodes of mineralisation. A protracted period of molybdenite formation related to Variscan metamorphism is proposed. A single, simple intrusion-related magmatic-hydrothermal model cannot explain the scatter in the Re–Os molybdenite ages (see text)

mineralisation (*Scheelite 1* and *2*), which in early studies was described as syngenetic-forming coevally with the volcano-sedimentary host rocks (Höll 1975; Höll and Maucher 1976) later dated as Early Palaeozoic in age (Höll and Eichhorn 2000). The laminated quartzitic scheelite ores from the Eastern ore field were interpreted as meta-exhalites (Höll and Schenk 1988) and the laminated scheelite ores of the K2 orebody (Fig. 3b) in the Western ore field were regarded as possible equivalents. Mineralised metabreccias associated with the K2 ore body were interpreted as metamorphosed hydrothermal eruption breccias originally underlying the W-rich exhalites (Höll and Schenk 1988; Schenk and Höll 1988).

Over many years the genetic concepts for Felbertal changed radically and this deposit was re-interpreted as a metamorphosed granite-related ore deposit of magmatic-hydrothermal origin (Brigleb 1991; Brigleb et al. 1985; Eichhorn et al. 1999a; Trudu and Clark 1986). A still unresolved key point in the whole debate is the timing of early stage mineralisation (*Scheelite 1*). Whereas Eichhorn et al. (1999a) postulate two stages of mineralisation, one of Cambrian (~ 520 Ma) and the other of Early Carboniferous (~ 340 Ma) age, other studies argue for an exclusive Early Carboniferous age for the tungsten mineralisation (Brigleb et al. 1985; Trudu and Clark 1986) and relate its genesis to the K1–K3 orthogneiss. Thus, in recent years, an intrusion-related model for W mineralisation has prevailed.

As pointed out in this study, *Scheelite 2* must be younger than 355 Ma because of crosscutting relationships of scheelite–quartz veins (Fig. 3a) and the 336 ± 19 Ma emplacement age of the K1-K3 orthogneiss. Eichhorn et al. (1999a) bracketed *Scheelite 2* formation between 355 and 335 Ma thereby abandoning previous concepts of a pre-Carboniferous age for all or at least of some *Scheelite 2* (Eichhorn et al. 1995, 1997).

Hence, debate for a pre-Variscan age can now only be made for *Scheelite 1*. Attempts to date *Scheelite 1* with the Sm–Nd and U–Pb methods met with little success. The published errorchron 581 ± 105 Ma age (Eichhorn et al. 1997) was calculated by combining

Scheelite 1 and *2*. Even after an Early Carboniferous age became accepted for *Scheelite 2* (Eichhorn et al. 1999a), a Cambrian age was still postulated for *Scheelite 1* (Höll and Eichhorn 2000)—even after a 517 ± 130 Ma Pb–Pb age for *Scheelite 1* published by the same authors was later corrected to 300 ± 45 Ma (p. 499, Eichhorn et al. 1999a). Remaining arguments for a Cambrian age for the first stage of scheelite mineralisation come from U–Pb dating of zircon from the gneissic host rocks (529 ± 17 Ma), and from the banded scheelite ores (507 ± 27 Ma, Eichhorn et al. 1999a; Höll and Eichhorn 2000). However, these zircon ages do not necessarily reflect the timing of the hydrothermal ore formation as the high Th/U ratios and the oscillatory and sector zoning of zircon reported by Eichhorn et al. (1999a) are more diagnostic of a magmatic origin of zircon than a hydrothermal one (Hoskin 2005).

To resolve the age discrepancy surrounding *Scheelite 1* we attempted to date scheelite using the Re–Os method. Unfortunately, *Scheelite 1*, represented by sample Höll-1, a quartzitic scheelite ore from the Eastern ore field, contained blank level Os precluding an age determination. Therefore, the age of *Scheelite 1* remains unconstrained. *Scheelite 2*, represented by sample AS99-FT3, also yielded near blank levels of Re and Os.

Age of the stockwork ores in the Eastern ore field

In addition to the banded scheelite-rich quartzite there is scheelite present in underlying stockwork ores in the abandoned Eastern ore field (Fig. 2). The latter form a network of metamorphosed quartz–scheelite veinlets and stringers and were interpreted as part of a feeder zone of Cambrian age (Eichhorn et al. 1999a; Höll and Eichhorn 2000).

Our sample AS99-FT4 from the Eastern ore field provides important data that contribute to the debate about the age of the stockwork zone. Two Re–Os model ages of ~ 342 and ~ 337 Ma (Table 1) clearly indicate that molybdenite in these quartz–scheelite stringers formed during the Early Carboniferous. Two runs representing two sub-samples from AS99-FT4 yield slightly different ages interpreted to reflect real geologic variation in the age of stockwork feeder ore, and the ages both clearly indicate Variscan timing. Microtextures support the presence of more than one molybdenite generation in this sample and help to explain the observed age variations: The dated sample contains (1) larger molybdenite flakes co-existing with Mo-rich scheelite and (2) fine-grained molybdenite formed by breakdown of Mo-rich scheelite (Fig. 4a–c). Fine-grained molybdenite is undoubtedly the product of Variscan metamorphic recrystallisation of Mo-rich *Scheelite 2* to Mo-poor *Scheelite 3*. This process occurred over a period of several million years (~ 345–335 Ma) as recorded at Felbertal. The 342.4 ± 1.2 Ma age is statistically identical with two ages from the K1 ore body in the Western ore field highlighting the importance of Early Carboniferous mineralisation in both the Eastern and Western ore fields. Following this interpretation the stockwork zone in the Eastern ore field cannot be seen as a Cambrian feeder zone. It is best interpreted as a metamorphosed magmatic-hydrothermal stockwork-like vein system of Early Carboniferous age. The Re–Os isochron ages show that it is impossible to statistically isolate events in the 345–340 Ma range from those in the 340–335 Ma range. The best interpretation is a continuum or a 10 million years episodic interval of magmatic/metamorphic hydrothermal activity associated with the deposition of W mineralisation at Felbertal.

Interpretation of Re–Os molybdenite ages from the Western ore field

The Re–Os model ages for molybdenite from Felbertal range from about ~ 358 to ~ 336 Ma. The scatter in the ages is considerably larger than the 2-sigma analytical uncertainty for individual runs (Table 1) and indicates several episodes of Variscan molybdenite formation at Felbertal. A major episode is present at ~ 340–335 Ma with evidence for ~ 344–342 Ma and ~ 358–355 Ma molybdenite as well. Except for the ~ 358 Ma age, these ages are all within the 2-sigma uncertainty of the not very well constrained emplacement age of the K1–K3 orthogneiss (U–Pb zircon, 336 ± 19 Ma, Eichhorn et al. 1995).

K1 ore body

Two molybdenites from sample AS99-FT1 from the K1 orebody give ~ 344 Ma ages, and a third age is slightly younger at 340.4 ± 1.1 Ma. Hand specimens and petrographic observations document that molybdenite in this sample is not a direct breakdown product of scheelite though some of the molybdenite is bound to later shear planes. Hence, we provide two interpretations for these ages: (1) magmatic-hydrothermal formation of molybdenite (and scheelite) in a quartz cupola overlying the K1 ore body, i.e. an intrusion-related genesis associated with the geochemically highly anomalous K1–K3 orthogneiss (favoured by JGR) and (2) molybdenite (and scheelite) formation related to Variscan regional metamorphism (favoured by HJS).

A genetic link between K1 scheelite mineralisation and the K1–K3 orthogneiss is also supported by other geochemical data. The K1–K3 orthogneiss exhibits several geochemical characteristics of specialised granites associated with W–Mo deposits (Finger et al. 1985). This muscovite–microcline gneiss has high SiO_2 (70–80 wt%) and is meta- to slightly peraluminous. It is also characterised by higher Nb and Rb contents compared to the Cambrian orthogneisses (Finger et al. 1985) and its $^{87}Sr/^{86}Sr$ and ϵ_{Nd} values indicate a crustal origin (Höll and Eichhorn 2000). Because of this chemical signature, and especially its metaluminous to only slightly peraluminous character, the K1–K3 orthogneiss cannot be classified as a typical S-type granite; a chemical resemblance to A-type granites has been suggested (Finger et al. 1985). The K1–K3 orthogneiss is anomalous in Be, Li, Bi, Sn, Cs, U, Th, Mo, and W (Höll and Eichhorn 2000) making it the ideal granite to which the spatially associated K1–K3 ores can be linked genetically.

K2 ore body

The pre-Variscan (Cambrian) age postulated for the K2 orebody was not confirmed by Re–Os molybdenite dating, which yields ages between ~ 358 and ~ 336 Ma (Table 1). Several closely spaced pulses of molybdenite formation can be distinguished in these samples. Since most of the model ages, except run CT-296A, are within the 2-sigma uncertainty of the K1–K3 emplacement age one possible interpretation could be that, similar to the K1–K3 ores, molybdenite formation is intrusion-related and part of the magmatic-hydrothermal process. This interpretation, however, is not supported by textures in the K2 ores (Fig. 4d–f). These show that molybdenite in the K2 ores is associated with Mo-rich *Scheelite 1* as well as Mo-poor *Scheelite 3* and that all these ore minerals are aligned in the mylonitic foliation (Fig. 3b). Hence, part of the molybdenite, at least in this sample, could be the product of metamorphic recrystallisation of Mo-bearing scheelite to Mo-free scheelite, a process continuously or episodically liberating Mo from the scheelite structure and making it available for the formation of molybdenite.

We think that most molybdenite ages in the K2 ores therefore date recrystallisation of scheelite related to protracted Variscan regional metamorphism and coeval deformation and eventually syn-tectonic magmatic-hydrothermal processes. To some degree the observed large variation in the data could also reflect mixing of molybdenite grains of slightly different age and origin. In our opinion, banded K2 ores are best interpreted as shear zone-hosted mylonitic quartz-scheelite ores and the Re–Os ages constrain prolonged formation of molybdenite to the Late Devonian/Early Carboniferous.

Because the yellowish fluorescent scheelite porphyroclasts (texturally they are comparable to *Scheelite 1* from the Eastern ore field) in the K2 ores are still undated it cannot be excluded that this scheelite is pre-Variscan in age. The two model ages of 355 and 358 Ma in K2 samples (Table 1) indicate that there could be an older molybdenite component present in K2 samples from the Western ore field, but the age of this component is not pre-Variscan.

Re–Os isochron ages and weighted mean ages, even with their relatively large uncertainties, indicate that formation of molybdenite, (emplacement of) the K1–K3 granite, development of a magmatic-hydrothermal vein system and Variscan regional metamorphism and deformation must have been broadly coeval. In summary, our results reflect the importance of combined Early Carboniferous magmatic and metamorphic processes for formation of the Felbertal W deposit.

Polymetamorphism in the Tauern Window?

Early studies (e.g., Frasl and Frank 1966) assumed a single Alpine phase of Barrovian type regional metmorphism in the Tauern Window, which reached upper greenschist to lower amphibolite facies conditions. At the northern margin of the Tauern Window in the Felbertal area (at Hintersee, a few kilometers to the south of the mine) metamorphic temperatures, ascribed to the Young Alpine overprint, were ~ 600°C (Hoernes and Friedrichsen 1974). This dominant regional metamorphism (''Tauernkristallisation'') in the Tauern Window is of Young Alpine age (~ 30–40 Ma, e.g., Grundmann 1989; Inger and Cliff 1994). At Felbertal this Young Alpine overprint of the scheelite deposit was dated at 29 ± 17 Ma (Sm–Nd scheelite, Eichhorn et al. 1995). This age is within error of 31 ± 5 Ma Sm–Nd and 30 ± 1 Ma Rb–Sr garnet-whole rock isochron ages from the K1–K3 orthogneiss (Eichhorn et al. 1997). From these data it is beyond doubt that the Felbertal scheelite deposit was affected by Young Alpine metamorphism but the question remains to what extent it was also overprinted by pre-Alpine metamorphism.

Variscan medium- (to high?) grade metamorphic assemblages have been documented from the Zwölferzug (Pestal 1983), which is a separate unit within the Habach terrane ~ 5 km N of Felbertal (Fig. 1). Garnet-bearing assemblages there were dated at 336 ± 32 Ma (Sm–Nd garnet-whole rock isochron, von Quadt 1992). U–Th–Pb electron microprobe ages of monazite yielding 373 ± 15 Ma (Finger and Bankhammer 2003) were interpreted as recording Devonian high-grade metamorphism.

Unequivocal evidence for Variscan mineral assemblages and coeval deformation in the Habach terrane was presented by Grundmann and Morteani (1982) from the Habachtal (about 15 km W of Felbertal). Discontinuously zoned, two-stage prograde garnets preserve synkinematic inclusion trails and are associated with andalusite (now pseudomorphosed to muscovite). Because of the regional-scale distribution of this assemblage and the enormous grain size of these andalusite pseudomorphs Grundmann (1989) favoured formation of this low-P assemblage during regional low-P metamorphism rather than contact metamorphism. *P–T* conditions of 420°C and 2 kbar were estimated for this low-P regional metamorphic event in the neighbouring Hollersbachtal (Koller and Richter 1984). From these regional observations and data it is obvious that the Habach terrane records polyphase metamorphism.

Other arguments for Variscan metamorphism and deformation of the Felbertal tungsten deposit are: (1) Three deformation events and two stages of garnet growth are distinguished in the Eastern ore field. The first garnet stage is characterised by folded inclusion trails of low-grade mineral assemblages in garnet cores and the second stage by inclusion-free rims (Thalhammer et al. 1989, p. 1163). (2) Field relationships between a metamorphosed dacitic dyke dated at ~ 340 Ma and metabasites in the Western ore field document that emplacement of the dyke post-dated formation of the prominent foliation in the metabasites (see Fig. 5 in Eichhorn et al. 1999a). (3) *Scheelite* 3 was dated at 319 ± 34 (Eichhorn et al. 1997); this scheelite generation formed synkinematically during metamorphic recrystallisation of *Scheelite 1* and *2*. Due to a lack of quantitative petrological data the grade of Variscan metamorphism cannot be ascertained at this time. If the yet undated first garnet stage in the Eastern ore field is Variscan, this event must have reached at least upper greenschist to lower amphibolite conditions.

Our Re–Os molybdenite ages support the importance of Variscan metamorphism in the central Tauern Window and associated with the Felbertal scheelite deposit. Our preferred interpretation is that the Re–Os ages record polyphase formation of molybdenite and that some of the molybdenite formed by metamorphic breakdown from Mo-bearing Scheelite 2. If this metamorphic molybdenite formation were related to the Young Alpine metamorphic overprint we would expect to have found Young Alpine Re–Os ages. On the contrary, the youngest Re–Os ages obtained are ~ 336 Ma. To conclude, there is good evidence that part of the structural inventory and metamorphic assemblages in the central Tauern Window are of Variscan age though there is still some uncertainty regarding the grade of this metamorphic event at Felbertal.

Conclusions

1. High precision Re–Os model ages for molybdenite from the Felbertal tungsten deposit range between ~ 358 and ~ 336 Ma and distinguish several phases of molybdenite deposition. These are interpreted as reflecting several episodes of Variscan metamorphic and/or magmatic-hydrothermal molybdenite formation. Molybdenite formed as early as ~ 358 Ma, but most ages indicate deposition at ~ 345–335 Ma. Recrystallisation of Mo-bearing yellowish fluorescent scheelite (*Scheelite 1*, *Scheelite 2*) to Mo-poor bluish fluorescent scheelite (*Scheelite 3*) during Variscan regional metamorphism provided Mo for formation of metamorphic molybdenite.
2. Two ~ 344 Ma Re–Os model ages for molybdenite that is not immediately associated with scheelite, obtained from the K1 ore body, confirm the Early Carboniferous age of this economically important tungsten ore body at Felbertal and support a genetic relationship with the Early Carboniferous K1–K3 orthogneiss. The orthogneiss may represent a highly fractionated and subsequently deformed granite intrusion (favoured by JGR) or, alternatively, this quartz-rich deformed microcline–muscovite gneiss may represent leucosomatic material derived during Variscan metamorphism (favoured by HJS). In turn, this interpretation leads to a proposed intrusion-related (+ subsequent metamorphic overprint) model for Felbertal (JGR) versus a purely metamorphic model for the W–(Mo) mineralisation (HJS).
3. Attempts to date Mo-bearing *Scheelite 1* from the laminated scheelite-rich quartzitic ore in the Eastern ore field using Re–Os were unsuccessful as Re and Os concentrations were at or near blank level. As there is no molybdenite associated with *Scheelite 1* from the Eastern ore field the age of this molybdenite-free ore stage is still unconstrained.
4. However, molybdenite associated with scheelite from banded quartz-scheelite mylonites from the K2 ore body in the Western ore field, regarded as equivalent to the scheelite-rich quartzite of the Eastern ore field, gave Variscan ages. This

molybdenite formed from continuous or episodic metamorphic recrystallisation of Mo-bearing scheelite.

5. Variscan regional metamorphism, magmatism, and deformation (e.g., formation of mineralised shear zones) in the central Tauern Window is confined to ~ 360–335 Ma by our data. This age range for regional metamorphism compares well with other parts of the European Variscides outside the Alps.

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