Field Trip Pre-EX-5

Tungsten deposit Felbertal, Salzburg, Austria

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1 Introduction

The Felbertal scheelite deposit in the Eastern Alps is one of the biggest producing tungsten deposits outside China. Wolfram Bergbau- und Hütten AG (WBH) operates the Felbertal scheelite mine since 1975. Current annual production from the underground mine is about 500,000 tonnes of ore grading 0.3 wt.% WO_3; in total about 16 million tonnes of ore have been produced so far.

The deposit is best described as stockwork mineralisation and diffuse dissemination of scheelite in polymetamorphic Early Palaeozoic rocks (mainly metabasites) intruded by Cambrian and Early Carboniferous granitoids. More continuous quartz-rich layers with fine-grained “sheeted” mineralisation parallel to the foliation were also mined in the past. Initially, Felbertal was classified as syngenetic exhalative-sedimentary tungsten deposit genetically related to mafic volcanism but nowadays epigenetic magmatic-hydrothermal models are favoured relating ore formation to Variscan granites. The Felbertal deposit is best interpreted as a poly-metamorphosed granite-related stockwork type tungsten deposit. There is accumulating evidence supporting a genetic relation of tungsten mineralisation with evolved Lower Carboniferous granites.

Key features of the ore deposit will be visited on this field trip. This guide is based on an older field guide (Raith and Schmidt, 2010) and a summary (in German) on Felbertal tungsten deposit available online on the IRIS data base (Weber and al., 2015). New results obtained during a recent project are also integrated (Kozlik, 2015).

2 History

The Felbertal deposit was discovered in 1967, following systematic exploration based on a conceptual model that put the target in connection with a submarine-exhalative “W-Hg-Sb formation” associated with mafic volcanism (Maucher, 1965). Until 1964, scheelite was known in Austria only from the magnesite-scheelite deposit at Tux, Tyrol, from the small gold-scheelite occurrences at Schellgaden, Salzburg and as a rare mineral in Alpine veins. All these occurrences were found by chance. At Tux, scheelite was mined in small quantities as by-product to magnesite intermittently from the 1950s until 1976. There, scheelite occurred in tectonically disrupted metacarbonate layers within low-grade phyllites and black schists of Upper Silurian to Lower Devonian age (Wenger, 1964; Höll and Maucher, 1968; Pirkl, 1986; Raith et al., 1995).

In the mid-1960s, two academic groups started with scheelite prospection in the Eastern Alps in Austria, one from Montanuniversität Leoben, the other from the University of Munich both using panning of stream sediments and subsequent UV lamping. In mountainous terrain, this is a cheap and fast method to determine the approximate location of scheelite occurrences. To identify the accurate position of the outcropping mineralisation requires subsequent night prospection with UV lamps.

Elevated scheelite contents were discovered in various stream sediments in the Upper Pinzgau area of the Hohe Tauern by both groups. The group around Rudolf Höll and Albert Maucher from the University of Munich alone tested some 370 creeks and brooks in the Hohe Tauern area of Salzburg, 153 of which contained scheelite.

On 27 July 1967, the Munich team tested the Felberbach at the junction of the Felber valley with the Salzach valley near Mittersill and discovered an unusually high concentration of scheelite (Höll, 1998). At that time, the UV lamps had much shorter operation periods than nowadays, and only a few additional samples could be tested. This allowed to exclude the Amerbach tributary and the uppermost ranges of Felber valley as source for the anomaly. The last sample was taken close to Tauernhaus Spital, near the entrance of the current underground mine. Here, a very high amount of scheelite detritus was observed, and the first scheelite-bearing boulders were discovered. By 6 August 1967, the ore bolder deposit (slightly dislocated scree in the Eastern Ore Zone) had been discovered and the outcrops of Eastern and Western Ore Zone delineated.

Following the discovery of the Felbertal deposit, mining rights were secured by Metallgesellschaft AG (Frankfurt, Germany) and detailed exploration of the deposit started. After 3000 m of diamond drilling (Fig. 1 b) and 700 m of exploration drifting, WBH was founded in 1975, as a joint venture between Metallgesellschaft AG (Germany), VOEST-Alpine AG (Austria) and Teledyne Wah Chang Corp. (USA). Following several changes in ownership, WBH now belongs to the Swedish Sandvik group.

Mining at the Eastern Ore Zone open pit mine started in 1975 (Figs. 1 c, d), the flotation plant became operational in 1976, and development of the underground mine in the Western Ore Zone commenced in 1977. Right from the beginning the company aimed to become an integrated producer of downstream tungsten products (tungsten carbide and tungsten powder), therefore a refining plant was constructed in the late 1970s at Bergla, Styria, some 320 road-kilometres east of Mittersill.

Due to the harsh climatic conditions, mining in the open pit was seasonal, from May to October only. By 1986, the upper Eastern Ore Zone had been mined out after a production of 2.5 Mt of ore grading 0.6 wt.% WO_3 at a strip ratio (waste / ore) of less than 1.5:1.

The underground mine was developed as modern trackless LHD operation. Initially, the dimensions of the Western Ore Zone were poorly known, and the first objective was underground exploration. Delineated resources increased from 0.9 Mt in 1976 to >9 Mt in 1983. Due to its location close to the Nationalpark Hohe Tauern and in an area of elevated avalanche risk, all auxiliary infrastructure such as change rooms, workshops and offices are located underground. The mining area is connected to the mill site by means of a 3 km long conveyor decline. With exception of the period between February 1993 and June 1995, the mine was continuously in operation.

Triggered by this major discovery, various exploration campaigns covered relevant portions of the Eastern Alps and a number of smaller scheelite occurrences were discovered in the following years (e.g., Neinavaie et al., 1985). However, no further significant economic orebody was discovered, and with the decline of tungsten prices in the early 1980s, these campaigns were largely abandoned.

3 Geological setting

3.1 Pre-Variscan units in the Tauern Window

The Alps formed due to subduction of a Mesozoic ocean and collision of the European and the Adriatic plates in the Cretaceous to Neogene. This collision belt was caused by convergence of the Adriatic continental upper plate and a subducting lower plate including the Mesozoic ocean and the European passive continental margin (Fig. 2, Dal Piaz et al., 2003; Schmid et al., 2004). The core of the collision zone is represented by the Penninic/Austroalpine wedge, a fossil subduction complex, consisting of continental and minor oceanic units thrust on the Molasse foredeep and European foreland. It is part of the Europe-vergent belt separated from the Adria-vergent Southern Alps, (non-metamophosed thrust-fold-belt and Neogene sediments) by the Periadriatic (Insubric) lineament (Dal Piaz et al., 2003).

In the Eastern Alps the Austroalpine tectonic units are overlying Penninic/Subpenninic and Helvetic units. In the internal zone of the orogen these units are exposed in several tectonic windows, the largest (160 x 40 km) being the Tauern Window (Fig. 2). The three major units in the Tauern Window are: (1) Pre-Variscan basement rocks, (2) Igneous rocks of Variscan age (Zentralgneis, *ca.* 360 – 270 Ma), (3) Permian to Mesozoic auto- to allochtonous sequences. They have all been metamorphosed during the Alpine orogeny and form a complex tectonic nappe system (Schmid et al., 2004; Schmid et al., 2013).

Pre-Mesozoic polymetamorphic basement rocks are widely exposed in the central Tauern Window in the *Habach Complex* (Habachserie Frasl, 1958). In the Felbertal area this complex was subdivided (from bottom to top) into the following units overlying a basal amphibolite member (Basisamphibolit) (Höll, 1975; Höll, 1977):

- Basal schist (Basisschieferfolge)
- Volcanic rock sequence (Eruptivgesteinsfolge)
- Phyllites (Habachphyllit)

Later the Volcanic rock sequence was subdivided and renamed into the Lower and Upper magmatic sequence (Kraiger, 1989; Höck et al., 1993). The Upper magmatic sequence is now assigned to the Variscan orogenic cycle (Fig. 3).

3.2 Central Gneisses

During the Variscan orogeny granitoids (Zentralgneis), classified as I-type and to a minor extent as S- and A-type granitoids (Finger and Steyrer, 1988; Finger et al., 1993) intruded these Late Proterozoic to Early Palaeozoic sequences (Fig. 3). They formed due to Variscan collision and amalgamation of northern Gondwana with Laurasia-Avalonia (Eichhorn et al., 2001). In the Tauern Window these igneous rocks were emplaced between the Upper Devonian and the Permian. Most widespread are high-K I-type metagranitoids falling into two age groups: Early (≈340 Ma) and Late Carboniferous (≈310 Ma) (Eichhorn et al., 2000). S-type granites are rare; the largest one being the Granatspitz gneiss, which forms a km-size dome structure to the SE of Felbertal tungsten deposit (Fig. 3). The age of this metagranitoid is debated: Permian (Eichhorn et al., 2000) vs. Late Carboniferous (314 Ma, Kebede et al., 2005; Kozlik et al., 2016b). Permian granites with A-type affinities are rare and have been related with post-orogenic crustal extension (von Quadt et al., 1999). Some metagranitoids in the Felbertal area such as the Felbertal augengneiss (Figs. 3, 4) or the K1-K3 orthogneiss (K1 Gneis) in the Western Ore Zone were emplaced during the Early Carboniferous (see below).

3.3 Metamorphic events in the Tauern Window

The dominant Barrovian-type regional metamorphism in the Tauern Window is of Young (Neo-) Alpine age (≈30-40 Ma, e.g., Grundmann, 1989; Hoinkes et al., 1999; Inger and Cliff, 1994); it reached upper greenschist to lower amphibolite facies conditions. Subduction-related high-pressure metamorphism in the Tauern Window is restricted to the Eclogite zone at the southern margin of the Tauern Window and to the Glockner nappe. For the polymetamorphic rocks at Felbertal P-T conditions of up to 530°C and 5-6 kbar were reported (Thalhammer et al., 1989). Metamorphic temperatures of 600°C were reported from Hintersee about 1 km to the S of the mine (Hoernes and Friedrichsen, 1974).

The extent and timing of pre-Alpine metamorphic events in the Habach Complex and related basement units in the Tauern Window is still debated. First evidence for polyphase metamorphism was provided by Grundmann and Morteani (1982) and P-T conditions of 420°C and 2 kbar were reported by Koller and Richter (1984). A Sm-Nd isochron age of 336 ± 32 for rocks from the Zwölferzug (Fig. 3) provides geochronological evidence for Variscan metamorphism in the Tauern Window (von Quadt, 1992). Re-Os molybdenite ages between ≈335 to 340 Ma confirm that the dominant metamorphic overprint of the Felbertal deposit is Early Variscan in age (Raith and Stein, 2006).

A Sm-Nd isochron age of 319 ± 34 Ma (Eichhorn et al., 1997) for one of the four scheelite generations (Scheelite 3, see below) was also attributed to Variscan regional metamorphism and so were ages as young as 282 ± 2 Ma (U-Pb dating on titanite, Eichhorn et al., 1995). Recent dating of uraninite inclusions within zircon from the Felbertal mine yielded a surprisingly young age of 268 ±13 Ma; this age was interpreted as a low-temperature thermal overprint (Finger et al., 2017).

Evidence for a pre-Variscan metamorphic event was recorded from other areas in the Tauern Window. Migmatitic leucosomes with 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. Moreover, von Quadt et al. (1997) reported eclogites of Silurian age (≈420 Ma).

4 Geology of Felbertal tungsten deposit

The two main geological units in vicinity of the ore deposit are: (1) Metamorphic rocks of the Habach Complex and Stubach Group.; (2) Metagranitoids and associated metavolcano-sedimentary sequences formed during the Variscan orogeny.

The *Basal amphibolite* (Basisamphibolit, a member of the Stubach Group) is underlying the Habach Complex to the S of the tungsten deposit. It shows MORB characteristics and formed in a back-arc setting (Frisch and Raab, 1987; Ordosch, 2017). Its age is controversial. Based on discordant U-Pb zircon ages (657-486 Ma, von Quadt, 1992) it was regarded as an equivalent of the Habach Complex. In contrast, concordant in-situ U-Pb zircon ages yielded 351-343 Ma (Kebede et al., 2005); this would indicate that the protoliths formed during the Variscan orogenic cycle.

The *Basal schist* (Basisschiefer; synonymous to Biotitporphyroblastenschiefer, Eiser Sequenz) is an up to 500 m thick sequence of metasediments (micaschist, paragneiss, graphitic quartzite) with intercalations of mafic to felsic volcanic rocks formed in a continental island arc (Gilg et al., 1989) or active continental margin setting (Höll and Eichhorn, 2000) (Fig. 4). The Late Devonian maximum sedimentation age indicates that the protoliths of these rocks were deposited during the initial stages of the Variscan orogeny (Kebede et al., 2005).

The *Magmatic sequence* (formerly Volcanic rock sequence, "Eruptivgesteinsfolge", Höll, 1975; Höll, 1977) consists of various meta-igneous and subordinately of metasedimentary rocks and is up to 4500 m thick. Fine-grained amphibolites predominate in the lower part, whereas various amphibolites, orthogneisses, and minor meta-pyroclastics and metasediments are more common in its upper part. This sequence is now subdivided into the Lower magmatic sequence (LMS) and Upper magmatic sequence (UMS, Kraiger, 1989; Höck et al., 1993; Pestal et al., 2009). The LMS includes a meta-ophiolite sequence with metamorphosed ultramafic to mafic igneous rocks; *i.e.,* serpentinite, hornblendite, coarse-grained amphibolite (metagabbro), fine-grained amphibolite (mafic dykes and eruptive flows). The amphibolites are tholeiitic in composition showing MORB affinities (with possible influence of a subduction component) and they formed in a marginal oceanic or back arc basin. The UMS consists of mafic to felsic metaigneous rocks (amphibolite, prasinite, biotite-epidote gneiss, albite gneiss, meta-agglomerate) with intercalations of siliciclastic sediments (micaschist, phyllite). Geochemical data indicate calc-alkaline characteristics and magma generation in a mature arc system, likely in a continental arc. The arc sequence grades into the overlying Habach phyllites, which consist of dark phyllites, micaschists, quartzites with local intercalations of mafic to felsic metavolcanics. The Habach phyllites either formed in an accretionary wedge or an intra-arc/back arc setting (Kupferschmied and Höll, 1994). The stratigraphic assignment to the Late Proterozoic (U. Riphaean-L. Vendian) based on archritarchs (Reitz and Höll, 1988) was not confirmed by U-Pb zircon dating (Kebede et al., 2005).

U-Pb dating and field observations revealed the intrusive nature of some of the orthogneisses in the LMS and UMS, which formerly were all interpreted as felsic metavolcanics. These orthogneisses largely represent I-type granitoids of Cambrian age, which are about 20 million years younger than the fine-grained amphibolites (for details see Höll and Eichhorn, 2000).

5 Ore deposit characteristics

The Felbertal scheelite deposit is situated in the upper ranges of the Felber valley, a tributary of the Salzach, some 10 km south of Mittersill, Austria. It is located in the Hohe Tauern at an outcrop elevation of 1175 to 2200 m. The Felber valley separates the deposit into two sectors, the Eastern and the Western Ore Zone (Fig. 1 a; Fig. 4). The Felbertal scheelite deposit is restricted to the bottom ~400 m of the Magmatic sequence ("Scheelit-führende Serie", Höll, 1975). The host rocks in both ore zones are fine-grained amphibolites (metabasalts) interlayered with coarse-grained amphibolite (Grobkornamphibolit, metagabbro), hornblendite (mafic metacumulate rock?) as well as leucocratic orthogneisses (metagranites, felsic metavolcanics; Fig. 4).

5.1 Eastern Ore Zone

In the Eastern Ore Zone (Ostfeld) hornblendite / coarse-grained amphibolite (Unterer and Oberer Hornblendit-Zyklus) alternate with schists and gneisses. The following succession of rocks has been mapped (Höll, 1975).

- Hangingwall schist
- Upper hornblendite cycle
- Intermediate Schist (Zwischenschiefer)
- Lower hornblendite cycle
- Footwall schist

Thalhammer et al. (1989) distinguished three hornblendite / coarse-grained amphibolite units alternating with fine-grained amphibolite / gneiss units (referred to as metavolcano-sedimentary units); this whole succession is tectonically imbricated. Various gneisses, derived from intermediate to acidic igneous protoliths, form elongate lenticular bodies and layers in the metabasites. A thicker orthogneiss body (Ostfeldgneis) underlies the lowermost hornblendite unit. Whereas in the early days all gneiss intercalations were interpreted as of volcanic origin, this leucocratic orthogneiss has been recognised as intrusive and was dated at 529 ± 17 Ma (Eichhorn et al., 1999a). For some metabasalts a boninitic origin was suggested (Thalhammer, 1987).

The Eastern Ore Zone was mined as an open pit operation between 1975 and 1986 (Figs. 1 c-d). It consisted of a discontinuous (?), elongate and slope-parallel WNW plunging ore body exposed between 880 m and 2240 m altitude; it was mined above 1700 m altitude. Post-glacially dismembered and displaced ores (Obere Erzblockschutthalde) as well as an about 30 m thick in-situ ore body were mined. The mined part of the ore zone in the Eastern Ore Zone was about 1000-1200 m long, less than 200 m wide and max. 30 m thick striking about WNW-ESE and plunging 25 to 55° WSW; *i.e.,* about subparallel to the mountain slope (Fig. 4). Metabasites alternate with various gneisses in the mineralised zone (Fig. 5). High-grade mineralisation (>2 wt.% WO_3, up to 10 wt.% in individual hand specimens) was hosted by an unusual lens-shaped (900 m x 50 m x up to 8 m) sheeted quartz mass showing fine mm-scale foliation (Quarzitisches Scheelitreicherz, Höll, 1975) mainly composed of fine-grained scheelite and quartz (Figs. 6 a, b).

Elongate scheelite grains in the foliated ore form mm-sized porphyroclasts and are partly re-crystallised together with the enclosing quartz matrix (see below). Thus, this ore texture is rather mylonitc – i.e. deformation-related – and not primary sedimentary (Höll et al., 1972) or reflecting banding caused by scheelite-quartz precipitation in fluid over-pressured open cavities (Höll and Eichhorn, 2000).

These foliated scheelite-quartz ores are spatially associated with zones of intense quartz veining forming an about 400 m wide stockwork zone (Fig, 5; 6 c). This stockwork zone was interpreted as a feeder zone underlying the foliated ores (Höll and Eichhorn, 2000). However, drill core loggings from the early days of exploration confirm that this stockwork-like scheelite mineralisation extends laterally as well as into the hanging wall of the foliated scheelite ores (Fig. 5, also see profiles in Höll, 1975). Although the highest tungsten concentrations were found in the foliated ore the whole quartz-veined sequence is mineralised and a ~200 m wide zone within the stockwork zone was also mined (Fig. 5).

Re-Os model ages of molybdenite from the stockwork zone range between 337-343 Ma (Raith and Stein, 2006). In situ-dating of relict scheelite cores (Scheelite 1) from the foliated scheelite ore yielded 335.5 ± 4.6 Ma (Raith et al., 2011). This Early Carboniferous age of scheelite rebut the idea that these ores formed during a Cambrian ore stage, a view repeatedly expressed by researchers from Munich (Eichhorn et al., 1995; Eichhorn et al., 1997; Eichhorn et al., 1999a; Höll and Eichhorn, 2000).

5.2 Western Ore Zone

In the Western Ore Zone (Westfeld) scheelite is only mined in the active underground mine. The mineralised zone (300 x 500 m in cross section) plunges at medium angles to WNW (Fig. 7). It has been mined for more than 850 meters along the plunge direction. In 2018 the deepest level of the mine was at 625 m. The downdip extension of the deposit is unknown. In the early days 8 distinct ore bodies (labelled K1 to K8) were distinguished and selectively mined. However, with increasing depth some of the ore bodies merge (Fig. 7).

Mineralisation is pervasive and the ore bodies are defined by the actual cut-off grade. Economic grades are commonly found in zones with intense quartz veining (Quartz 1) (Figs. 8 a-c, Figs. 12 c, d, Figs. 13 a, b).

The Western Ore Zone is divided into three major tectonic units (Fig. 9). A barren wedge of Basal schists (Basisschieferschuppe) separates two mineralised wedges each containing several ore bodies (Schmidt, 1988); ore bodies K1 to K4 are located in the upper wedge and K5 to K8 in the lower one. K1 and K3 ores were mined at the contact of the Variscan K1-K3 orthogneiss to the host rocks. The horse-shoe shape (in plan-view) of this gneiss is caused by a large-scale Alpine (?) fold structure with an about SW plunging fold axis. The K1-K3 orthogneiss can be traced to depths of about 950 in the mine (Fig. 10) though smaller orthogneiss lenses have been discovered at even deeper mine levels more recently. The leucocratic orthogneiss is strongly foliated, especially at its margins (Fig. 11 a). In less deformed parts apophyses and intrusive contacts have been preserved (Fig. 11 d). Elongate to planar lenses and rafts of non-mineralised host rocks occur as deformed xenoliths in the K1-K3 orthogneiss (Fig. 11 a). These observations confirm the intrusive nature of the gneiss protolith. A chemically very similar orthogneiss is exposed in the Eastern Ore Zone (Kozlik and Raith, 2017).

Two ore bodies (K1-K3) of major economic importance were spatially associated with the K1-K3 orthogneiss. They are structurally controlled by NE-SW and E-W trending shear zones, preferentially developed at the margins of the gneiss (Fig. 9) and the host rocks that converge towards deeper levels in the mine. Metre-thick foliated masses of pure quartz are developed at the margins and within the gneiss. The major quartz mass within the K1-K3 orthogneiss has a lens-like morphology and plunges at about 45° to NW/NNW (Schenk, 1990a); it extends to >300 m towards depth and is up to 30 m thick. Main scheelite in the K1-K3 ores (Scheelite 2, see below) forms large up to cm-sized porphyroclasts and is of greyish colour, fatty lustre and yellowish fluorescence. This type of scheelite has been observed in deformed scheelite-quartz veins within the Lower Carboniferous K1-K3 orthogneiss (Figs. 11 b, c) thus excluding a pre-Variscan age of this mineralisation. Locally bluish beryl occurs in these veins (Fig. 11 f).

The K2 ore body includes foliated scheelite-quartz ores, quartz veins and a W-rich breccia (Figs. 12 a, b). Fine-grained scheelite and quartz are strongly re-crystallised defining a mylonitic fabric. Scheelite porphyroclasts (several mm in size, yellowish fluorescent) re-crystallised to fine-grained scheelite (bluish fluorescent) which is aligned in stringers (Fig. 12 b). Elongate to planar xenoliths of metabasites included in the scheelite-quartz masses are scheelite-free. These ores resemble the foliated high-grade scheelite-quartz ores from the Eastern Ore Zone (Figs. 6 a, b). In the upper nowadays inaccessible mine levels the foliated K2 ores were associated with a scheelite-bearing strongly deformed metabreccia. The latter was interpreted as volcanic eruption breccia (Eruptionsbrekzie) and the associated foliated ores as exhalites (Höll and Schenk, 1988; Schenk and Höll, 1989); *i.e.,* as syngenetic ores. An alternative explanation is that these ores are scheelite-quartz mylonites and that the associated breccia could either be of tectonic or of magmatic-hydrothermal origin. The K2' ore body is a set of deformed dm-thick composite quartz veins. Scheelite is concentrated in the marginal parts of the deformed veins. In February 2009 it was exposed at level 775 (Figs. 8 a-c).

An E-W oriented ore body in the immediate hanging wall of the Basisschiefer wedge is referred to as K4. The K4 ores are either alternations of metabasite and gneiss with intense Quartz 1 veining (*e.g.*, level 1164; Figs. 12 c, d) or shear zones; the latter are exposed in the hangingwall of the Basisschiefer wedge where they form a 30-40 m thick tectonised zone mainly composed of cataclastic biotite-chlorite schists containing tectonic lenses of more competent rocks (*e.g.,* coarse-grained amphibolite).

More recently, the so-called SD-gneiss (scheelite-dotted gneiss) was delineated as separate mineralisation. It is a fine-grained biotite-albite gneiss with dissemination of scheelite largely independent from quartz veining and characteristically intersected by barren xenolithic fragments of mafic (amphibolitic) material (Kozlik, 2015). This gneiss body can be traced from level 1201 to the very bottom of the mine at level 625. Tungsten content increases with depth, with occurrences below level 880 of economic interest. At level 625 the size of the orebody on plan view is about 15 x 90 m.

Ore bodies K5 to K8 are located in the lower ore-bearing wedge in the footwall of the Basisschiefer wedge. In the K5 ore body scheelite occurs often in stockwork like Quartz 1 veins mainly in coarse grained amphibolite, as well as disseminated in the metabasites. In addition, intercalations of metre-thick mineralized orthogneisses were observed on level 1050 and 1065 (Fig. 12 f).

The K6 orebody can be interpreted as an equivalent to the K2 orebody from the hangingwall unit. Emplaced within the intermediate schists in the footwall of the Basisschiefer wedge it has been mined from level 1065 to level 883. The mineralisation is also associated with strongly deformed breccia, surrounded by foliated scheelite-quartz veins.

With increasing importance for the production at Felbertal, K7 is with a strike length of over 250 m the laterally most extensive orebody. At its centre it has a width of about 30 m, while it tapers off to the East and West. The ore is characterised by cm thick quartz veins apparently bedded within the intermediate schist unit. However, the strike of the quartz veins is slightly different compared to the strike of the hornblende schist. The hangingwall contact is marked by a set of brittle cm wide faults that are characterised by an infill of calcite. Other than the remaining orebodies (plunging to WNW), the K7 follows the NW-dip of the main units and thus recedes from the centre of the deposit.

In the K8 area, small but very high-grade mineralisation was recently discovered between levels 940 and 1000 and of lesser grade between 700 and 757. Many different rock types can be observed within these mineralised zones, while scheelite is usually connected to quartz and locally very coarse grained (cm size).

5.3 Scheelite stages and their postulated ages

Initially, three and later four stages (generations) of scheelite were distinguished at Felbertal (Höll et al., 1972; Höll, 1975; Höll et al., 1987; Schenk, 1990b; Schenk and Höll, 1991; Höll and Eichhorn, 2000; Raith and Stein, 2006; Raith and Schmidt, 2010; Kozlik et al., 2016a):

Scheelite 1 is fine-grained (up to 0.4 mm), white with yellowish-white fluorescence and has Mo contents of around 0.3 to 1.8 wt.% (mean 1.1 wt.% Mo) and shows fine-scale oscillatory zoning under cathodoluminescence (CL; Fig. 14 a). It has been reported from the foliated scheelite ores and underlying stockwork mineralisation in the Eastern Ore Zone. In the Western Ore Zone the foliated scheelite-quartz ores from the K2 ore body can be regarded as possible equivalents (Fig. 14 b). It is typically associated with metamorphic scheelite (Scheelite 3), which forms via recrystallisation of older scheelite material or overgrowths (Figs. 14 a, b). 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). A Cambrian age has repeatedly been postulated for Scheelite 1 (Eichhorn et al., 1995;

Eichhorn et al., 1999a; Höll and Eichhorn, 2000). An in-situ U-Pb age of scheelite yielded 335.5 ± 4.6 Ma (Raith et al., 2011) and proves the Variscan age of this scheelite stage.

Scheelite 2 is fine- to coarse-grained (up to cm scale), grey with greasy lustre, yellow fluorescent with 0.1 to 1.7 wt.% Mo substitution. It is widespread in the Western Ore Zone and less common in the Eastern Ore Zone. Sometimes growth zoning can be observed in CL (Fig. 14 c). Scheelite 2 often exhibits brittle deformation with micro-fractures filled with Scheelite 3 (Fig. 14 d). Scheelite 2 was originally thought to be of Cambrian age (e.g., Eichhorn et al., 1995) but was later accepted to be of Early Carboniferous age (e.g., Eichhorn et al., 1999a) when it was clear that scheelite-quartz veins with Scheelite 2 crosscut the ≈340 Ma K1-K3 orthogneiss (Figs. 11 b, c).

Scheelite 3 commonly occurs as rims and overgrowths or fracture fillings within Scheelite 1 and *2* (Figs. 14 a, b, d, e). It is grey to white with blue fluorescence reflecting its low Mo content. It is often associated with fine-grained molybdenite, which formed from metamorphic breakdown of Mo-bearing Scheelite 1 and 2 (Schenk, 1990b; Raith and Stein, 2006). Under CL it shows much brighter luminescence than Scheelite 1 and 2. Diffuse zoning can be seen in recrystallised Scheelite 3 grains (Fig. 14 f). In foliated ores it is intimately intergrown with Scheelite 1 and aligned in the foliation. The Sm-Nd isochron age of 319 ± 34 Ma of Scheelite 3 is interpreted as the age of metamorphic recrystallisation of older scheelite material during Variscan metamorphism (Eichhorn et al., 1997).

The Sr isotope composition of Scheelite 1-3 is quite radiogenic. The $^{87}Sr/^{86}Sr$ ratios of Scheelite 1 range from 0.72078 to 0.76417, of Scheelite 2 from 0.70724 to 0.76832 and of Scheelite 3 from 0.74331 to 0.80689 (Kozlik et al., 2016a).

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 (Quarz 2, Figs. 13 d-f) and has been interpreted as scheelite mobilised during Alpine regional metamorphism. The Neo-Alpine age of Scheelite 4 is supported by an imprecise Sm-Nd isochron age of 29 ± 17 Ma (Eichhorn et al., 1997).

In summary: The stages 1 to 3 are all of Variscan (Early Carbonifereeous) age. The age of Scheelite 1 and 2 is not resolvable and both are interpreted as magmatic-hydrothermal scheelites. Stage 3 and 4 formed during the subsequent Variscan and Alpine regional metamorphic overprints of the Felbertal deposit.

6 Petrography, geochemical characterisation and age of the host rocks

This summary is mostly based on the review paper by Höll and Eichhorn (2000) with addition of new data from M. Kozlik's PhD thesis (Kozlik, 2015).

6.1 Fine-grained amphibolite

This is the dominant lithology in the Felbertal scheelite deposit (Figs. 13 a, c). These fine-grained (<0.5 mm) banded and foliated rocks are composed of variable amounts of major calcic amphibole, plagioclase, biotite, garnet and epidote group minerals and minor chlorite, muscovite, carbonate, quartz and opaques. Hornblende prasinites and hornblende schists are also grouped with this lithology. Their protoliths in the Lower magmatic series were interpreted as tholeiitic MOR basalts, those of the Upper magmatic series as calc-alkaline volcanic arc basalts (Höck, 1993). Alternatively a pure volcanic/continental arc setting was proposed for the complete magmatic sequence (Fig. 15 a, Höll and

Eichhorn, 2000). Fine-grained amphibolites show flat REE patterns similar to MORB but are enriched in LIL elements, especially in Rb (Figs. 15 b, c). Zircons from a fine-grained amphibolite yielded a U-Pb SHRIMP age of 547 ± 27 Ma interpreted as the emplacement age (Eichhorn et al., 1999a). These rocks therefore are the oldest dated ones in the Habach Complex.

6.2 Hornblendite and coarse-grained amphibolite

Both rock types are of dark green colour and can be coarse-grained forming up to several m thick layers and lenses emplaced as own units between the fine-grained amphibolites and the Basal schists; i.e. Lower and Upper Hornblendite Cycle. Hornblendite units are usually fine grained but can also be coarse grained (ratio about 70:30). Fine-grained amphibolites also occur as intercalations within them. Hornblendites are predominantly (>75 vol. %) composed of calcic amphiboles (hornblende, actinolite) and minor to accessory biotite, plagioclase, carbonate, epidote group minerals and opaque phases. Very rarely, magmatic clinopyroxene relics of possible cumulate origin are preserved. The associated coarse-grained amphibolites are distinguished by higher plagioclase contents and a very coarse fabric (Figs. 12 e, f). These rocks are high in MgO, Cr, V and low in TiO_2. Similar to the fine-grained amphibolites the hornblendites are characterised by flat to slightly LREE depleted REE patterns and also show enrichment in Rb (Figs. 15 b, c). The hornblendites and coarse-grained amphibiolites have been interpreted as metasomatically enriched volcanic arc magmas (e.g., boninites, Thalhammer, 1987). The coarse-grained amphibolites likely are metagabbros A conventional U-Pb zircon upper intercept age of 496 ± 2 Ma from a hornblendite from the Habach Complex was interpreted as the time of the magmatic emplacement (von Quadt, 1992). The coarse-grained amphibolite was dated at 482 ± 5 Ma (Eichhorn et al., 2001).

6.3 Pre-Variscan orthogneisses

Intermediate to felsic orthogneisses occur as several meters thick intercalations throughout the whole magmatic sequence (Figs. 6 d, e). Petrographically, a variety of gneiss types is distinguished including biotite-albite gneiss, epidote-biotite-albite gneiss, hornblende gneiss, muscovite-albite gneiss etc. The gneisses are composed of variable amounts of plagioclase, quartz, biotite, muscovite ± epidote; K-feldspar is only a minor constituent. At the contacts between gneiss and hornblendite biotite- and epidote-richer varieties are developed; these show more intense deformation (Thalhammer, 1987). Their chemical composition indicates that they derived from intermediate to acidic magmas of an Early Palaeozoic arc system; i.e., they show chemical similarities with calc-alkaline I-type volcanic arc granites (Fig. 15 a, Höll and Eichhorn, 2000). Initially, these pre-Variscan gneisses were interpreted as metavolcanics but intrusive contacts and age data rather support a plutonic origin for at least some of them. The leucocratic albite-muscovite gneiss (Ostfeldgneiss; Figs. 6 d, e) underlying the foliated scheelite-quartz ores in the Eastern Ore Zone was dated at 529 ± 17 Ma (Eichhorn et al., 1999a). Orthogneisses in the Western Ore Zone referred to as Older and Younger K2 gneiss are also of intrusive origin. These gneisses are associated with the metabreccia ("eruption breccia"; see above). Gneiss clasts from the breccia were dated at 529 ± 18 Ma, the Younger K2 gneiss yielded an identical age of 529 ± 17 Ma (Eichhorn et al., 1999a).

6.4 Variscan orthogneisses

Variscan metagranitoids are common throughout the Tauern Window. Different types of Zentralgneis have been distinguished in the central Tauern Window based on field relationships, petrography, geochemistry and ages (Finger and Steyrer, 1988; Eichhorn et al., 2000; Kozlik and Raith, 2017).

At Felbertal mine the K1-K3 orthogneiss in the Western Ore Zone testifies to this Variscan magmatic activity. A Rb-Sr whole rock age of 316 ± 10 Ma was the first prove that this granite gneiss is of Carboniferous age (Pestal, 1983). Later Rb-Sr and conventional U-Pb dating on zircons yielded ages of 332 ± 20 Ma and 336 ± 19 Ma, respectively (Eichhorn et al., 1995) which are within the uncertainty of the earlier Rb-Sr age. Recent in-situ U-Pb analyses on zircon of the two varieties of K1-K3 orthogneiss and the associated aplitic gneiss render more precise Early Carboniferous ages between 336-341 Ma (Kozlik et al., 2016b).

The K1-K3 orthogneiss is a medium-grained homogeneous muscovite microcline gneiss containing K-feldspar (microcline), quartz, plagioclase/albite, phengitic mica, biotite and minor epidote-group minerals and garnet (Finger et al., 1985; Kozlik and Raith, 2014; Kozlik and Raith, 2017). Relics of magmatic plagioclase and K-feldspar are sometimes preserved, the other minerals are metamorphic. A biotite-richer dark-coloured and a leucocratic biotite-poor light-coloured variety can be distinguished (Fig. 11 c). In addition, hololeucocratic aplitic gneisses are associated with the K1-K3 orthogneiss (Fig. 11 e). The dark biotite-richer variety is developed towards the peripheral parts of the gneiss body. The intensity of deformation varies within the gneiss, the margins being more prone to intense foliation (Fig. 11 a).

The K1-K3 orthogneiss is characterised by high SiO_2 (70-80 wt.%). The protoliths are metaluminous to peraluminous magnesian monzogranites with calc-alkaline to calcic magma characteristics (Kozlik and Raith, 2017). Chemically it is similar to the Felbertal augengneiss, which is, however, less differentiated. With respect to granite type classification the K1-K3 orthogneiss is ambiguous showing overlapping I- to A-type characteristics (Finger et al., 1985). It has high concentrations of the trace elements Rb, Nb, Ta, Be, Li, Bi, Sn, Cs, Th, Mo and W and shows REE patterns with LREE enrichment, pronounced negative Eu anomalies and flat HREE distribution (Fig. 15 b). Compared to average continental crustal granites the K1-K3 orthogneiss is especially enriched in Cs, Rb, F, U, Nb and Ta (Kozlik and Raith, 2014). Its initial $^{87}Sr/^{86}Sr$ values range from 0.704 to 0.708 and the εNd values from –4 to –6 (Höll and Eichhorn, 2000). The initial εHf_t values vary from −7.6 to −4.3 and indicate a Mid-Proterozoic continental crustal source (Kozlik et al., 2016b).

Compared to the other types of Zentralgneis in the central Tauern Window it becomes clear that the K1-K3 orthogneiss in the mine and the associated hololeucocratic aplitic gneiss are the most differentiated granite melts. Extended magmatic differentiation for example explains the systematic decrease in combined Zr/Hf and Nb/Ta ratios (Fig. 17). The closest chemical and genetic (?) relationships exist with the Felbertal augengneiss. Magmatic differentiation, especially fractional crystallisation, seems to be the key process in forming these evolved melts although fractional crystallisation alone cannot explain the relations between the dark and the light-coloured K1-K3 orthogneiss (Kozlik and Raith, 2017).

Chemical data allow a clear distinction of the K1-K3 orthogneiss and the Cambrian orthogneisses (Briegleb et al., 1985; Finger et al., 1985; Höll and Eichhorn, 2000). Whereas the latter can be interpreted as the intermediate to felsic members of arc related magmatism, the K1 protolith is a specialised syn-orogenic (?) granite with unusual trace element composition.

Dykes crosscutting the older gneisses, metabasites and scheelite-bearing quartz veins are exposed in the Western Ore Zone (Figs. 13 c, d). These dykes have been referred to as porphyritic, lamprophyric or dacitic dykes in the literature. Petrographically, they are biotite-albite and muscovite-biotite-plagioclase gneisses. They are important for constraining the relative timing of scheelite mineralisation because they crosscut scheelite-bearing quartz veins and shear zones containing Scheelite 2 as well as the K1 gneiss but are practically non-mineralised; they only contain traces of remobilised Scheelite 4 formed during Alpine metamorphism. One of these dacitic dykes was dated at 340 ± 5 Ma by Eichhorn (1999a). This age overlaps within the 2 sigma uncertainties with the U-Pb ages of the K1-K3 orthogneiss (Kozlik et al., 2016b), the Re-Os molybdenite ages (Raith and Stein, 2006) and the U-Pb age of Scheelite 1 (Raith et al., 2011) indicating that emplacement of the orthogneiss precursor, tungsten mineralisation, emplacement of the barren dykes and Variscan regional metamorphism occurred during a geologically short time interval during the Hercynian orogeny. The age data are not precise enough to resolve these events.

Combined in-situ U–Pb, Lu–Hf and trace element LA–ICP–MS analyses were performed on zircons from the W mineralized K1–K3 orthogneiss and associated aplite gneiss (Kozlik et al., 2016b). The textural and trace element characteristics suggest the presence of magmatic and hydrothermal zircon (Fig. 18). Magmatic zircons have lower concentrations of W, Nb, U, B and REE+Y and they form euhedral cathodoluminescence (CL) bright cores with distinct oscillatory zoning (zone a). Higher trace element abundances occur in CL-dark zircons with weak oscillatory zoning (zone b) overgrowing the zircon cores and in granular textured zircons restricted to the aplite gneiss and even higher ones in U-rich Cl-dark zircons (zone b') lacking any zoning or internal texture (Fig. 18).

7 Mineralogy

Scheelite is the only mineral of economic interest. Fluorite is the most common fluorine mineral associated with scheelite. Calcite is a common gangue mineral next to quartz. It is to be noted that scheelite is the only W carrier. Wolframite and tin minerals like cassiterite are de facto missing. Sulfides and sulfosalts are much more common in the Western Ore Zone.

The following other minerals have been reported from Felbertal tungsten deposit (Weber and al., 2015): Pyrrhotite, pyrite, chalcopyrite, molybdenite, apatite and beryl are quite common; less common are tungstenite-molybdenite solid solutions, marcasite, galena, arsenopyrite, sphalerite, pentlandite, magnetite and hematite. Sulfosalts include galenobismutite, cosalite, bismuthinite, heyrovskyite, lillianite, makovickyite and mummeite, as well as members of the aikinite-bismuthinite series (friedrichite, hammarite, krupkaite, gladite, pekoite) and native bismuth. Very rare minerals are bornite, cobaltite, emplektite, enargite, tetrahedrite, stibnite, „stannite“, tellurides (hessite, joseite-like phases), cassiterite, Nb-Ta minerals (columbite, pyrochlore-group), powellite, wolframite phenakite and chrysoberyl. Recently, cupromakovickyite, cupromakopavonite, felbertalite, kupcikite, cuprobismutite and other members of the aikinite-bismuthinite (aikinite, emilite, lindströmite, paarite, salzburgite) were reported (Werner Paar, personal communication). For some of these new minerals Felbertal tungsten deposit is the type locality.

8 Controversial genetic models

When discovered Felbertal was regarded as the type locality of strata-bound tungsten deposits. The genetic concept of strata-bound and stratiform tungsten deposits goes back to researchers at University of Munich (Maucher, 1965; Höll, 1966; Höll and Maucher, 1968; Höll, 1977). The main postulates of this genetic model were: (a) the co-genetic formation of W with Sb and Hg minerals in ore deposits referred to as the "Sb-W-Hg formation"; (b) the strata-bound character of tungsten mineralisation often hosted by black schists and genetically related with submarine volcanism; (c) a genetic link of mineralisation with mafic and/or felsic volcanism; (d) time-bound formation of these deposits preferably in the Early Palaeozoic; (e) spatial control of these ore deposits by suture zones, *i.e.* major lineaments at the margins of continents; (f) mobilisation and regeneration of Sb-Hg by subsequent geological processes within these belts.

Scheelite prospecting in the Eastern Alps, based on this then new model, led to the discovery of many scheelite showings including the discovery of Felbertal tungsten deposit (see Introduction, Höll, 1969; Höll, 1971; Höll, 1975; Höll, 1977; Höll, 1998). The main target of mining in the Eastern Ore Zone was the "banded" scheelite-quartz ore (Scheelitreicherz; Figs. 6 a, b) and the associated stockwork ores (Fig. 6 c). The lamination in the former was interpreted as a sedimentary fabric in cherts of exhalative origin (Höll et al., 1972) and was the main argument supporting the syngenetic/syndiagenetic model proposed in those days. According to this model exhalative hydrothermal fluids genetically linked with submarine mafic volcanism precipitated tungsten on or close to the seafloor. Metabreccias associated with the K2 ores in the Western Ore Zone were explained with eruptive volcanism (Höll and Schenk, 1988). Discordant mineralised quartz veins, which did not fit to the syngenetic model, were explained as products of metamorphic mobilisation and the formation of the large scheelite crystals (Scheelite 2) were similarly explained by metamorphic processes.

Another model proposed magmatic pre-concentration (*e.g.,* fractionation of metasomatised mantle melts) of tungsten followed by formation of an economic ore deposit due to intense metamorphic mobilisation of tungsten into quartz veins during polymetamorphism (Thalhammer, 1987; Thalhammer et al., 1989).

All these authors rejected any genetic link to Variscan granites, which were identified in the Western Ore Zone (*i.e.*, K1-K3 orthogneiss) only in the early eighties. After recognition of this gneiss as an intrusive metagranitoid of Carboniferous age (Pestal, 1983; Jahoda, 1984) and its close spatial association with high-grade ores (K1-K3 ore bodies) granite-related genetic models were favoured by a group of researchers (Pestal, 1983; Briegleb et al., 1985; Finger et al., 1985; Trudu and Clark, 1986; Briegleb, 1991; Raith and Stein, 2006).

The epigenetic model was especially propagated by D. Briegleb the former mine geologist at Felbertal. He interpreted the K1 orthogneiss as a highly fractionated residual granitic liquid, which was emplaced along suitable structures during the Variscan orogeny at the base of the older magmatic sequence. Granite-derived hydrothermal fluids formed Quartz 1 veins and associated scheelite mineralisation and caused K-, Rb-, F-, Si- metasomatism. This was succeeded by pre-Alpine deformation and metamorphism causing local remobilisation of scheelite, emplacement of calc-alkaline dykes (porphyrites, lamprophyres). During the Alpine orogeny minor scheelite (Scheelite 4) was remobilised into Alpine quartz veins (Quartz 2).

In the following the epigenetic model and a granitic genetic relationship was also accepted by researchers from Munich (Eichhorn et al., 1999a). However, these authors still argue for a *two-stage* formation of the Felbertal deposit; a first stage of Cambrian (≈520 Ma) and a second stage of Lower Carboniferous (≈340 Ma) age. Scheelite 1 from the banded ores in the Eastern Ore Zone and the K2 ores in the Western Ore Zone were still claimed to be of Cambrian age whereas the Early Carboniferous age of Scheelite 2 and its genetic link with the K1-K3 orthogneiss has been accepted.

Re-Os dating of molybdenite could only confirm the Variscan event. The model and isochron ages range between 358 and 336 Ma and record several pulses of magmatic hydrothermal and metamorphic molybdenite formation (Fig. 16, Raith and Stein, 2006). These ages confirm the Early Carboniferous age of the K1-K3 ores. Foliated ores from the K2 orebody, regarded as equivalents of the Cambrian "Scheelitreicherz" also yielded Variscan ages and so did molybdenites from the stockwork zone in the Eastern ore field.

The "deathblow" for the syngenetic and the two-stage epigenetic (Cambrian and Early Carboniferous) models comes from in-situ U-Pb dating of Scheelite 1 from the foliated ores in the Eastern Ore Zone. The age of 335.5 ± 4.6 Ma (Raith et al., 2011) obtained for the relict scheelite cores perfectly fits the 336-340 Ma ages of the K1-K3 orthogneiss; hence, a genetic link of W mineralisation to this chemically unusual granite is unavoidable.

In summary, the Felbertal deposit is best interpreted as a poly-metamorphosed granite-related stockwork type tungsten deposit. There is accumulating evidence supporting a genetic relation of tungsten mineralisation with evolved Lower Carboniferous granites.

9 Mining

The Felber valley separates the deposit into an Eastern and a Western Ore Zone (Fig. 1 a). Due to spatial relation between the deposit morphology and the topography, mining of the Eastern Ore Zone was by open pit (Figs. 1 c, d), while the Western zone is mined by underground methods.

The Eastern Zone open pit mine operated from 1975 to 1986. The plunge of the Ore Zone was sub-parallel to the slope of western flank of the Brentling peak (Fig. 1 c). This resulted in a very low strip ratio of 1.5:1 (waste:ore) despite the small lateral extension of the orebody. Mining was undertaken from 1750 m to 2200 m a.s.l. The pit was essentially only a small ravine down-dip along the slope of the mountain (Fig. 1 c). A large portion of the orebody was slightly dislocated by post-glacial slumping and developed as "ore bolder deposit".

Outside of the "ore boulder" area, classical drill and blast open pit mining was applied, with bench heights of 10 m, using electro-hydraulic drill rigs and hydraulic shovels. Transport from the pit to the mill was by dump truck. The entire operation was run by a subcontractor. Due to severe climatic conditions, access to the open pit was restricted to the period from mid-May to October. Highest annual production was achieved in 1980 with 320,000 tonnes. Stockpiling allowed uninterrupted production at the milling facilities.

Total production from the open pit was 2.5 Mt with an average grade of about 0.6 wt.% WO_3. Following completion of mining, the area was re-cultivated and is now used again as alpine pasture.

Development of the underground mine in the Western Ore Zone started in 1977. The mineralised zone has a section of about 500 by 300 m and a down-plunge extension of more than 850 m, from the outcrop at about 1280 m a.s.l. to the currently deepest exposure at 625 m a.s.l. (Fig. 13). The deposit remains open to depth.

In general, scheelite mineralisation is pervasive, and the ore body definition is largely controlled by the cut-off grade. The mineralised zone is divided by a large fault zone incorporating a slice of sterile schists ("Basisschieferschuppe"; Figs. 8, 9). Within the diffusive mineralisation, up to eight elongated WNW-plunging ore lenses are developed, some of which merge downdip to a single larger ore body.

Due to the location close to the National Park, and to provide adequate shelter in case of high avalanche risk in winter, almost all infrastructure of the mine is located underground (Figs. 19, 20). This includes change rooms, canteen, offices and workshops.

Access from the Felber valley and location of the main infrastructure is on level 1175 m a.s.l. The mine was developed from the onset as trackless operation with diesel powered LDH equipment (Fig. 19 a; Figs. 20 a, b). Standard section of drifts and ramps is around 25 m². By 2018, more than 60 km of drifts and ramps had been developed, but many are not accessible any more. The individual sublevels are connected by means of a spiral ramp, with a 12% inclination, various service and ventilation raises and ore passes.

To assure year-round safe access to the mine and to improve environmental performance, it was decided to connect the mine with the mill by a 3 km adit (Spross, 1984). A crushing plant was erected in a large underground cavern on level 850, comprising screening plant, a jaw crusher for primary crushing and two cone crushers for secondary crushing. A 12 mm-product is delivered by conveyor belt to fine ore bins with some 5000 tonnes capacity close to the portal and then with another set of conveyors to the plant. From 1985 onwards, this system allowed replacing overland truck haulage through the Felber valley.

The first phase of underground mining concerned the ore between mine level (mL) 1175 (then also the haulage level) and the outcrop of the mineralisation at around 1280 mL. Most of the mining was undertaken as open stoping, although all of the stopes have been filled with hydraulic sandfill or paste fill in the meantime.

Subsequently, the ore between the 1175 mL and the feed level of the crusher station (850 mL) was developed in several stages and mined. In the late 1990s, mining advanced below the level of the crusher, which requires intermediate haulage by truck from the active stopes to the run-of-mine ore bin at 910 mL. By the end of 2017, active stoping reached the interval from 650 mL to 675 mL, while development drifting advanced towards 625 mL.

For an underground environment, mined ore grades are fairly low, just below 0.3% WO_3 on average. Thus, large-scale low-cost mining methods have to be employed to allow economic extraction. The mining method for the main orebody is sublevel caving, using 25 m sublevel interval and stope dimensions of up to 40 to 80 by 80 to 100 m with multiple draw points.

Other mining methods currently employed at the Felbertal mine are transversal sublevel stoping, top to bottom over several sublevel intervals, with delayed backfill (normally a mixture of unconsolidated waste rock from underground development and hydraulic sandfill) or longitudinal sublevel stoping bottom to top with smaller sublevel intervals (12-20m). The latter is a variation of cut & fill mining.

Selection of the mining method depends on grade, ground conditions and geometry of the individual ore zones. The rather flat dip (around 45-55°) and increasingly difficult ground conditions in the lower sublevels pose constraints on the flexibility of the mining approach.

Drilling equipment at the Felbertal mine includes two-boom jumbos for drifting (Fig. 19 b) and longhole rigs for ring drilling in the stopes, both, with classic top hammer or hydraulic in-hole hammer. The company also owns a raise bore machine for drilling slots in the stopes and service shafts. Blasting employs emulsion cartridges, loose ANFO explosives, pump emulsion and NONEL detonators.

Mucking and haulage to ore passes or truck loading bays is by 15-tonne scooptrams (Figs. 20 a, b). Mucking from open stopes is undertaken with remote control. Ore produced on the lower sublevels is transported by 30 or 50 tonne ADTs to the ore bin above the crushing plant.

Since 1988, a part of the tailings from the flotation plant is used as hydraulic backfill in the mine (Walser, 1992). This has two advantages: first, decrease of cavities in the underground environment and thus increased stability and lower risk of dilution, and second, reduced storage requirements for tailings on surface. However, loose sandfill will never consolidate, and groundwater circulation poses the risk of washing out the fill. In 2008, the company installed a pastefill plant to produce consolidated fill from tailings and a binder. Fly ash is used as binder, which has economic advantages over cement and adequate technical behaviour.

Annual development comprises 2750 m of drifting, installation of 6000 rock bolts (split sets and cable bolts) and 3000 m³ of shotcrete with steel fibres (Fig. 20 c). Backfill requirements are around 200,000 t per year.

Diamond drilling (Fig. 20 d) and sludge hole drilling is undertaken for exploration and stope definition in the underground environment. The annual diamond drilling volume was around 2500 m until recently, while 5000 m are planned for 2018. Due to geometrical constraints, drilling cannot adequately test the down-plunge continuity of the orebody. A dedicated exploration drift was developed into the hangingwall of the main orebody on level 725, and another one is now planned for level 625.

To allow adequate communication, a leaky feeder underground communication system covers the entire underground development. Mine planning and resource modelling uses state-of-the-art computer programmes providing three-dimensional visualisation.

In total, about 65 persons including maintenance and service personnel are employed in the mine that operates generally on a 5-day / two-shift basis.

10 Beneficiation

To upgrade the low-grade ore a flotation plant was constructed in 1976, directly at the Felbertauern highway, some 1000 m below and (as the crow flies) 3 km north of the open pit (Figs. 21 a, b). The capacity was initially 250,000 tonnes per year (tpa) but was increased to the current capacity of close to 400,000 tpa by the early 1980s. Introduction of sensor-based sorting in around 2010 allowed to further increase the beneficiation capacity to over 500,000 tpa. Crushing facilities are located underground (Fig. 20 e). From the onset, it was only planned to produce low-grade ("non-commercial") concentrates at the mill, as further upgrading at the Bergla refinery occurs within the same company, and a much higher recovery of tungsten is possible when accepting lower-grade concentrates.

Capacity of the flotation plant is 72 t per hour, with a head grade of around 0.35 wt.% WO_3. The beneficiation circuit briefly comprises of milling by ball mill in closed-circuit to 80% passing 200 µ (seventy mesh), rougher flotation and cleaning stages to produce a concentrate with 30-35% WO_3 at some 86% recovery (Fig. 21 b). The concentrate is dewatered by vacuum drum filter, packed in 1.5-tonne "big bags" and trucked to the refinery in Bergla.

The company is constantly trying to improve the mill performance and undertakes various tests to optimise the flow sheet.

Tailings management in an area of outstanding natural beauty and dense population is a highly sensitive issue. Initially, a small tailings pond was used close to the mill side in the Felber valley which is now inactive. Due to topographic and environmental constraints, additional capacity was then provided in a tailings management facility in the Pinzgau valley near Stuhlfelden, some ten kilometres north of the plant (Fig. 21 c).

Design, construction and operation of the 10 km slurry pipeline were and still are a technical challenge. The tailings are highly abrasive, and a critical minimum velocity of the transport needs to be constantly achieved to avoid sedimentation. An elaborated system of emergency pumps and compressed air containers to operate valves without electricity assures that sedimentation can be avoided in case of power failures. A 4 km tailings pipeline with 200 m head to supply the mine with tailings for backfilling purposes is operated with high pressure pumps.

Since 1983, some 11 Mt of tailings were placed in a number of separate basins at the Stuhlfelden tailings facilities. The tailings itself do not contain any dangerous reagents, and the content of sulphides and heavy metals is low. They are classified as inert non-class A tailings according to the European mine waste regulations. Re-cultivation of the tailings ponds is an ongoing measure, and the older portions of the facilities are now used again as pasture (Fig. 21 c).

The plant includes an assay laboratory employing XRF and AAS techniques and an XRD to determine mineralogical composition of the ore feed. A metallurgical laboratory allows testing for example new flotation reagents. The facilities are also used by Wolfram Bergbau's International Mining Department for project work abroad.

A total of 27 persons are employed at the plant. Other than almost all flotation plants world-wide, the Felbertal facilities are operated discontinuously, for 5.5 days per week only.

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*Fig. 1: **a**. Location of the Eastern Ore Zone (EOZ, open pit) and Western Ore Zone (WOZ, underground) in the Felber Valley; view to ≈S. **b**. Exploration drilling in the open pit area, 1972. **c**., **d**. Early mining operation in the open pit (mid-1970s). All photos from WBH archives.*

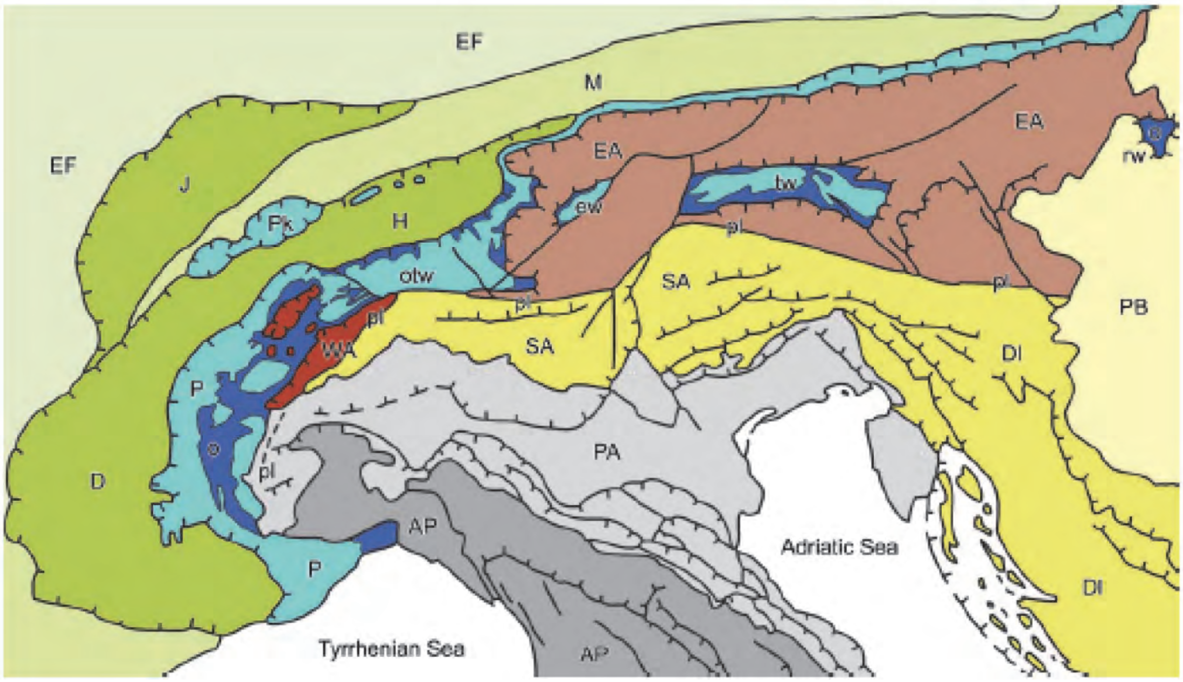

Fig. 2: Tectonic map of the Alps (from Dal Piaz et al., 2003) showing the location of the Tauern Window in the Eastern Alps. (1) Europe-vergent collisional belt: i) Western (WA) and Eastern (EA) Alps; ii) Penninic domain: continental and ophiolitic (o) nappes in the Western Alps and tectonic windows (otw: Ossola-Ticino, ew: Engadine, tw: Tauern, rw: Rechnitz); Pre-Alpine klippen (pk); iii) Helvetic-Dauphinois (H-D) domain; iv) Molasse foredeep (M); v) Jura belt (J). (2) Southern Alps (SA), bounded to the north by the Periadriatic lineament (pl). Pannonian basin (PB), European (EF) and Po Valley-Adriatic (PA) forelands, Dinaric (DI) and Appeninic (AP) thrust-fold belts.

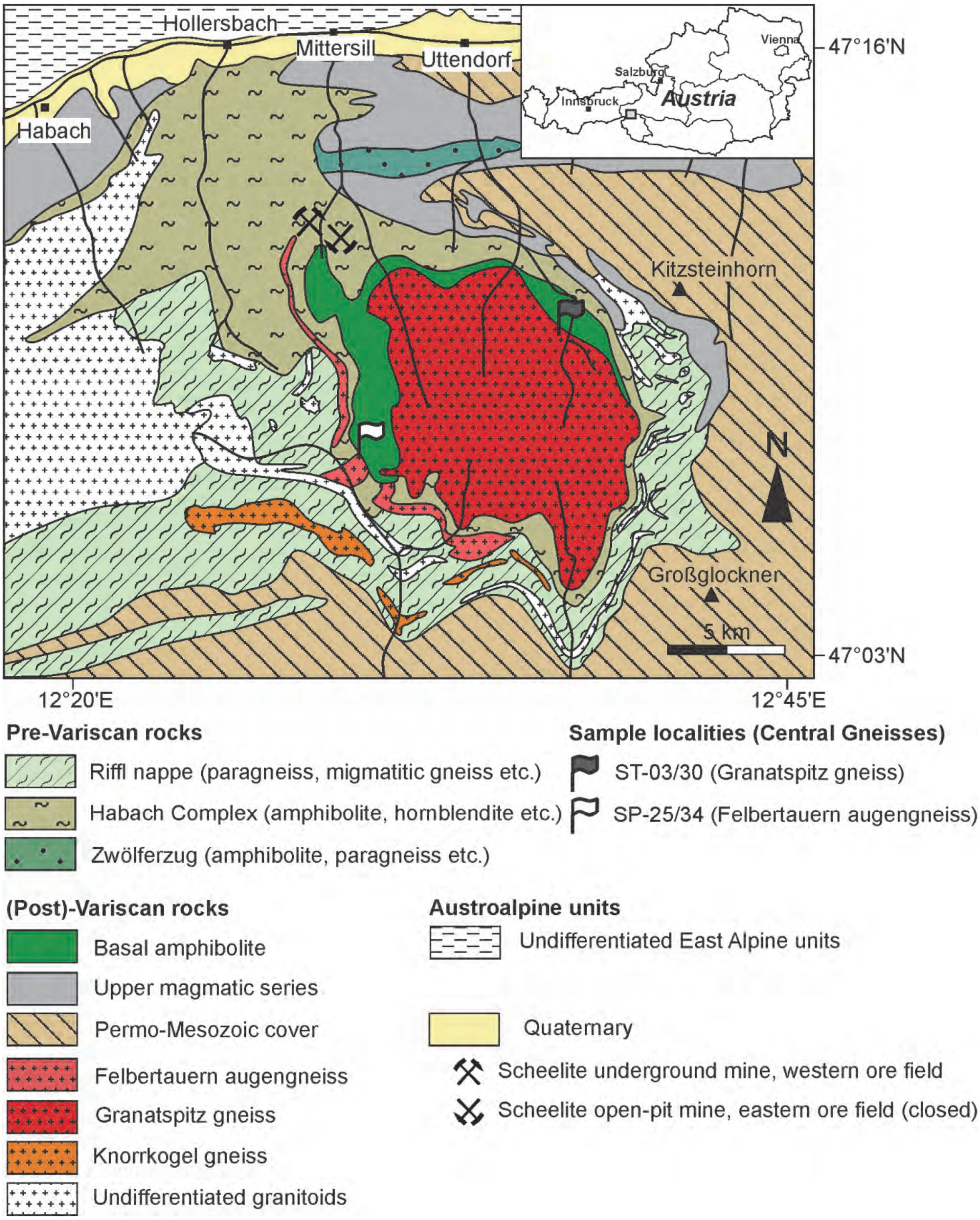

Fig. 3: Geological sketch map of the central part of the Tauern Window (from Kozlik et al., 2016b).

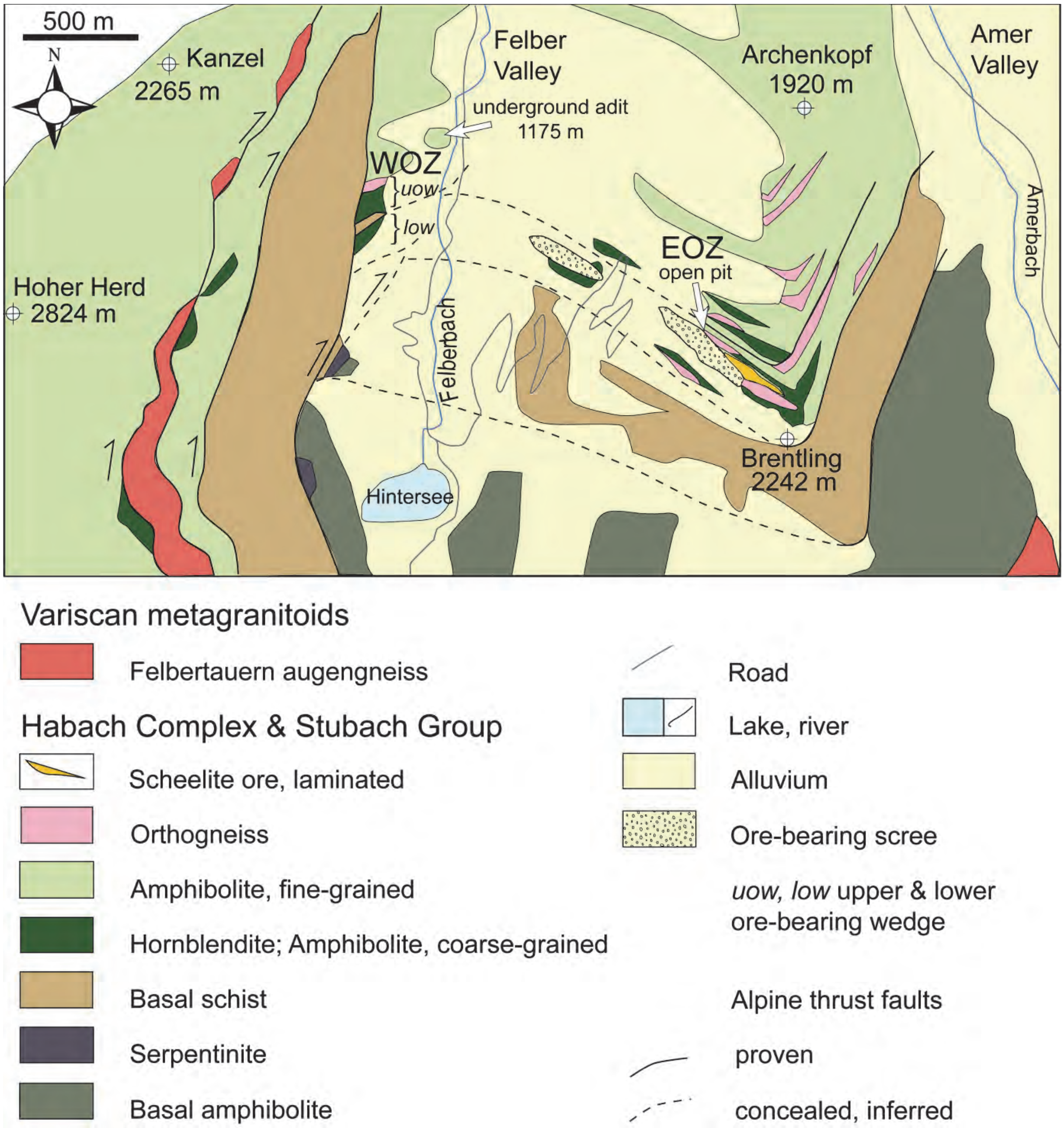

Fig. 4: Simplified geological map of the area around the Felbertal tungsten deposit (after Höll and Eichhorn, 2000). EOZ Eastern Ore Zone, WOZ Western Ore Zone. Alpine thrust(-slip) faulting caused the stacking of the Basal Amphibolite (Stubach Group) and rocks of the Habach Complex as well as the tectonic imbrication within units of the Habach Complex and the Felbertal scheelite deposit.

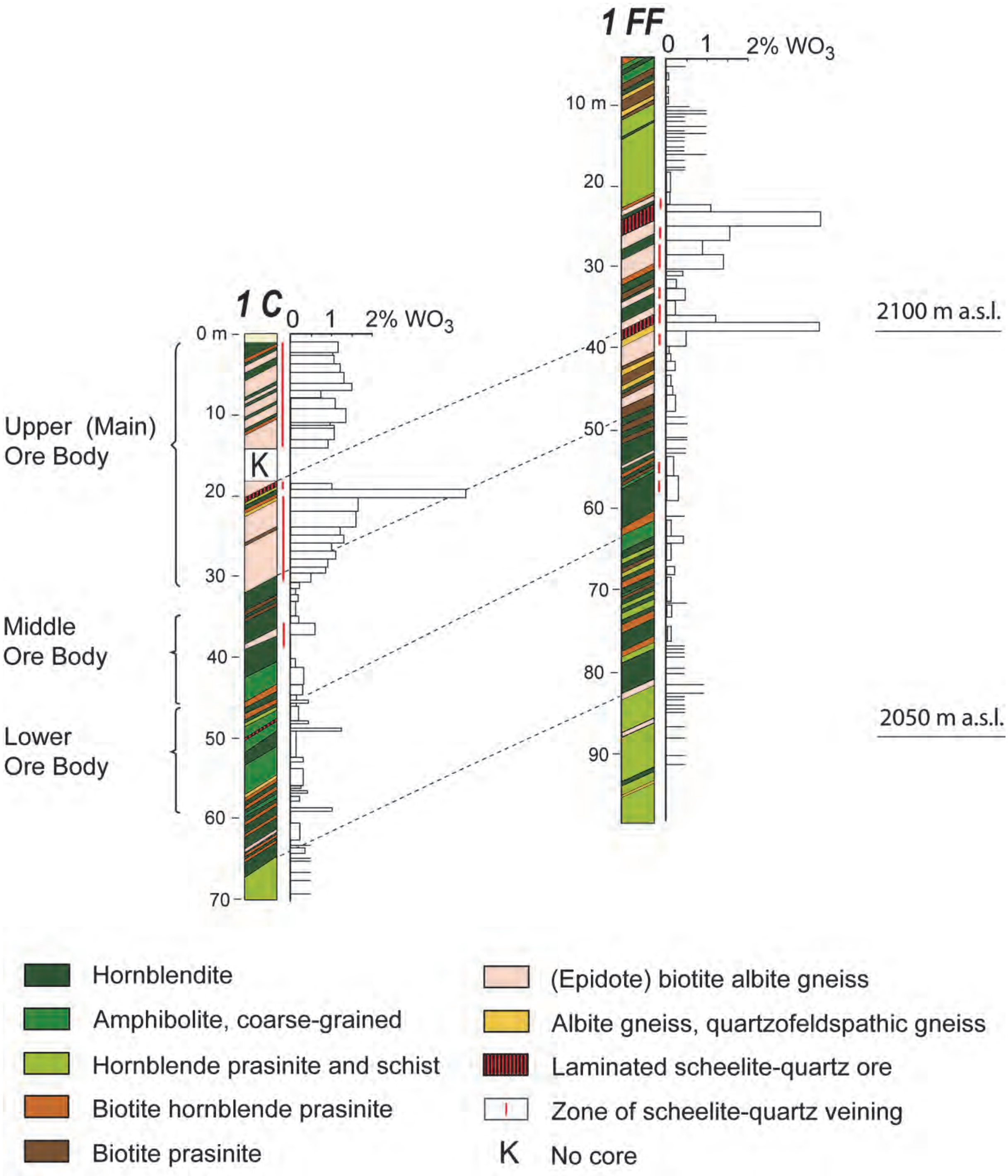

Fig. 5: Drill core logs from exploration drillings 1C and 1FF in the Eastern Ore Zone (based on Höll, 1975). Typically, the whole magmatic sequence composed of alternating layers of hornblendite, various metabasites and gneisses is mineralised. Very high (>2 wt.% WO_3) ore grades occurred in the foliated (laminated) scheelite-quartz ores, though high-grade ore zones (>1 wt.% WO_3) are not restricted to these ores but are also associated with stockwork-like quartz veins (see Fig. 6 c) throughout the whole sequence.

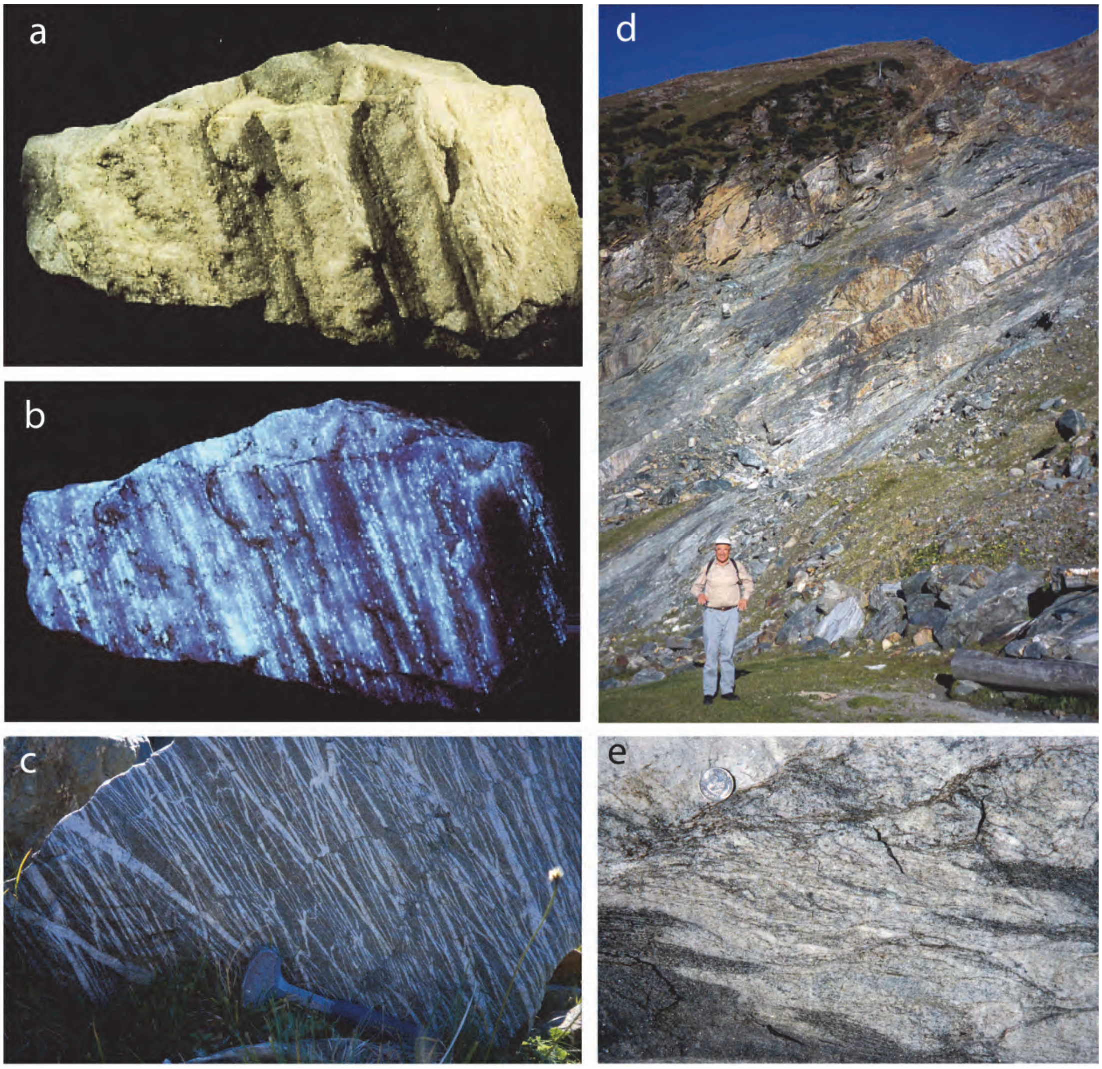

Fig. 6: ***a, b.*** *Foliated high-grade scheelite ore (Quarzitisches Scheelitreicherz) from the Eastern Ore Zone. b. in UV light. Photograph from WBH archives.* ***c****. Stockwork like quartz veins with scheelite in boulder. These stockwork ores were interpreted as the feeder zone of the foliated ores (Höll and Eichhorn, 2000). Boulder from Eastern Ore Zone; photo J.G. Raith, September 1999.* ***d****. Alternation of ultramafic/mafic and felsic metaigneous rocks in the abandoned open pit. The felsic gneisses (Ostfeldgneis) derived from I-type granitic protoliths emplaced at ≈520 Ma. The person in the foreground is R. Höll, who discovered the deposit in 1967. Open pit at ≈1929 m, Ostfeld; photo J.G. Raith, September 1999.* ***e****. Tectonically reworked intrusive contact of leucocratic orthogneiss with biotite-rich metabasites. Boulder in open pit at ≈1930 m, Ostfeld; photo J.G. Raith, September 1999.*

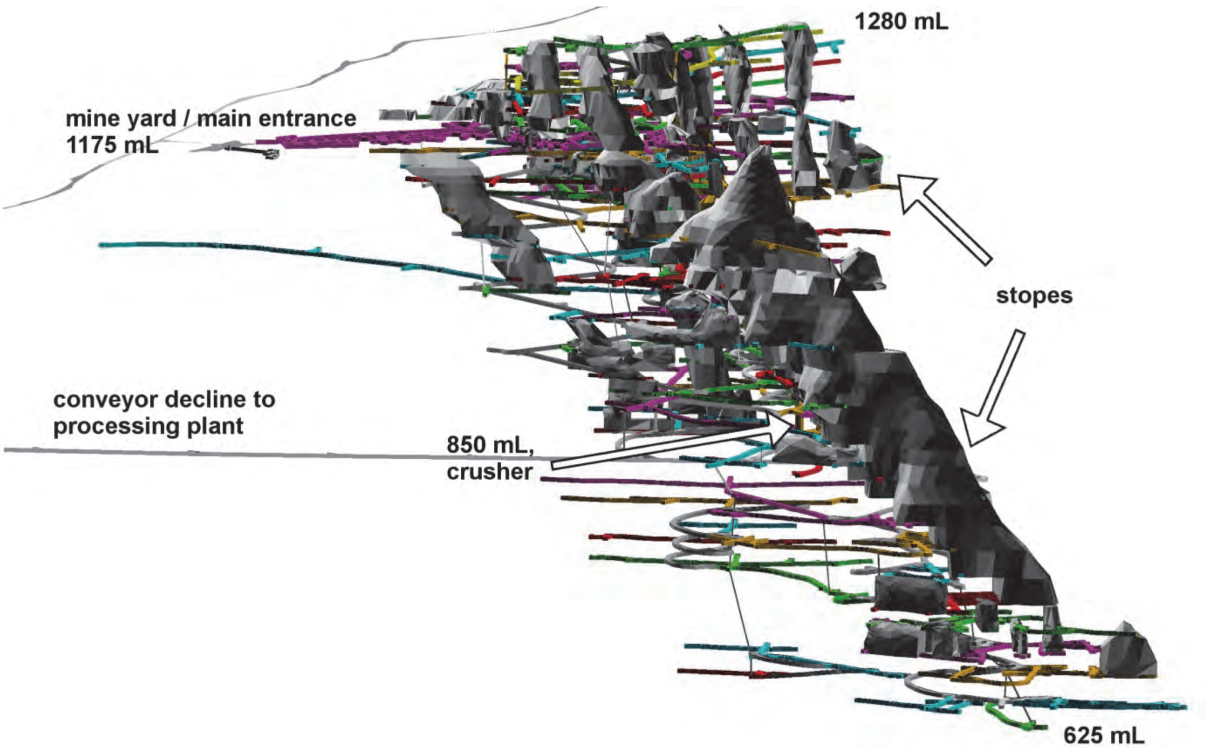

Fig. 7: 3D model of the underground mine in the Western Ore Zone (Westfeld) showing location of the different mining levels and stopes as per August 2018.

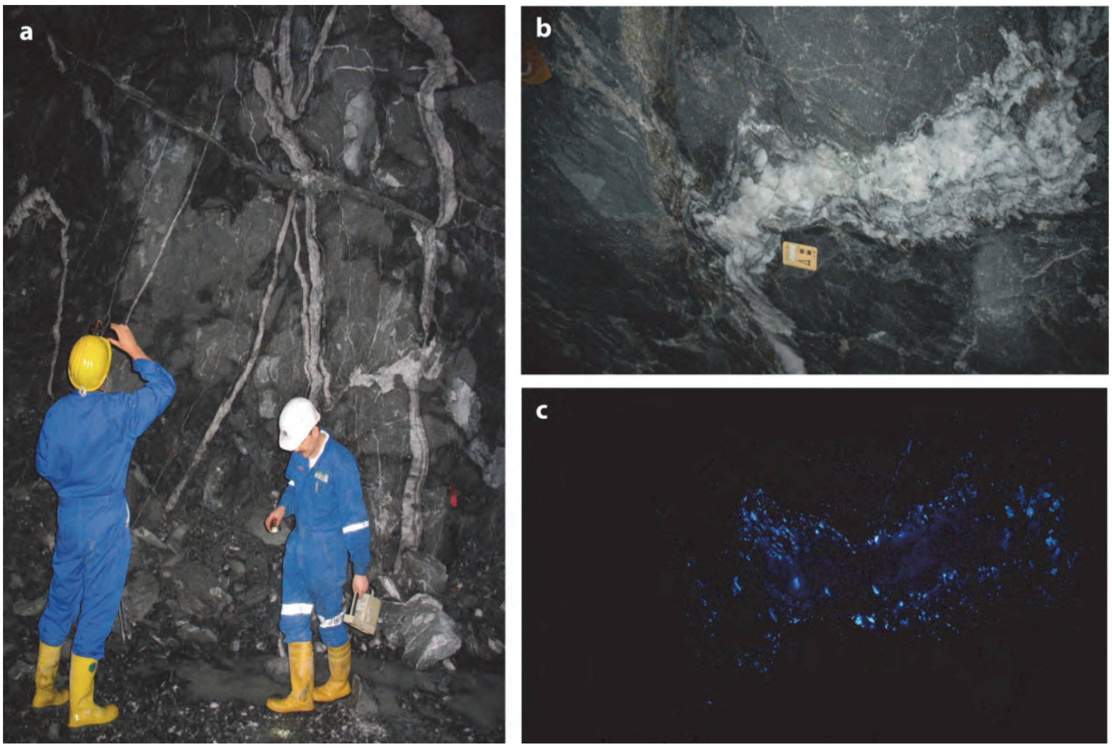

*Fig. 8: **a**. Deformed quartz veins in metabasite. K2' orebody, level 775, Westfeld; photo J.G. Raith, February 2009. **b, c**. Deformed quartz-scheelite vein (Quartz 1) in metabasites. Scheelite is concentrated at the vein selvages. Larger scheelite porphyroblasts (Scheelite 2) show yellowish fluorescence in UV light (photo c). K2' orebody, level 775, Westfeld; photo S. Schmidt, February 2009.*

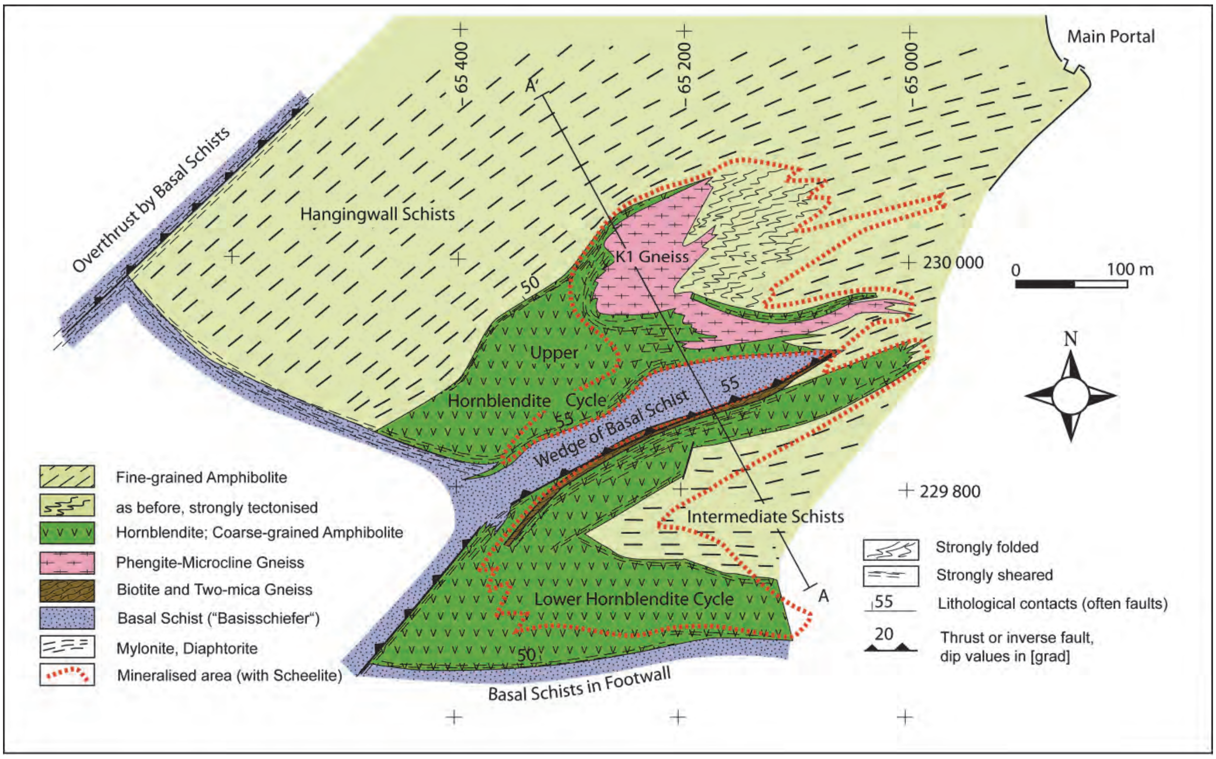

Fig. 9: Geological sketch of level 1175 of the Western Ore Zone showing the two ore-bearing wedges (Lower and Upper Hornblendite Cycle) separated by a barren wedge of Basal Schists (from Schmidt, 1988).

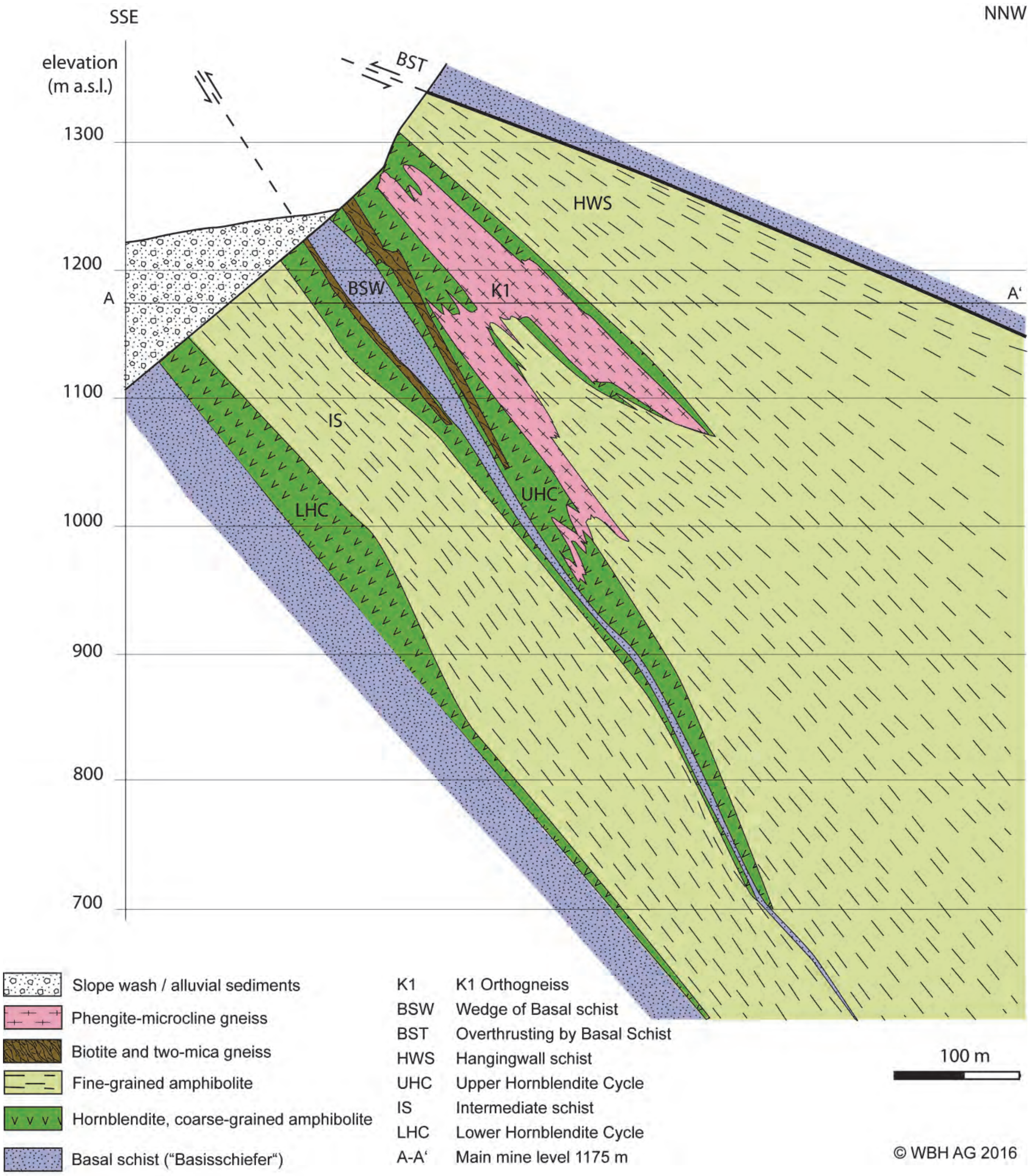

Fig. 10: SSE-NNW profile through the Western Ore Zone; for exact location see A-A' on Fig. 9 (from Schmidt, 1988, updated for deeper mine levels in 2016).

*Fig. 11: **a**. Well-foliated K1-K3 orthogneiss with deformed quartz vein (Quartz 1) and rafts of strongly deformed hornblende-biotite schists. K1' ore body, level 1164; photo J.G. Raith, February 2009. **b**. ≈10 cm thick deformed quartz vein containing elongate scheelite (grey, Scheelite 2) in K1-K3 orthogneiss. The mineralised vein crosscuts the Early Carboniferous granite gneiss (336-341 Ma, Kozlik et al., 2016b) but shows penetrative deformation. Upper part of K1 orebody, level 1152; photo J.G. Raith, September 1999. **c**. Sharp contact between dark- and light-coloured K1-K3 orthogneiss varieties. A quartz–scheelite vein (white) crosscuts the gneiss but is aligned in the foliation; level 1164; photo M. Kozlik, 2013. **d.** Folded apophyses of dark-coloured K1-K3 orthogneiss intruding amphibolite; level 1164 m; photo J.G. Raith, February 2013; rectangular scale length ≈8 cm. **e.** Dike of aplite gneiss aligned in dark foliated fine-grained amphibolite; dyke is about 1 m thick; level 940; photo M. Kozlik, 2013. **f.** Quartz-scheelite vein with beryl (Be) crosscutting K1-K3 orthogneiss; level 1164; pen for scale is 12 cm; photo M. Kozlik, 2013.*

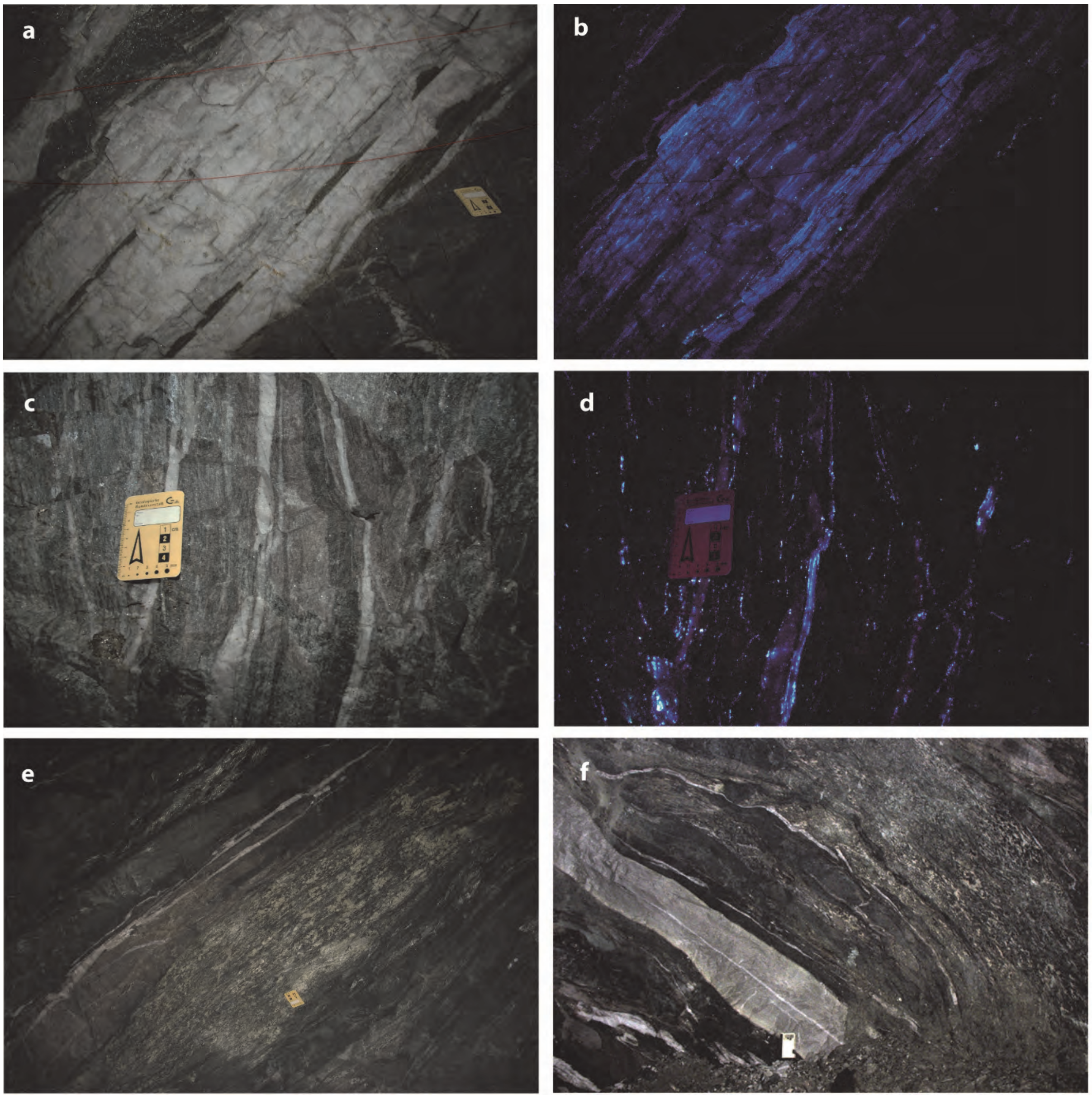

*Fig. 12: **a.** Foliated scheelite ore. Note the foliation-parallel thin rafts of darker and scheelite-free/-poor host rocks within the about 1 m thick scheelite-quartz mass. K2 ore body, Level 1000. **b.** in UV light; photos S. Schmidt, February 2009. **c.** Interlayered gneiss (grey) metabasite (greenish) sequence truncated by about foliation-parallel quartz veins (Quartz 1). **d.** in UV light. The higher scheelite concentrations are associated with the quartz veins but minor scheelite is also present as disseminations throughout the host rocks. K4 ore body, level 1164; photos S. Schmidt, February 2009. **e**. Lens of coarse-grained amphibolite (metagabbro), gneiss (brown grey) and hornblendite in phyllonitic biotite-chlorite schist (upper left). K4 ore body immediately in the hanging wall of the Basisschiefer, level 1110; photo J. G. Raith, February 2009. **f**. Intercalation of felsic gneiss in metabasites. A thicker layer of coarse-grained amphibolite is to be seen to the right. This scheelite-bearing quartz veins (Quartz 1) crosscut the gneiss and the metabasites. K5 orebody, level 1050; photo J.G. Raith, February 2009.*

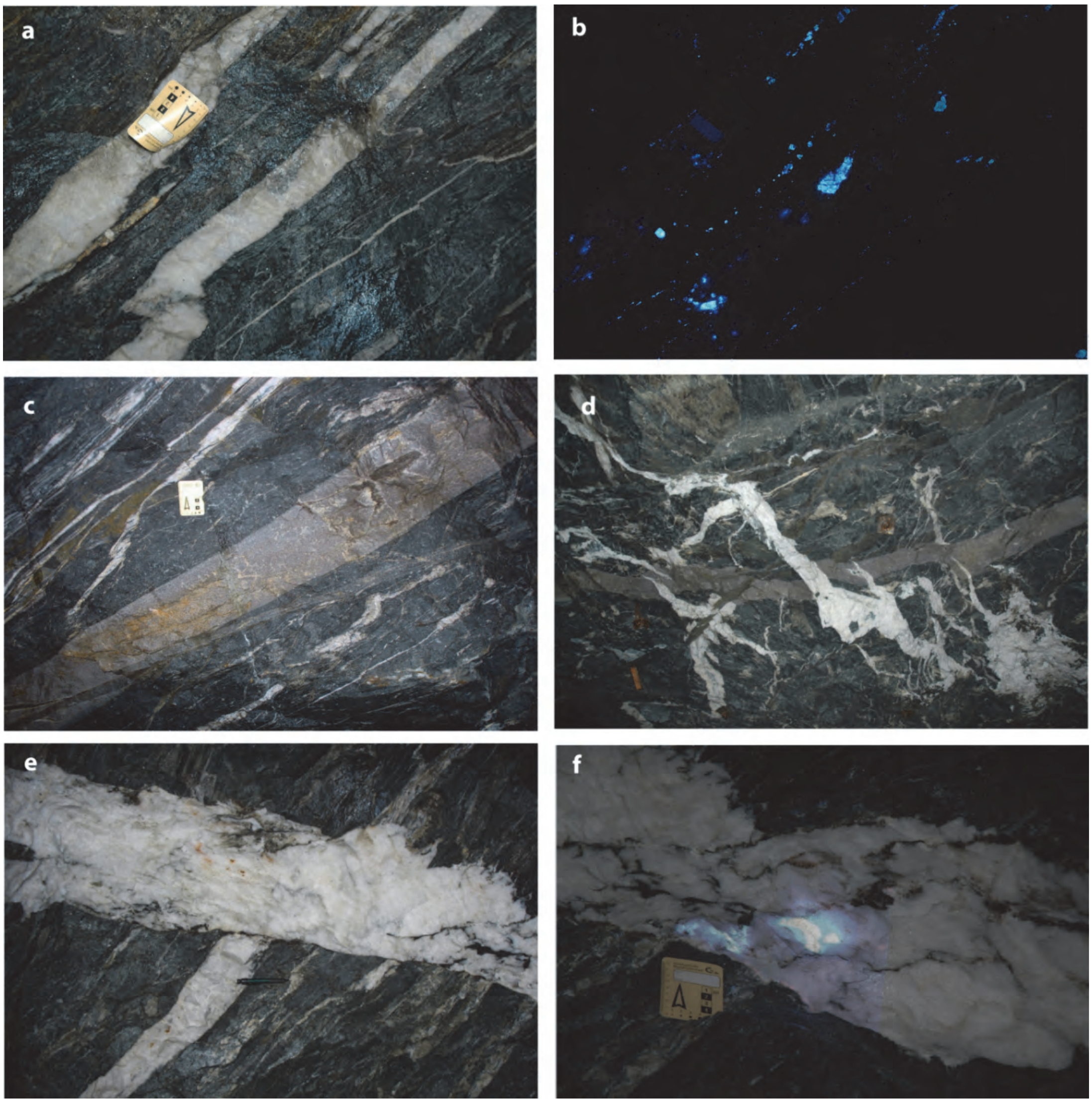

Fig. 13: ***a, b****. Two scheelite-bearing quartz veins (Quartz 1) in dark-coloured host rocks (so called "Schwarzerz"). b. in UV light. The veins are aligned in the main foliation of fine-grained amphibolite. Scheelite is concentrated in the veins forming larger porphyroclasts (greyish in normal, yellowish fluorescence in UV light; Scheelite 2). Finer-grained re-crystallised scheelite (white, bluish fluorescence, Scheelite 3) is aligned in stringers. Level 1152 hanging wall; photos S. Schmidt, February 2009.* ***c****. Dyke of ≈340 Ma non-mineralised biotite gneiss crosscutting scheelite-bearing quartz veins (Quartz 1) in hornblende schist. In contrast to the schist the dyke is not mineralised (UV photo not shown). Level 1152 hanging wall; photo J.G. Raith, February 2009.* ***d****. The same biotite gneiss dyke dissected by younger quartz veins (Quartz 2) of Alpine age. Both the dyke and the younger quartz veins postdate scheelite-bearing Quartz 1 veins. Level 1152 hanging wall; photo J.G. Raith, February 2009.* ***e, f****. Discordant quartz vein (Quartz 2) crosscutting and displacing a scheelite-bearing quartz vein (Quartz 1). Level 1152 hanging wall; photo J.G. Raith, February 2009. f. Detail of e. Combined normal and UV light. Up to 5 cm large crystals of scheelite showing bluish-whitish fluorescence (Scheelite 4) in Quartz 2 vein. These younger veins and Scheelite 4 formed due to local remobilisation of quartz and scheelite during Alpine (≈30 Ma) regional metamorphism. Level 1152 hanging wall; photo S. Schmidt, February 2009.*

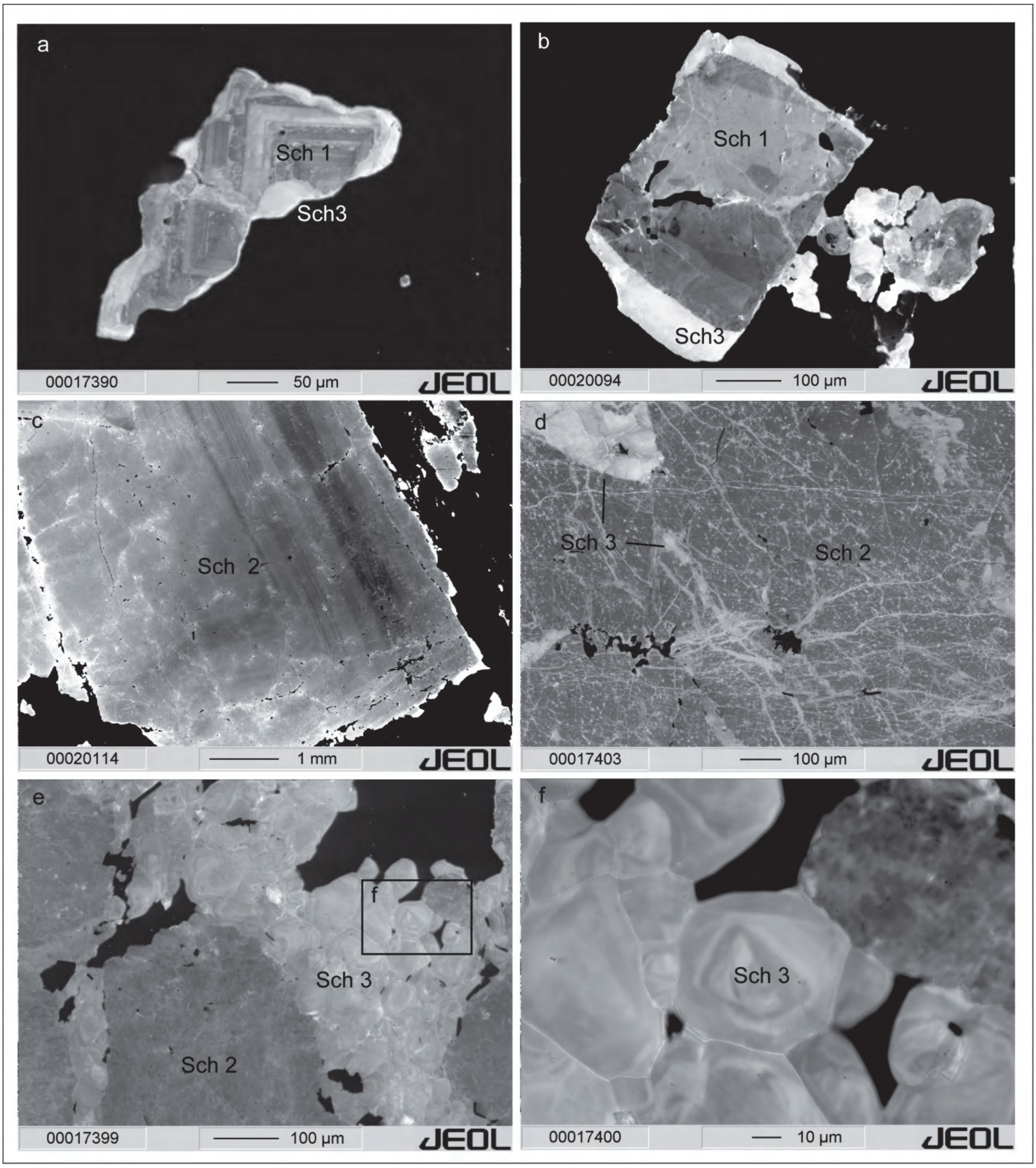

Fig. 14: Cathodoluminescence (CL) micro-images of scheelite from the Felbertal deposit. ***a****. Scheelite 1 (Sch1) with fine oscillatory zoning replaced by and overgrown by CL-brighter Scheelite 3 (Sch3); foliated scheelite-quartz ore, Ostfeld.* ***b****. Scheelite 1 with rim of Scheelite 3; K2 orebody, Westfeld.* ***c****. Large Scheelite 2 (Sch2) porphyroblast with growth zoning; K1 orebody; Westfeld.* ***d****. Microfractures in Scheelite 2 filled with CL-brighter scheelite 3.* ***e****. Recrystallised Scheelite 3 overgrowing and replacing Scheelite 2; K1 orebody, Westfeld.* ***f****. Detail of e showing diffuse zoning in Scheelite 3.*

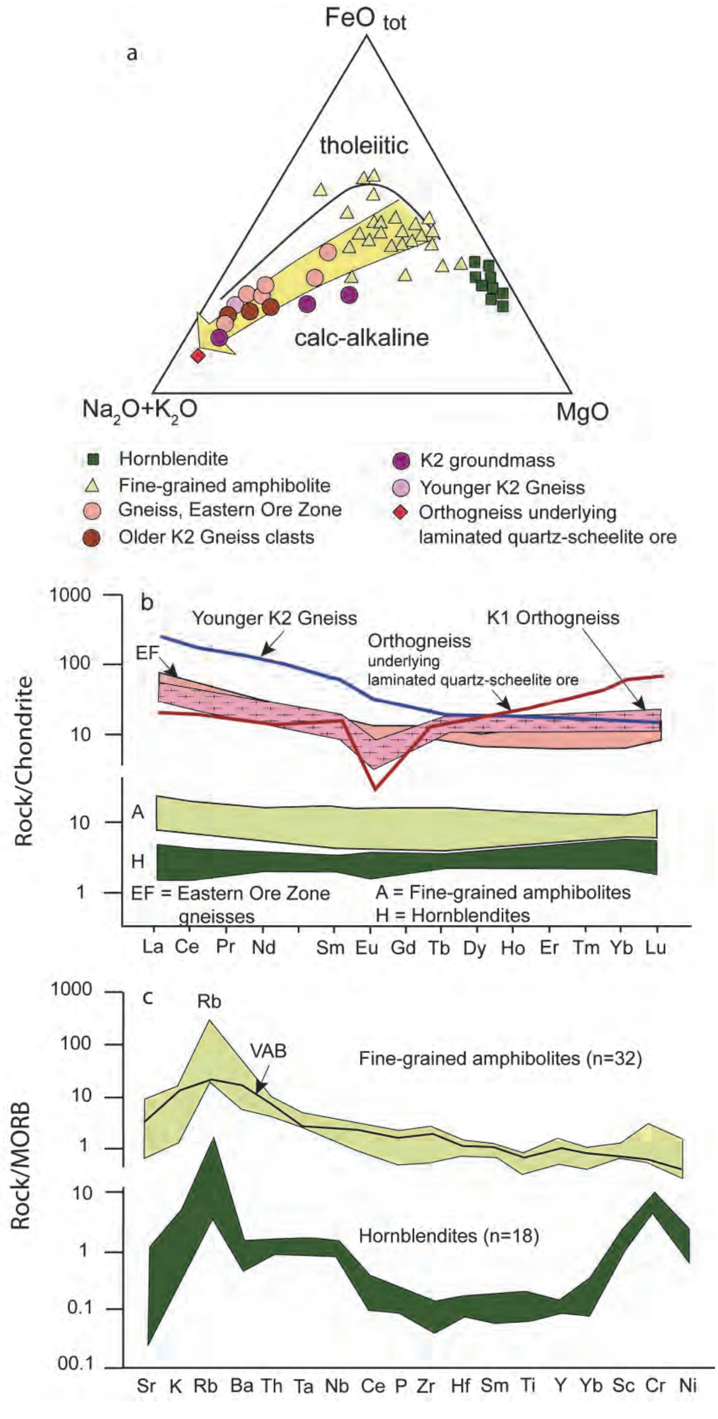

*Fig. 15: Diagrams illustrating the chemical composition of rocks of the Habach Complex and the Lower Carboniferous K1-K3 orthogneiss (from Höll and Eichhorn, 2000). **a**. AMF plot. Most rocks of the Habach Complex follow a calc-alkaline trend typical for arc-related magmatism. A few fine-grained amphibolites from the Lower Magmatic Series are tholeiitic in composition. **b**. Chondrite-normalised REE patterns. Fine-grained amphibolites (A) and hornblendites (H) show flat REE patterns. Cambrian (Younger K2 Gneiss, EF gneisses from Eastern Ore Zone) and Early Carboniferous (K1-K3) orthogneisses show more evolved LREE enriched patterns. **c**. MORB-normalised spidergrams for hornblendites and fine-grained amphibolites, the latter showing chemical similarities with volcanic arc basalts (VAB). Both rock types are enriched in LIL elements, especially in Rb, relative to MORB due to fluid-induced alteration related to ore deposit formation.*

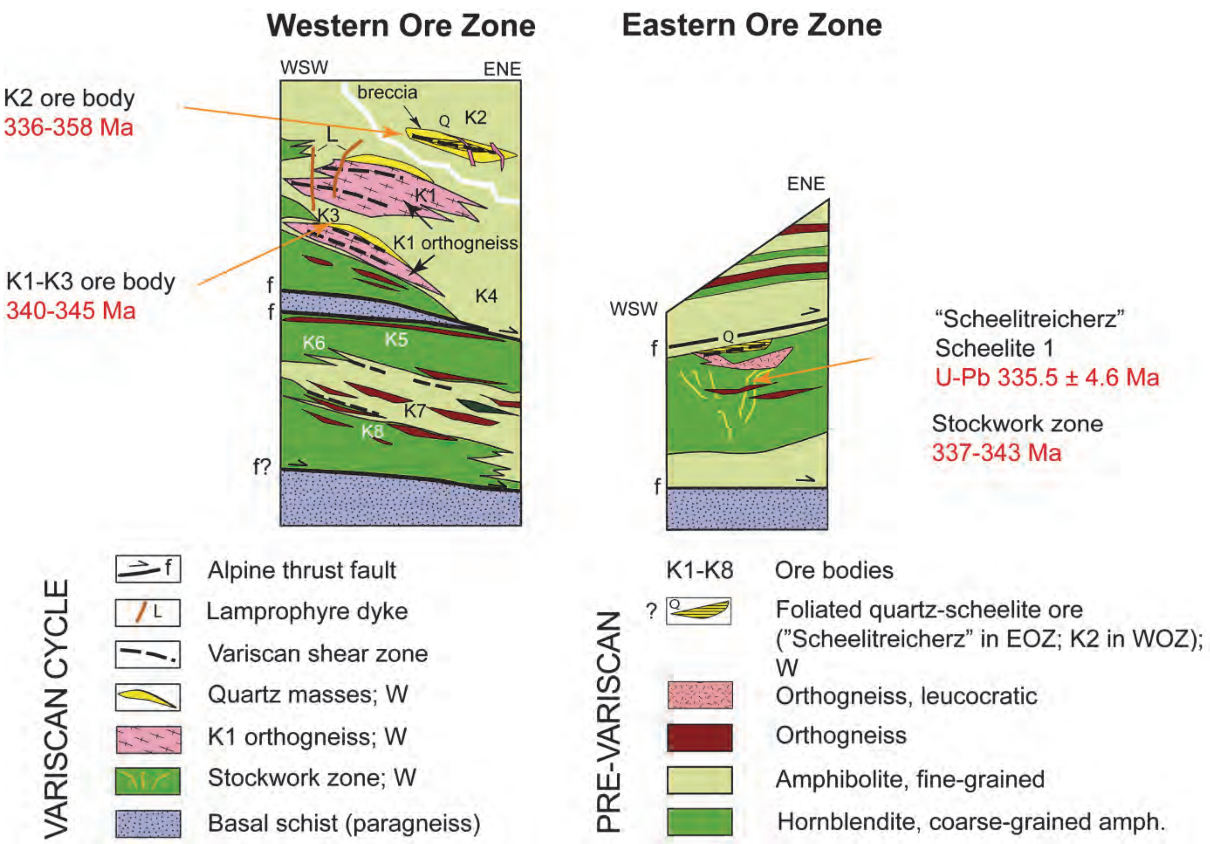

Fig. 16: Schematic sketch of the geology of the Eastern and Western Ore Zones (based on Höll and Eichhorn, 2000). K1 to K8 refer to the different ore bodies (see text). Re-Os molybdenite ages (Raith and Stein, 2006) are shown in red. The U-Pb age of Scheelite 1 is from the Scheelitreicherz (Raith et al., 2011). All ages are consistent with Variscan ore formation.

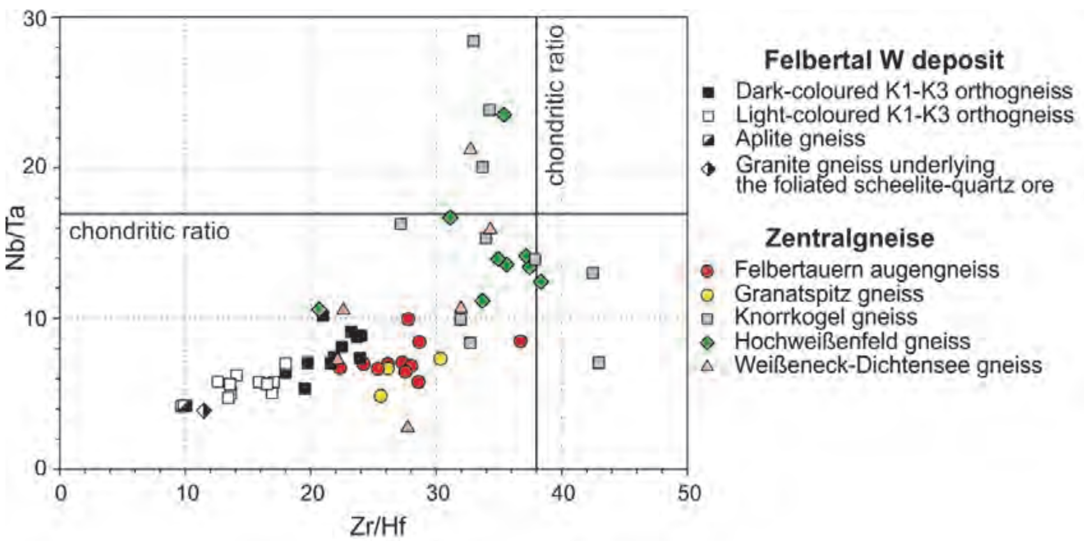

Fig. 17: Diagram of Nb/Ta versus Zr/Hf showing data of Variscan metagranites in the Felbertal tungsten deposit and comparing them to other regional types of Zentralgneis. Decreasing ratios of Nb/Ta and Zr/Hf are interpreted as effects of enhanced magmatic differentiation (from Kozlik et al., 2016b).

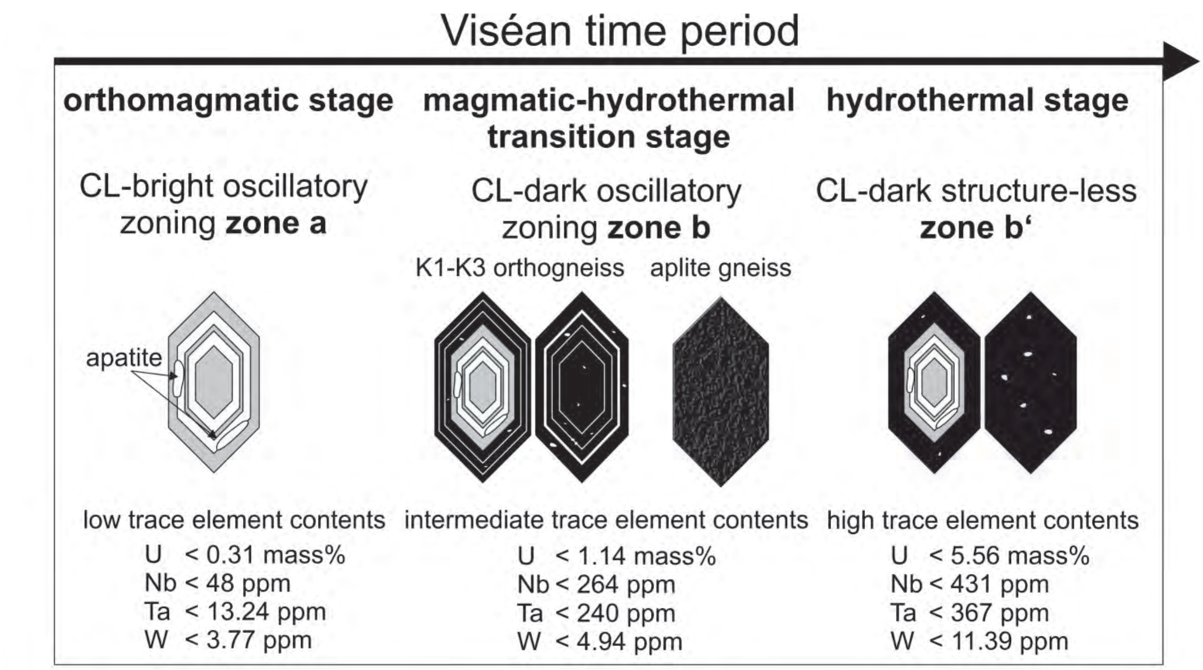

Fig. 18: Model summarizing zircon formation in the K1–K3 orthogneiss during the Early Carboniferous (from Kozlik et al., 2016b).

*Fig. 19: **a**. Portal of the Felbertal underground mine. **b**. Drilling with modern computer-controlled two-boom jumbo.*

*Fig. 20: **a**. Remote-controlled scooptram with 15 tonnes capacity. **b**. Mucking into an ADT truck for underground haulage from the lower sublevels. **c**. Shotcreting of development drifts. **d**. Underground diamond drilling. **e**. Primary jaw crusher in the underground crushing station.*

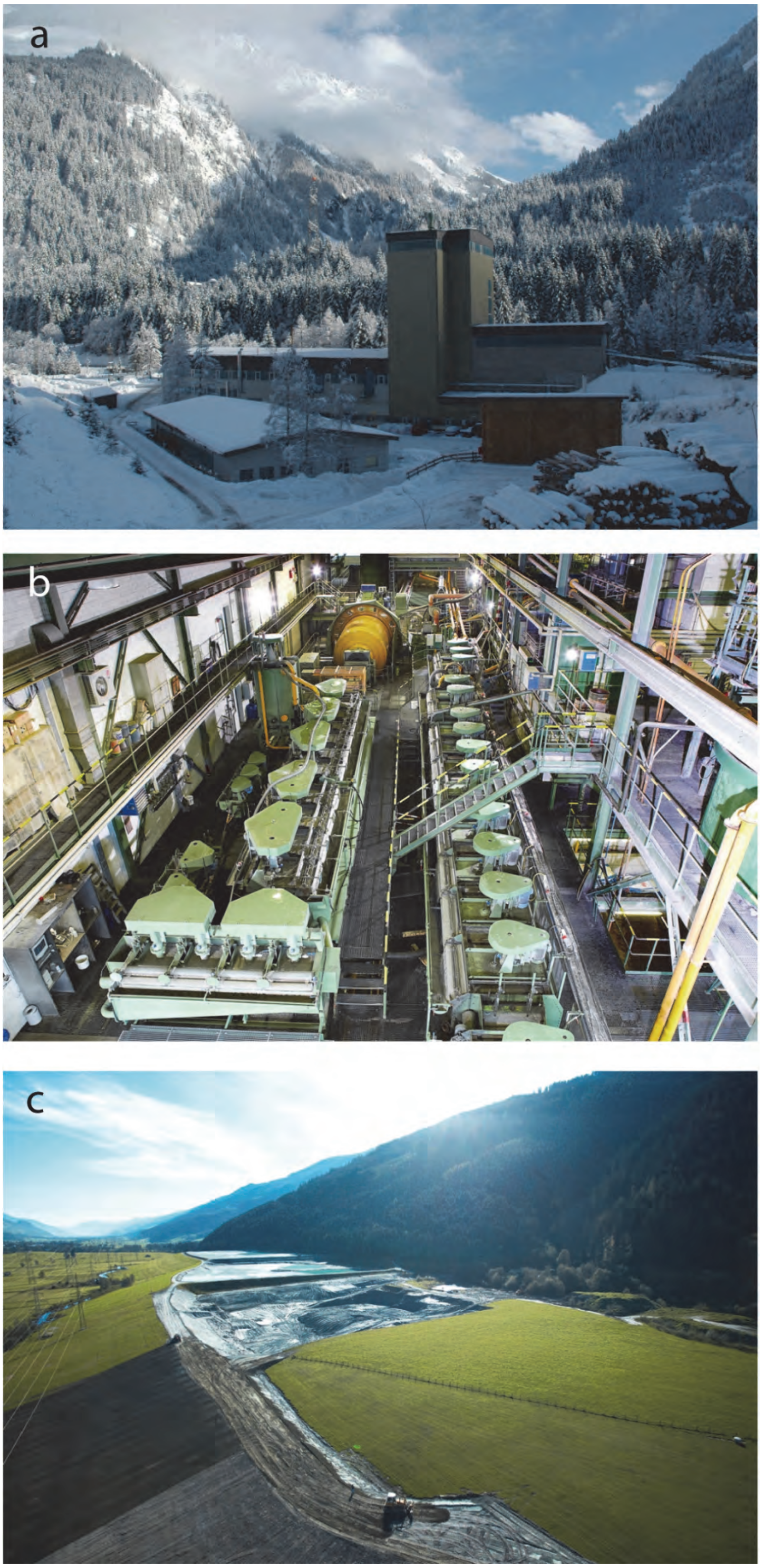

Fig. 21: ***a****. Beneficiation plant 3 km north of the mine, directly at the Felbertauern highway.* ***b****. Overview of milling and flotation circuit.* ***c****. Tailings management facilities in the Pinzgau valley near Stuhlfelden showing the extent of the re-cultivation measures that occur concurrently with the operation.*

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