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Tungsten deposit Felbertal, Salzburg, Austria

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1. Introduction

The Felbertal scheelite deposit near Mittersill, Austria, located in the Hohe Tauern range of the central Eastern Alps is one of the best-known tungsten deposits in the world. Wolfram Bergbau- and Hütten AG (WBH) operates the Felbertal scheelite mine since 1975 and produced so far some 12.5 million tonnes of ore, grading 0.50 wt% WO_3. In 2008, the mine was the second-largest tungsten mine in the western world, after Cantung in NW Canada.

The deposit is overall strata-bound, but best described as stockwork mineralisation and diffuse dissemination of scheelite in a polymetamorphic basic to ultrabasic volcano-sedimentary sequence intruded by a Variscan granitoid. The Eastern Ore Zone contained also more continuous quartz-rich layers with fine-grained "sheeted" mineralisation parallel to the foliation. Initially classified as syngenetic exhalative-sedimentary deposit genetically related to mafic volcanism alternative epigenetic granite-related models are now favoured.

2. Location and history

The Felbertal scheelite deposit is situated in the upper ranges of the Felber valley (Felbertal), a tributary of the Salzach, some 10 km south of the small town of Mittersill, Austria. As the crow flies, Munich is 125 km to the NW, Salzburg 75 km to the NE. It is located in the central chain of the central Eastern Alps (Hohe Tauern), at an outcrop elevation of 1175 to 2200 m. The Felber valley separates the deposit into an Eastern and a Western Ore Zone (Fig. 1a).

The 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. Scheelite occurred in carbonatic layers within epizonal black schists of Upper Silurian to Lower Devonian age. Both, synsedimentary-exhalative as well as epigenetic models are considered for the Tux deposit (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 the Mining University in Leoben, the other from the University of Munich. Scheelite is very brittle and thus not a good placer mineral. However, due to the high density contrast, it can still be easily identified in stream sediments close to the outcrop location. Due to the fluorescence under UV light, typical scheelite prospection consists of panning of stream sediments and subsequent UV lamping under dark cloth. 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 lamp.

The Leoben group aimed at occurrences in similar tectonic setting and lithology as the Tux deposit, while the Munich group was more generally interested in settings related to Palaeozoic submarine basic volcanism. Elevated scheelite contents were discovered in various stream sediments in the Upper Pinzgau area of the Hohe Tauern by both groups. The group around Höll and 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 the 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 boulder deposit (slightly dislocated scree in the Eastern Ore Zone) had been discovered and the outcrops of Eastern and Western Ore Zone delineated.

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, all these campaigns were abandoned.

Following the discovery of the Felbertal deposit, mining rights were secured by Metallgesellschaft AG of Frankfurt, Germany and detailed exploration of the deposit started. After 3000 m of diamond drilling (Fig. 1b) and 700 m of exploration drifting, Wolfram Bergbau- und Hüttengesellschaft was founded in 1973, 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. 1c, 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. It is currently planned to process some of the sub-grade material available on dumps in the open pit area.

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 (Spross, 1978, 1984). Due to its location close to a National Park and in an area of elevated avalanche risk, all auxiliary infrastructure 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.

By the end of 2008, the underground mine had produced 9.6 Mt of ore with 0.4-0.5 wt% WO_3. With exception of a two-year period in the mid-1990s, the mine was continuously in operation. Annual capacity is in the range of 0.4 Mt at 0.4 wt% WO_3, making it one of the most important tungsten mines in the Western world, and the biggest in Europe.

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 operations in the open pit (mid-1970s). All photos from WBH archives.

3. Geological setting

3.1. The Tauern Window in the Eastern Alps

The Alps formed due to subduction of a Mesozoic ocean and collision of the European (Penninic–Helvetic) and the Adriatic (Austroalpine–Southalpine) plates in the Cretaceous–Neogene. This classical collision belt was generated 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). 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-metamorphosed 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 largely overlying Penninic and Helvetic units. In the internal zone of the orogen the latter are exposed in several tectonic windows, the largest (160×40 km) being the Tauern Window.

Three major geologic units, which were all deformed and metamorphosed during the Alpine orogeny, are distinguished in the Tauern Window: (1) pre-Variscan rocks and basement, (2) igneous rocks of Variscan age (*ca.* 360–270 Ma); these dominant metagranitoids are referred to as Central Gneiss ("Zentralgneis"), (3) Permian to Mesozoic auto- to allochtonous metavolcano-sedimentary and metasedimentary rocks (Fig. 3).

Historically, the two main units of the Tauern Window are (Frasl, 1958): 1. The Schist Cover ("Schieferhülle") further subdivided into a Lower and an Upper Schist Cover and, (2) the Central Gneiss. Permo-Mesozoic rocks compose the Upper Schist Cover (Bündnerschiefer Series, Carbonate Rock Series, Wustkogel Series), whereas the Lower Schist Cover is composed of Pre-Permian rocks, namely the Habach Series ("Habachserie")[1] and polymetamophic crystalline basement rocks ("Altkristallin"). Both units were intruded by the Central Gneiss precursors during the Variscan orogeny. The Habach Complex is the largest (40×25 km) coherent area (Fig. 3) of Pre-Mesozoic volcano-sedimentary rocks in the central Tauern area and because it hosts the Felbertal tungsten deposit it will be dealt with in more detail in the following.

3.2. Pre-Variscan units in the Tauern Window

The largest area with Pre-Mesozoic volcano-sedimentary units is exposed in the central Tauern Window in the Habach Complex but comparable smaller units occur in the eastern and western parts of the Tauern Window, too (Fig. 3).

In the Felbertal area the Habach Complex was subdivided (from bottom to top) into the following units overlying a basal amphibolite member ("Basisamphibolit"; Höll, 1975, 1977):

- Basal schist unit ("Basisschieferfolge")
- Volcanic rock sequence (Eruptive sequence, "Eruptivgesteinsfolge")
- Phyllites ("Habachphyllit")

The tectonic contacts between the Basal schist unit and the underlying amphibolite and the overlying magmatic sequence are thrusts of Alpine age (Fig. 4).

This early subdivison was modified by Kraiger (1989), Höck (1993), Höck *et al.* (1993), who subdivided the volcanic rock sequence into two magmatic sequences: the Lower Magmatic Sequence (LMS) interpreted as the subvolcanic part of an ophiolite formed in a marginal basin and the calc-alkaline Upper Magmatic Sequence (UMS) showing characteristics of

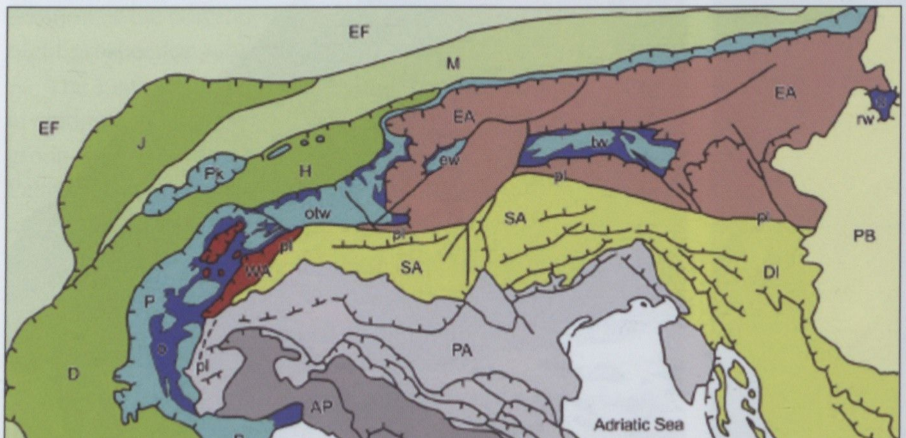

Fig. 2. Tectonic map of the Alps (from Dal Piaz *et al.*, 2003) showing the location of the Tauern Window in the Eastern Alps. (1) Europe-vergent collisional belt: **i)** Western (WA) and Eastern (EA) Alps; **ii)** Penninic domain: continental and ophiolitic (o) nappes in the Western Alps and tectonic 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.

[1] In the later literature also referred to as H. Formation, H. Group, H. Complex or H. Terrane. Because these rocks are metamorphosed, fossil-free with still unclear age relationships the term Habach Complex is used in this paper.

a continental island arc. The Habach pyllites were interpreted as the sedimentary cover of the UMS with minor intercalations of volcanic rocks showing within plate characteristics.

Höck *et al.* (1993) also extended this classification to the whole Pre-Mesozoic volcano-sedimentary units in the Tauern Window, distinguishing:

- Ophiolites
- Island arc systems
- The Eiser Sequence

Ophiolites are present in the LMS and in the Basisamphibolit (syn. Stubach Group). In the LMS the ophiolites include metamorphosed ultramafic to mafic igneous rocks; *i.e.,* lenticular bodies of serpentinites, hornblendites, metgabbros (coarse-grained amphibolites), dykes and eruptive flows (fine-grained amphibolites). At the Felbertal scheelite deposit, rocks of the LMS are regarded as a dismembered ophiolite and include fine-grained amphibolite, with intercalations of layers of hornblendite, medium-grained amphibolite and amphibolite with hornblende phenocrysts (Kraiger, 1989; Höck *et al.*, 1993). The fine-grained and some of the medium-grained amphibolites are tholeiitic in composition, having MORB affinities (with possible influence of a subduction component) and they formed in a marginal oceanic or back-arc basin. The other rocks within the LMS resemble the overlying island arc sequence (Höck *et al.*, 1993). The island arc system is composed of basic to acidic igneous rocks (amphibolites, prasinites, biotite-epidote gneisses, albite gneisses, meta-agglomerates) with intercalations of clastic sediments (micachists, phyllites). Geochemical data indicate calc-alkaline magma characteristics and magma generation in a mature arc system, likely in a continental arc. The island arc sequence is in stratigraphic contact with the overlying dark phyllites (Habach phyllites).

The Eiser sequence ("Biotitporphyroblastenschiefer") is composed of metasediments (biotite-rich schists, metagreywackes, graphitic quartzites, garnet-micaschists) and intercalated mafic to acidic metavolcanics. The latter also formed in an arc setting, likely in an oceanic arc. At the scheelite deposit, this sequence is correlated with the Basal schist unit, composed of predominantly metasediments with intercalations of minor amphibolites and felsic intrusives that formed at an active continental margin (Höll & Eichhorn, 2000).

The contact between the Basal schist unit and the LMS has been interpreted as stratigraphic (Höll, 1975) *versus* tectonic (Kraiger, 1989); the latter author interpreted the contact as a larger tectonic melange zone. The age relationships between these two units are unresolved.

U-Pb dating and careful field observations revealed the intrusive nature of some of the orthogneisses in the whole magmatic sequence, which formerly were all regarded as felsic metavolcanics. These orthogneisses largely represent I-type grani-

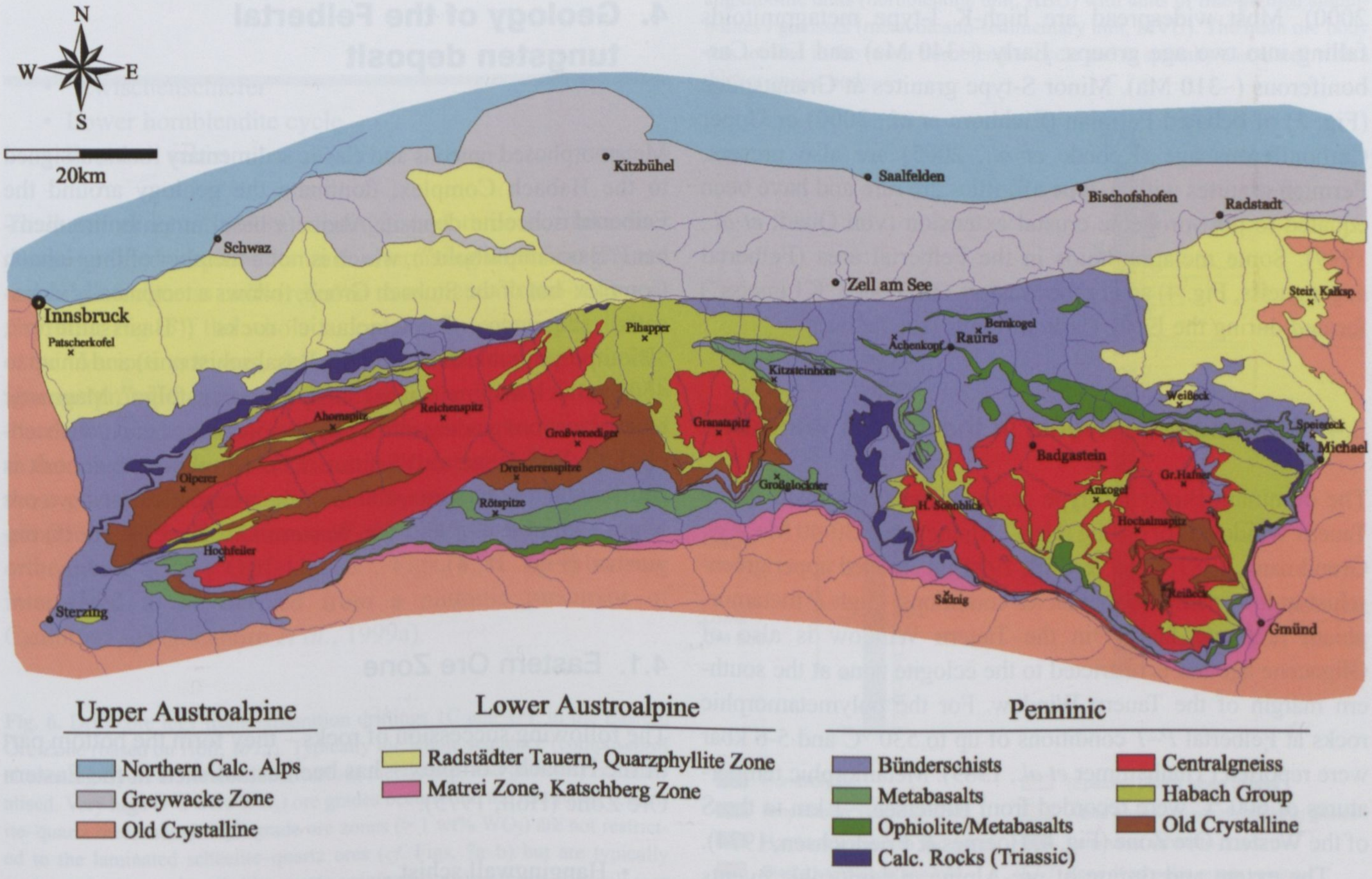

Fig. 3. Geological sketch map of the Penninic Tauern Window and its Austroalpine framework (Höck, 2000).

toids of Cambrian age, which are slightly younger than the fine-grained amphibolites (Eichhorn *et al.*, 1999a). As a consequence, the former Volcanic rock sequence has been renamed to Magmatic rock formation in the more recent papers (*e.g.*, Höll & Eichhorn, 2000).

The Magmatic rock formation is a sequence of 1.5 to 4 km-thick igneous rocks of variable composition and minor metasedimentary rocks. Fine-grained amphibolites (tholeiitic to minor calc-alkaline protoliths) in the lower section are correlated with the ophiolitic unit (*cf.* LMS). The upper section (*cf.* UMS) is composed of amphibolites (calc-alkaline protoliths) and a variety of intrusive orthogneisses, likely formed at an active continental margin. The Habach phyllites (dark phyllite, minor micachist, quartzite, metavolcanics) are part of an accretionary wedge (Höll & Eichhorn, 2000).

3.3. Central Gneisses

During the Variscan orogeny, granitoids (orthogneisses constituting the Central Gneiss, Fig. 3), classified as I-type and to a minor extent as S- and A-type granitoids (Finger & Steyrer, 1988; Finger *et al.*, 1993) intruded these Early Palaeozoic sequences. 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 to the 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. 3) 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). Some metagranitoids in the Felbertal area (Felbertal augengneiss, Fig. 4) and in the Western Ore Zone ("K1 gneiss") formed during the Early Carboniferous (see below).

3.4. 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; Inger & Cliff, 1994); it reached upper greenschist to lower amphibolite facies conditions. High-*P* metamorphism (eclogite facies) in the Tauern Window is also of Oligocene age but is restricted to the eclogite zone at the southern margin of the Tauern Window. 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 recorded from Hintersee, ~1 km to the S of the Western Ore Zone (Fig. 4, Hoernes & 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 in the Habach Complex was provided by Grundmann & Morteani (1982) and *P-T* conditions of 420 °C and 2 kbar were reported by Koller & 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 Sm-Nd isochron age of 319 ± 34 (Eichhorn *et al.*, 1997) for one of the four scheelite generations (Scheelite 3, see below) at Felbertal 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). 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 & Stein, 2006).

Evidence for even older metamorphic events has been 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 in the Habach Complex. Von Quadt *et al.* (1997) reported eclogites of Silurian age (~420 Ma). Re-Os molybdenite ages of 414-417 Ma at Felbertal could correspond with this Silurian metamorphic event (Raith *et al.*, 2003).

4. Geology of the Felbertal tungsten deposit

Metamorphosed igneous and clastic sedimentary rocks, assigned to the Habach Complex, dominate the geology around the Felbertal scheelite deposit. Above a basal amphibolite member ("Basisamphibolit"), which is not a member of the Habach Complex but of the Stubach Group, follows a tectonically imbricated sequence of metaclastic rocks ("Basisschiefer", "Biotitporphyroblastenschiefer", Basal schist unit) and an up to 4500 m thick magmatic unit ("Eruptivgesteinsfolge", Magmatic rock formation) grading into a phyllite-dominated unit ("Habachphyllit"; Fig. 4; see also Section 3.2). The scheelite deposit is restricted to the bottom ~400 m of the magmatic unit. Two ore zones – the Eastern and the Western Ore Zones – are distinguished (Figs. 1a, 4).

4.1. Eastern Ore Zone

The following succession of rocks – they form the bottom part of the Habach Complex – has been established in the Eastern Ore Zone (Höll, 1975).

- Hangingwall schist
- Upper hornblendite cycle

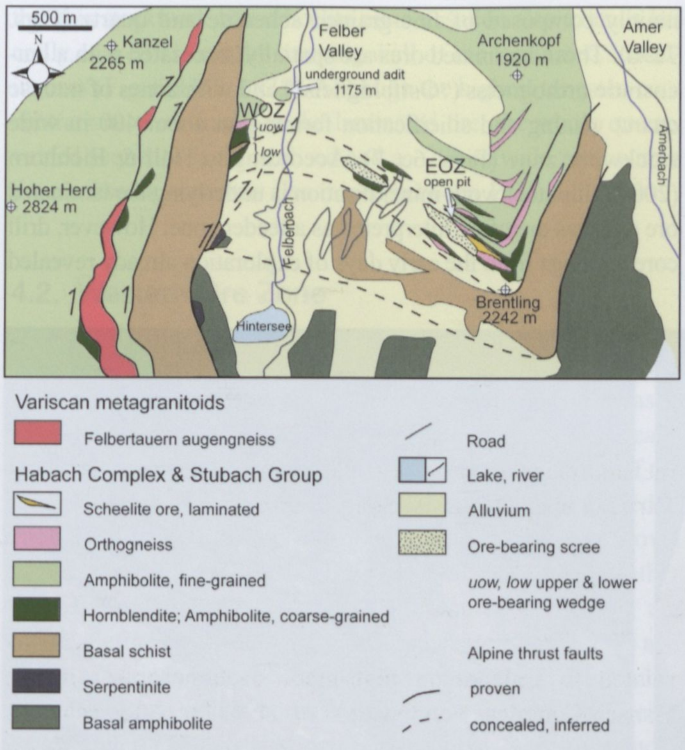

Fig. 4. Simplified geological map of the area around the Felbertal tungsten deposit (from Höll & Eichhorn, 2000) showing the location of the Eastern Ore Zone, EOZ, and the Western Ore Zone, WOZ. Alpine thrust(-slip) faulting caused the stacking of the Basal Amphibolite (Stubach Group) and rocks of the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

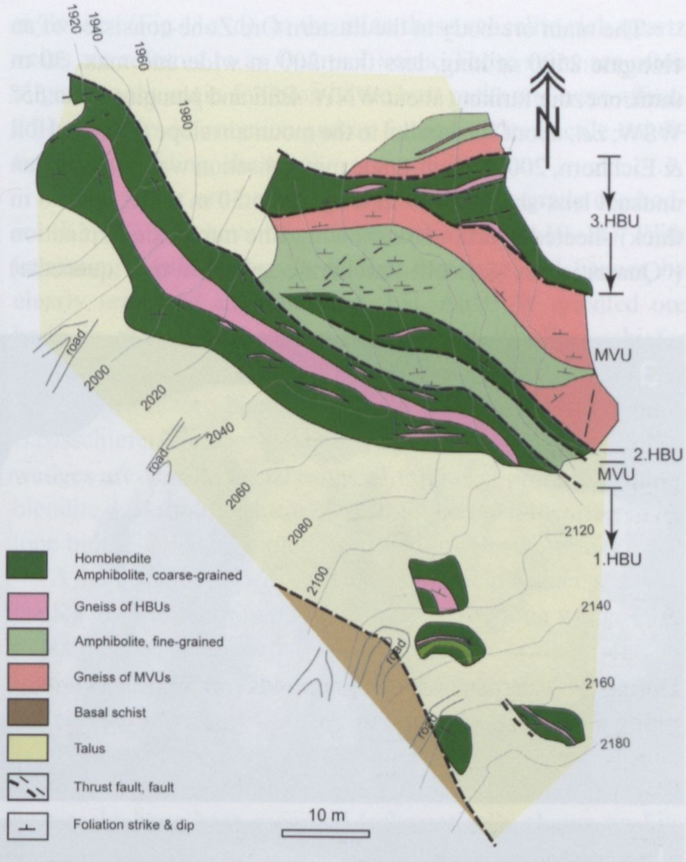

Fig. 5. Geological map of the Eastern ore field (from Thalhammer *et al.*, 1989) showing the repeated succession of hornblendite / coarse-grained amphibolite units (hornblendite unit, HBU) with units of fine-grained amphibolites / gneisses (metavolcano-sedimentary unit, MVU). The main ore body was located in the lower hornblendite cycle and is spatially associated with a thicker gneiss body.

- "Zwischenschiefer"
- Lower hornblendite cycle
- Footwall schist

Thalhammer *et al.* (1989) distinguished three hornblendite/coarse-grained amphibolite units alternating with fine-grained amphibolites/gneiss units (referred to as metavolcano-sedimentary unit; Fig. 5); the whole succession is tectonically imbricated. Various gneisses, derived from intermediate to acidic igneous protoliths, form elongate lenticular bodies to layers in the metabasites. A major thicker orthogneiss body is located in the lowermost hornblendite unit. Whereas in the early days these gneiss intercalations were interpreted as of volcanic origin (Höll, 1975; Thalhammer *et al.*, 1989), at least one major orthogneiss body ("Ostfeldgneis", Figs. 5, 6, 7d–e) is now interpreted to be derived from a plutonic precursor of Cambrian age (Eichhorn *et al.*, 1999a).

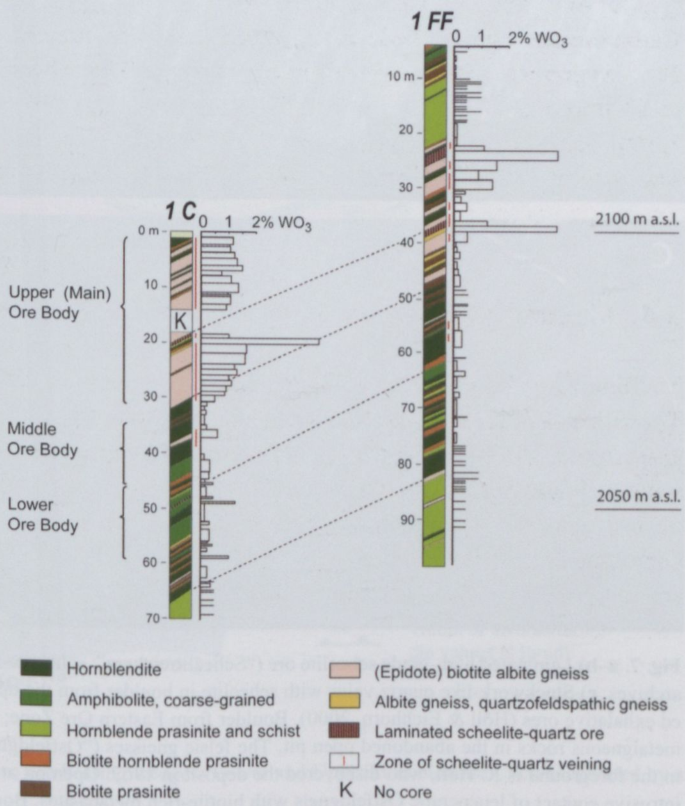

Fig. 6. Drill core logs from exploration drillings 1C and 1FF in the Eastern Ore Zone (based on Höll, 1975). Typically the whole sequence (composed of alternating layers of hornblendite, various metabasites and gneisses) is mineralised. Very high (> 2 wt% WO_3) ore grades occurred in the laminated scheelite–quartz ores, though high-grade ore zones (> 1 wt% WO_3) are not restricted to the laminated scheelite–quartz ores (*cf.* Figs. 7a–b) but are typically associated with stockwork-like quartz veining occurring in the footwall (see Fig. 7c) as well as in the hangingwall of the laminated ores.

The main ore body in the Eastern Ore Zone consisted of an elongate 2500 m long, less than 200 m wide and max. 30 m thick ore zone striking about WNW–ESE and plunging 25 to 55° WSW; *i.e.,* about subparallel to the mountain slope (Fig. 1c; Höll & Eichhorn, 2000). High-grade mineralisation was hosted by an unusual lens-shaped (900 m long, up to 50 m wide, up to 8 m thick) sheeted quartz mass showing fine mm-scale lamination ("Quarzitisches Scheelit-Reicherz", scheelite-rich quartzite) mainly composed of fine-grained scheelite and quartz (Figs. 7a–b). These laminated ores are spatially associated with a leucocratic orthogneiss ("Ostfeldgneis") and with zones of intense quartz veining and silicification forming an about 400 m wide stockwork zone (Figs. 6c, 7). According to Höll & Eichhorn (2000), this stockwork mineralisation is underlying the laminated ore and was therefore interpreted as a feeder zone. However, drill core loggings from the early days of exploration already revealed

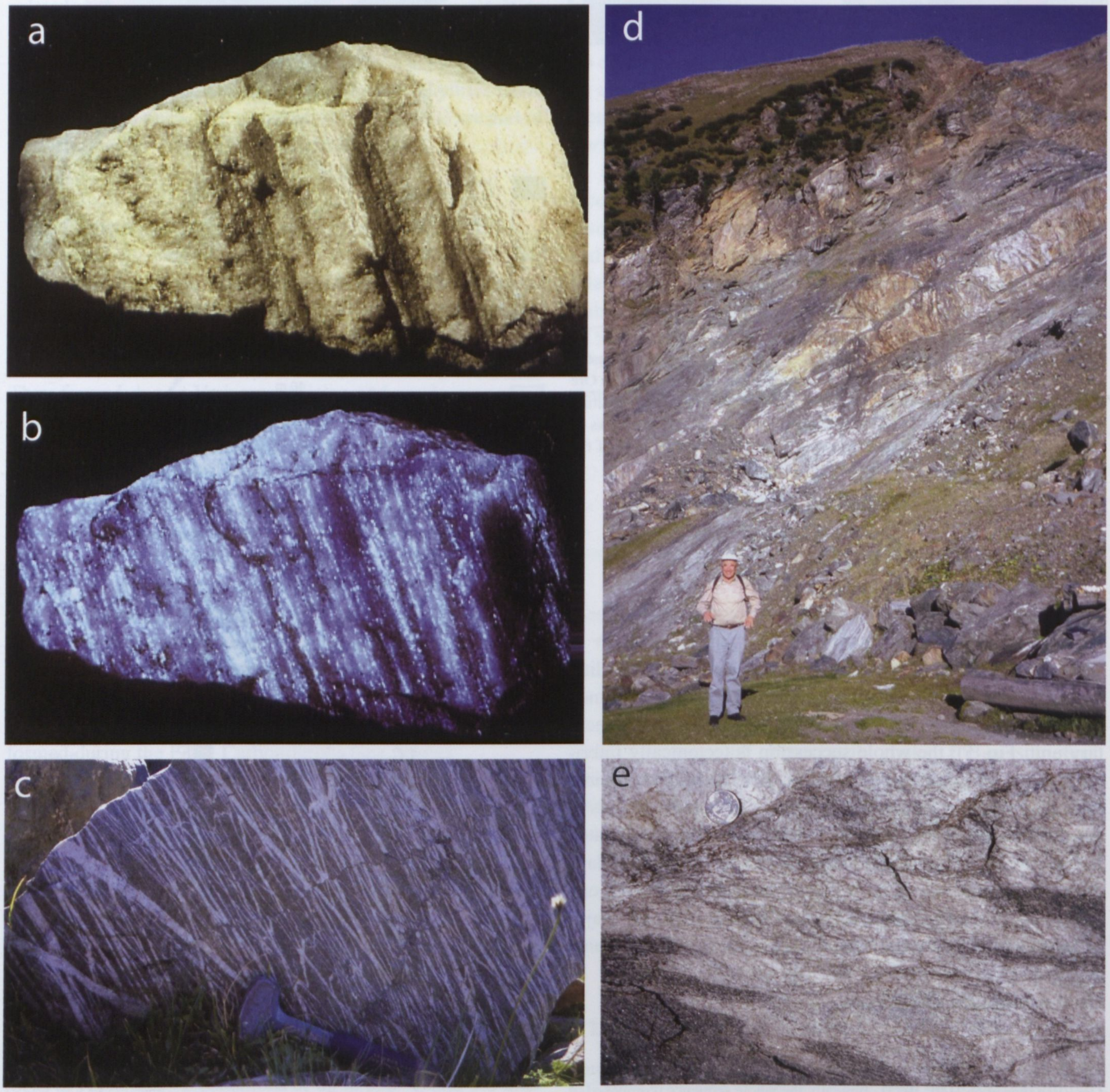

Fig. 7. a–b) Laminated high-grade scheelite ore ("Scheelitreicherz"; scheelite-rich quartzite) from the Eastern Ore Zone. (b) in UV light. Photograph fom WBH archives. **c)** Stockwork-like quartz veins with scheelite in boulder from the open pit. These stockwork ores were interpreted as the feeder zone of the laminated exhalative ores (Höll & 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 ("Ostfeldgneiss") 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 Ostfeldgneis with biotite-rich metabasites. Boulder in open pit at ~1930 m, Ostfeld; photo J.G. Raith, September 1999.

that this stockwork-like scheelite mineralisation also extends laterally as well as into the hanging wall of the laminated scheelite ores (Fig. 6; Höll, 1975). Although the highest tungsten concentrations were found in the laminated ore, the whole quartz-veined sequence is mineralised and a ~200 m wide zone within the stockwork zone was also mined between 1975 and 1986.

4.2. Western Ore Zone

The Western Ore Zone is separated into 3 major tectonic wedges (Figs. 8–9). A barren wedge of clastic rocks ("Basisschieferschuppe") separates two mineralised wedges, each containing several ore bodies (Schmidt, 1988). Features of the mineralisation as exposed in February 2009 are documented in Figs. 10–12. A 3D model of the underground mine is shown in Fig. 13. It is to be noted that the mineralisation is of a rather pervasive nature and the ore bodies, named K1 to K8, are merely defined by the cut-off grade. Scheelite is ubiquitous and found in various host rocks (fine- and coarse-grained amphibolite, hornblende schist, hornblendite, biotite schist, orthogneiss, quartz-rich rocks etc.) although economic ore grades commonly correlate with the total quartz content. Economic ore bodies are therefore commonly zones with intense stockwork-like quartz veining (Fig. 10a) or shear zones containing scheelite–quartz mylonites (Fig 11c–d). In the mine these scheelite-rich quartz veins are referred to as Quartz 1 veins. These veins are often aligned to the main foliation of the host rocks and were affected by ductile deformation and/or formed under ductile conditions (*e.g.*, folding, shearing).

In the upper ore-bearing wedge three high-grade ore bodies (K1, K2, K3) have been distinguished (Figs. 10–11). With increasing depth, these ore bodies converge and cannot be clearly separated anymore (Fig. 13). An E–W oriented ore body in the immediate hanging wall of the Basisschiefer wedge is referred to as K4. Ore bodies K5 to K8 are located in the lower ore-bearing wedge in the footwall of the Basisschieferschuppe. The host rocks in both ore-bearing wedges are various metabasites of the lower and upper hornblendite cycle, which due to Alpine folding and shearing envelope biotite-epidote-amphibolite and hornblende schists.

A horseshoe shaped muscovite-microcline gneiss, called the K1 gneiss, is exposed in the upper ore-bearing wedge (Fig. 8). Its horseshoe shape is caused by a large-scale Alpine (?) fold structure with an about SW plunging fold axis. The K1 gneiss is a leucocratic orthogneiss showing strong foliation, especially at its margins (Fig. 11a). In less deformed parts apophyses of the K1 granite and intrusive contacts with the host rocks have been recorded (schematically shown on Fig. 9). Moreover, elongate to planar lenses and rafts of host rocks

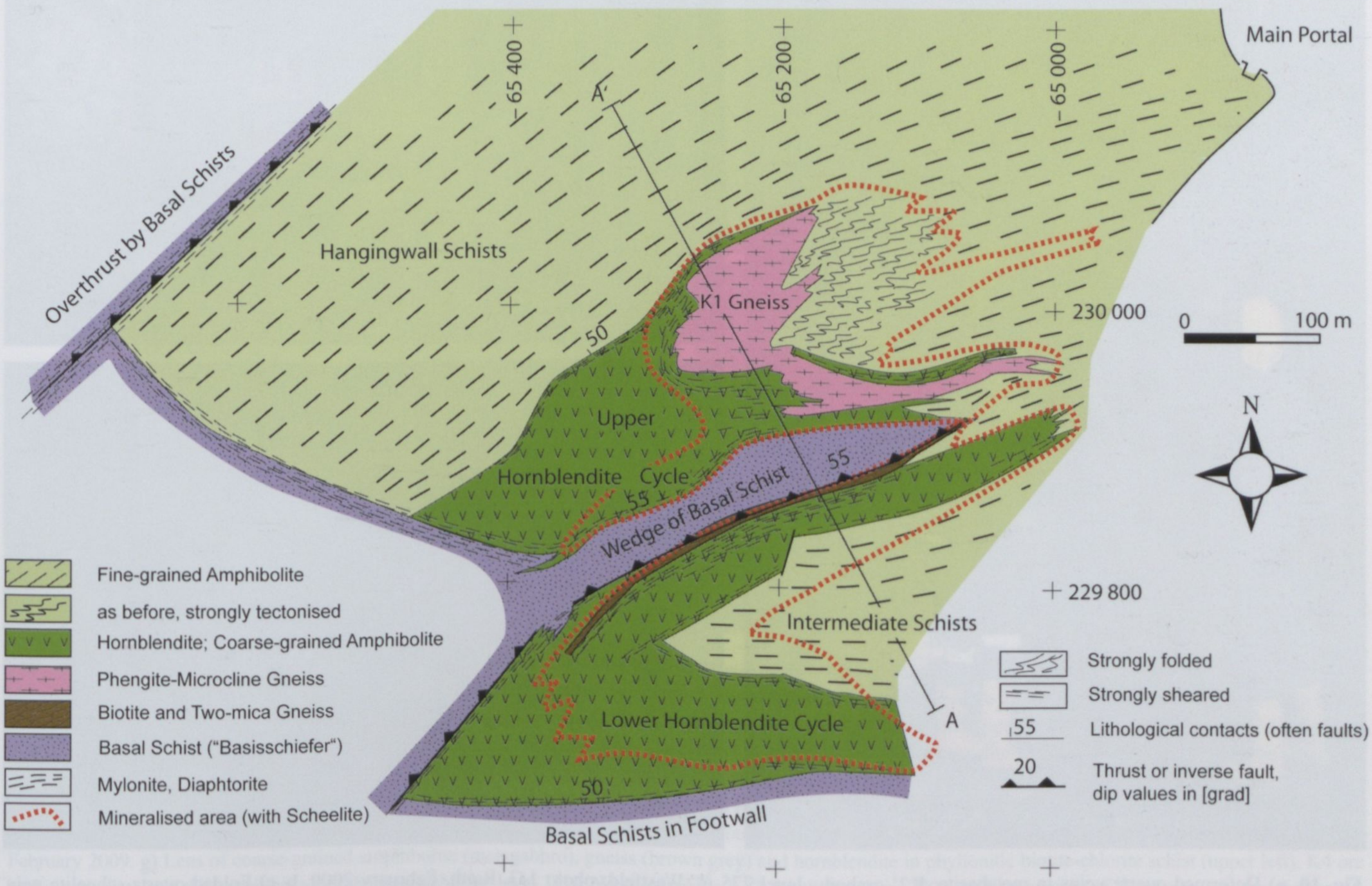

Fig. 8. Geological sketch of level 1175 of the Western Ore Zone showing the two ore-bearing wedges (Lower and Upper Hornblendite Cycle) separated by a barren wedge of Basal Schists (from Schmidt, 1988).

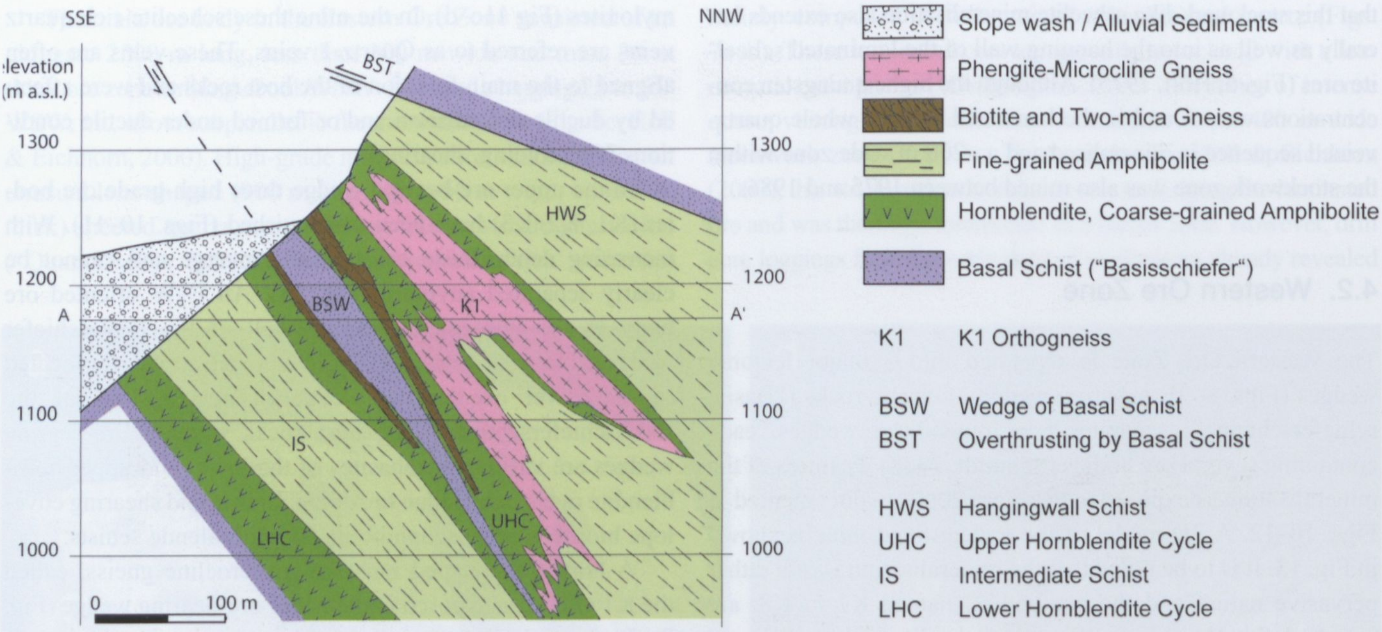

Fig. 9. SSE–NNW profile through the Western Ore Zone; for exact location see A–A' on Fig. 8 (from Schmidt, 1988).

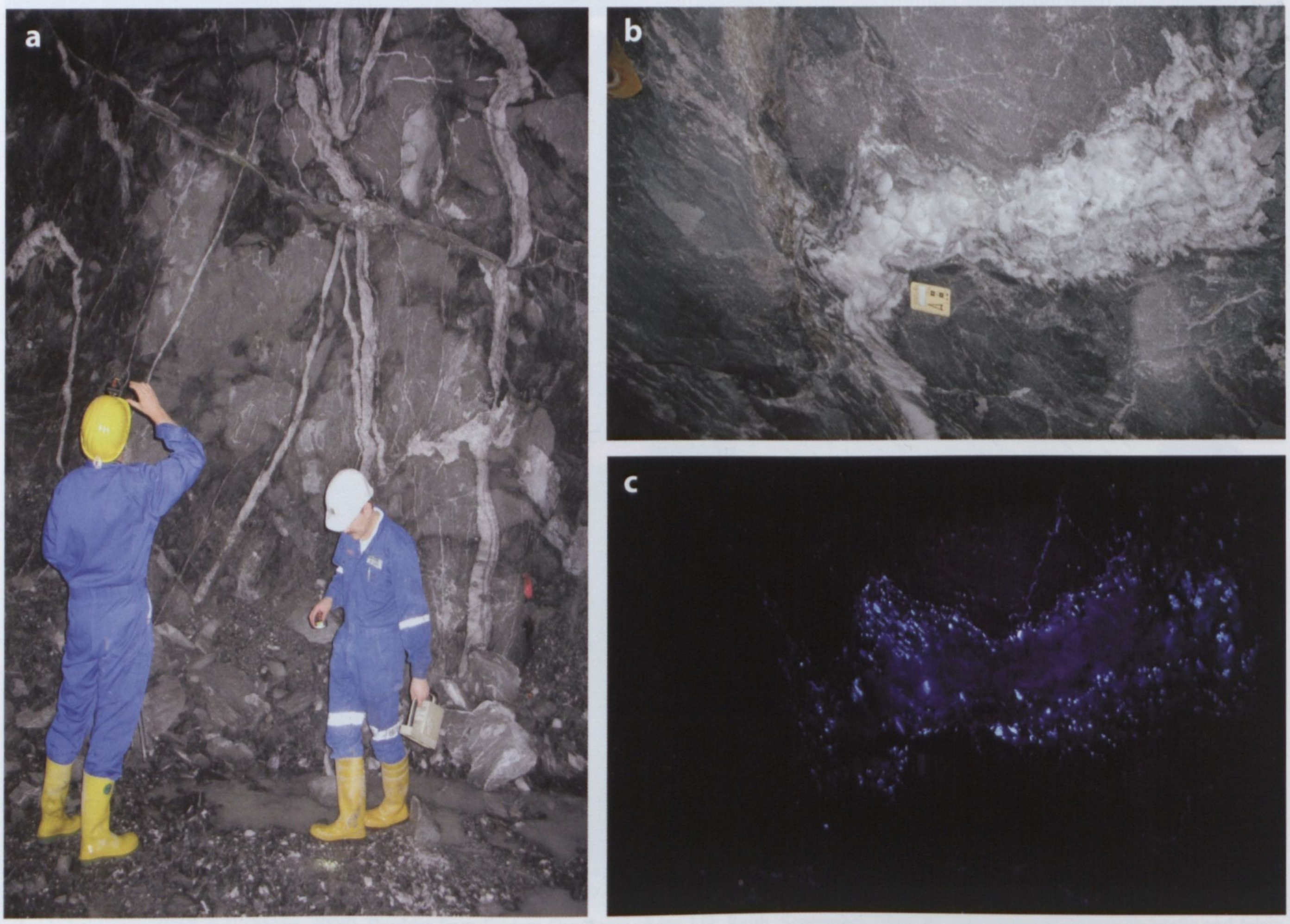

Fig. 10. a) Deformed quartz veins in metabasite. K2' orebody, level 775 m, Westfeld; photo J.G. Raith, February 2009. **b–c)** Folded quartz-scheelite vein (Quartz 1) in dark metabasites. Scheelite is concentrated toward the vein selvages. Larger scheelite porphyroblasts (Scheelite 2) show yellowish fluorescence in UV light. K2' orebody, level 775 m, Westfeld; photo S. Schmidt, February 2009.

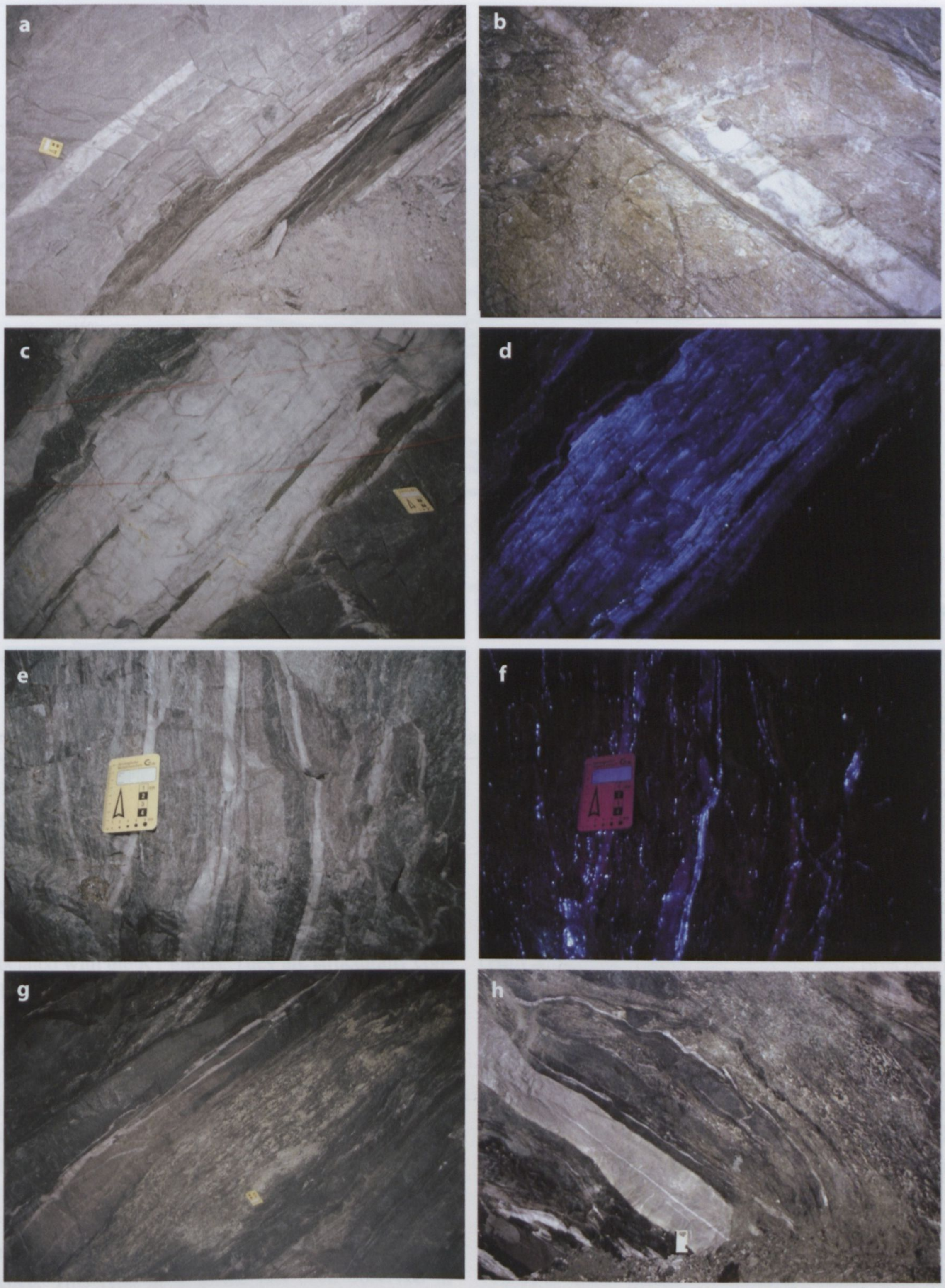

Fig. 11. a) Well-foliated K1 gneiss with deformed quartz vein (Quartz 1) and rafts of strongly deformed hornblende-biotite schists. K1' ore body, level 1164, Westfeld; photo J.G. Raith, February 2009. **b)** A ~10 cm thick deformed quartz vein containing elongate scheelite (grey, Scheelite 2) in K1 gneiss. The mineralised vein crosscuts the Early Carboniferous granite gneiss (336 ± 19 Ma, Eichhorn *et al.*, 1995) but shows penetrative deformation. Upper part of K1 orebody, level 1152, Westfeld; photo J.G. Raith, September 1999. **c)** Laminated scheelite ore. Note the foliation-parallel thin rafts of darker and scheelite-free/-poor host rocks within the about 1 m thick laminated scheelite–quartz mass. K2 ore body, Level 1000 m, Westfeld. **d)** The same in UV light; photos S. Schmidt, February 2009. **e)** Interlayered gneiss (grey) metabasite (greenish) sequence truncated by about foliation-parallel quartz veins (Quartz 1). **f)** The same 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, Westfeld; photos S. Schmidt, February 2009. **g)** 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, Westfeld; photo J. G. Raith, February 2009. **h)** 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 ore-body, level 1050, Westfeld; photo J.G. Raith, February 2009.

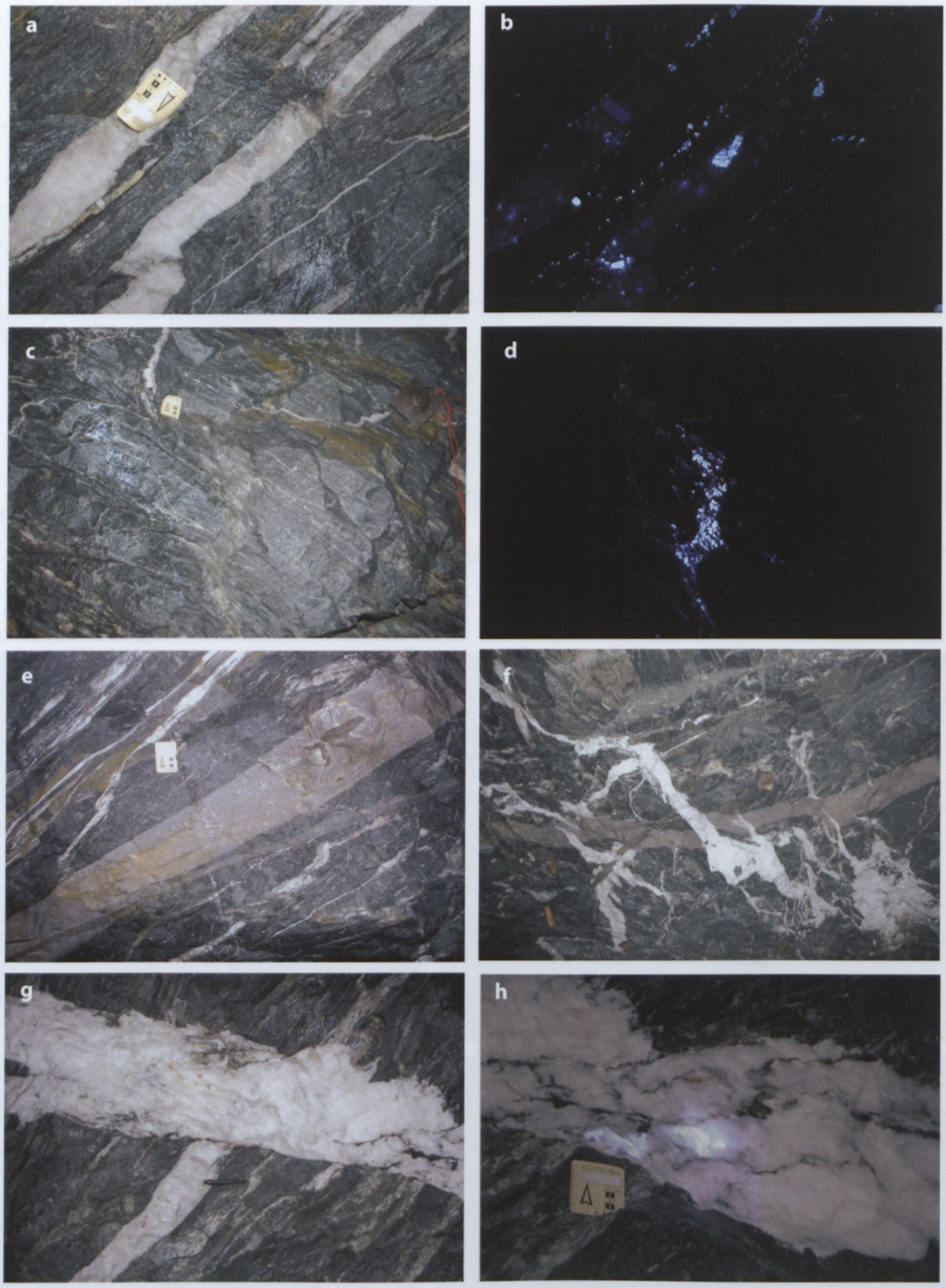

Fig. 12. a–b) Two scheelite-bearing quartz veins (Quartz 1) in dark-coloured host rocks (so-called “Schwarzerz”), (b) in UV light. The veins are aligned in the main foliation of fine-grained amphibolite. Scheelite is concentrated in the veins forming larger porphyroclasts (greyish in normal, yellowish fluorescence in UV light; Scheelite 2). Finer-grained re-crystallised scheelite (white, bluish fluorescence, Scheelite 3) is aligned in stringers. Level 1152 hanging wall, Westfeld; photos S. Schmidt, February 2009. **c–d)** Dark scheelite ore (“Schwarzerz”), (d). in UV light. Scheelite occurring along a discordant zone of fluid transport in dark coloured metabasite. Level 1152 m hanging wall, Westfeld; photos S. Schmidt, February 2009. **e)** Dyke of 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 m hanging wall, Westfeld; photo J.G. Raith, February 2009. **f)** 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 m hanging wall, Westfeld; photo J.G. Raith, February 2009. **g–h)** Discordant quartz vein (Quartz 2) crosscutting and displacing a scheelite-bearing quartz vein (Quartz 1). Level 1152 m hanging wall, Westfeld; photo J.G. Raith, February 2009. (h) Detail of (g). Combined normal and UV light. Up to 5 cm large crystals of scheelite showing bluish-whitish fluorescence (Scheelite 4) in Quartz 2 vein. These veins and this last scheelite generation formed due to local remobilisation of quartz and tungsten during Barrovian-type Young Alpine metamorphism. Level 1152 m hanging wall, Westfeld; photo S. Schmidt, February 2009.

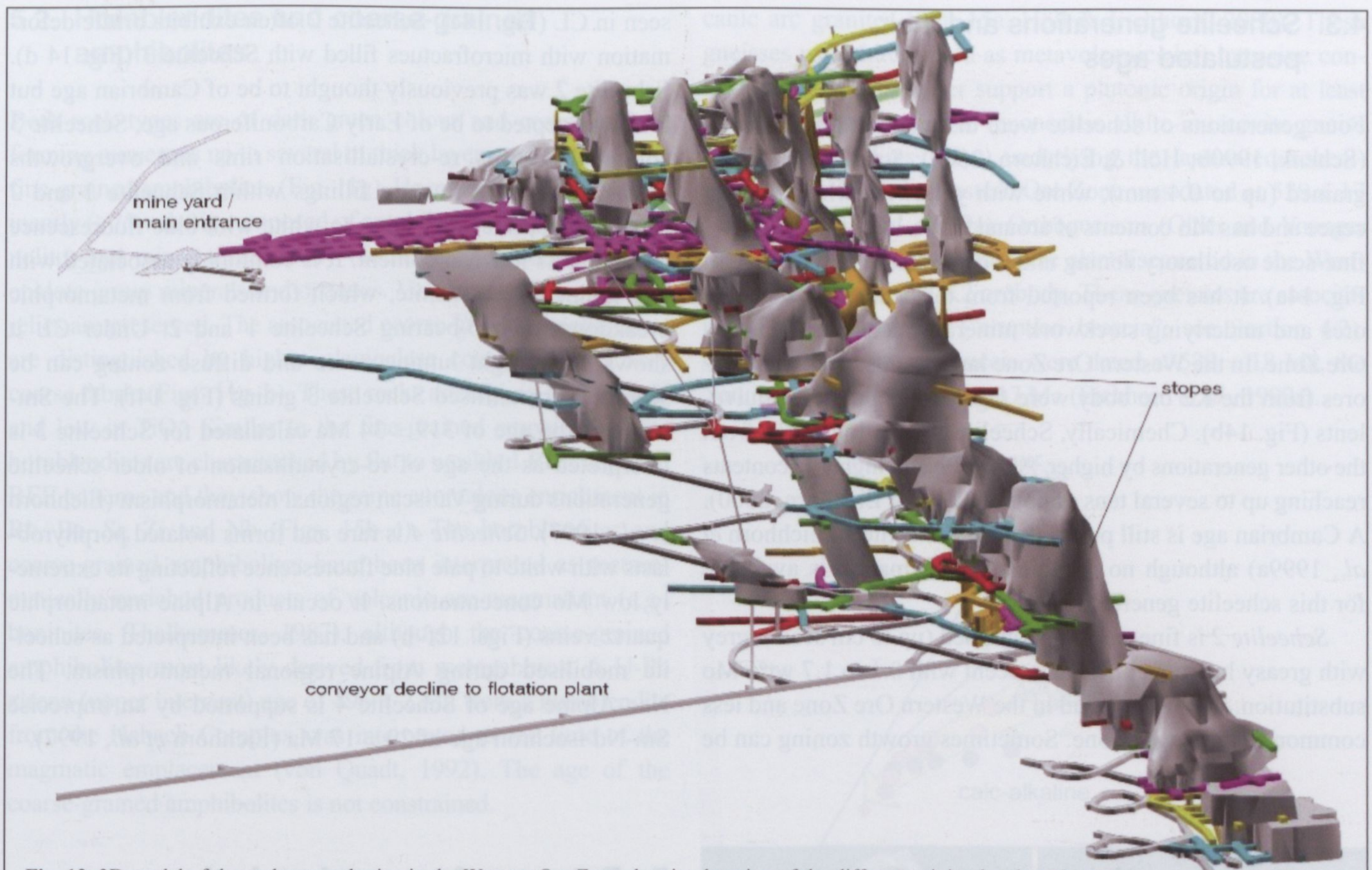

Fig. 13. 3D model of the underground mine in the Western Ore Zone showing location of the different mining levels and stopes.

occur as deformed xenoliths in the K1 gneiss (Fig. 11a). These observations confirm the intrusive nature of the gneiss protolith. This Lower Carboniferous granite gneiss is neither exposed in the Eastern Ore Zone nor on the surface in the Western one.

Two ore bodies (K1-K3) of major economic importance are spatially associated with the K1 gneiss. They are structurally controlled by NE–SW and E–W trending shear zones, preferentially developed at the margins of the gneiss (Fig. 8) and the host rocks, converging towards deeper levels in the mine. Metre-thick foliated masses of pure quartz are developed at the margins of and within the gneiss. As can be deduced from geological maps and profiles (Schenk, 1990a) the major quartz mass within the K1 gneiss has a lentoid morphology which plunges about NW to NNW; it extends to >300 m towards depth and is up to 30 m thick. Scheelite in the K1-K3 ores (Scheelite 2, see below) forms large up to cm-sized porphyroclasts and is of greyish colour and yellowish fluorescence. This type of scheelite has been observed in deformed quartz veins within the Lower Carboniferous K1 gneiss (Fig. 11b) thus excluding a pre-Variscan age of this mineralisation.

The K2 ores are finely laminated scheelite–quartz ores of high grade (Figs. 11c–d). Fine-grained scheelite and quartz are strongly re-crystallised defining a mylonitic fabric. Scheelite porphyroclasts (several mm in size, yellowish fluorescent) re-crystallising to even smaller scheelite (bluish fluorescent) are aligned in stringers (Figs. 11c–d). Elongate to planar xenoliths included in the scheelite–quartz masses are scheelite-free. These ores are similar to the high-grade laminated scheelite–quartz ores from the Eastern Ore Zone (Figs. 7a–b). In the upper mine levels (not preserved and accessible any more) the K2 ores were associated with a scheelite-bearing strongly deformed breccia. The latter was interpreted as volcanic eruption breccia ("Eruptionsbrekzie") and the associated laminated ores as exhalites (Höll & Schenk, 1988); *i.e.,* as syngenetic ores. An alternative explanation, favoured by the first author, is that these ores are scheelite–quartz mylonites. The associated breccia could either be of tectonic or of magmatic-hydrothermal origin.

Ore body K2' is the continuation of these laminated ores towards depth and in February 2009 it was exposed at level 775 (Figs. 10a, c–d). It is a set of deformed dm-thick composite quartz veins. Scheelite is concentrated in the marginal parts of the deformed veins (Figs. 10b–c).

The K4 ores currently mined are either metabasite-gneiss sequences with intense Quartz 1 veining (*e.g.*, level 1164; Figs. 11e–f) or shear zones; the latter are exposed in the hanging-wall of the wedge of basal schists 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, Fig. 11 g).

The K5 ore body is situated in the footwall of the Basisschiefer wedge. Scheelite is found in Quartz 1 veins as well as disseminated in the metabasites. In addition to the metabasites intercalations of metre-thick mineralized orthogneisses were observed on level 1050.

4.3. Scheelite generations and their postulated ages

Four generations of scheelite were distinguished at Felbertal (Schenk, 1990b; Höll & Eichhorn, 2000): *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% and shows fine-scale oscillatory zoning under cathodoluminescence (CL; Fig. 14a). It has been reported from the laminated scheelite ores and underlying stockwork mineralisation in the Eastern Ore Zone. In the Western Ore Zone laminated scheelite–quartz ores from the K2 ore body were regarded as possible equivalents (Fig. 14b). 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 & Eichhorn, 2000). A Cambrian age is still postulated for Scheelite 1 (Eichhorn *et al.*, 1999a) although no reliable age information is available for this scheelite generation.

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 one. Sometimes growth zoning can be seen in CL (Fig. 14c). Scheelite 2 often exhibits brittle deformation with microfractues filled with Scheelite 3 (Fig. 14 d). Scheelite 2 was previously thought to be of Cambrian age but is now accepted to be of Early Carboniferous age. Scheelite 3 commonly forms re-crystallisation rims and overgrowths around as well as fracture fillings within Scheelite 1 and *2* (Figs. 14a–b, d–e). It is grey to white with blue fluorescence reflecting its low Mo content. It is commonly associated with fine-grained molybdenite, which formed from metamorphic breakdown of Mo-bearing Scheelite 1 and 2. Under CL it shows very bright luminescence and diffuse zoning can be seen in recrystalllised Scheelite 3 grains (Fig. 14f). The Sm-Nd isochron age of 319 ± 34 Ma calculated for Scheelite 3 is interpreted as the age of re-crystallisation 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 (Figs. 12f–h) 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).

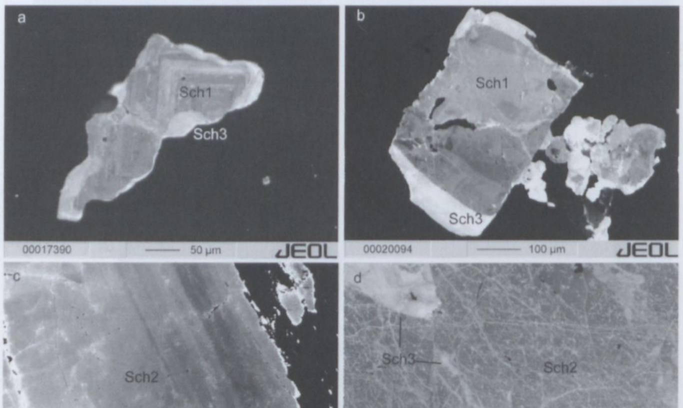

Fig. 14. Cathodoluminescence (CL) images of scheelite from the Felbertal deposit. **a)** Scheelite 1 (Sch1) with fine oscillatory zoning overgrown by CL-brighter Scheelite 3 (Sch3); laminated scheelite–quartz ore, Ostfeld. **b)** Scheelite 1 with rim of Scheelite 3; K2 orebody, Westfeld. **c)** Large 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.

5. Petrography, geochemical characterisation and age of the host rocks

For a more complete compilation the reader is referred to the review paper by (Höll & Eichhorn, 2000). Only a brief summary is given in the following.

5.1. Fine-grained amphibolites

These are fine-grained (<0.5 mm) banded and foliated rocks composed of variable amounts of major amphiboles, plagioclase, biotite, garnet and epidote group minerals and minor chlorite, muscovite, carbonate, quartz and opaques. Hornblende prasinites and hornblende schists also belong to this group of amphibolites. The protoliths of 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 whole magmatic sequence (Fig. 15 a, Höll & Eichhorn, 2000). Fine-grained amphibolites show flat REE patterns similar to MORB but are enriched in LIL elements, especially in Rb (Figs. 15b–c). These rocks could have been derived from pillow basalts as well as tuffs. Zircons from a fine-grained amphibolite yielded a U-Pb SHRIMP age of 547 ± 27 Ma interpreted as an emplacement age (Eichhorn *et al.*, 1999a). Hence, these rocks are the oldest rocks of the Habach Complex.

5.2. Hornblendites and coarse-grained amphibolites

Both rock types are of dark green colour and coarse-grained forming numerous up to several m thick layers and lenses in the fine-grained amphibolites (Fig. 11g). Hornblendites are predominantly (>75 vol. %) composed of amphiboles (hornblende, actinolite) and minor to accessory biotite, plagioclase, carbonate, epidote group minerals and opaques. Very rarely, clinopyroxene relics are preserved. The associated coarse-grained amphibolites are distinguished by higher plagioclase contents and a very coarse fabric (Figs. 11g–h). 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 weakly LREE depleted REE patterns and they show the same anomalous enrichment in Rb, Ba, Sr, Zr and Nb (Figs. 15b–c). The hornblendites and coarse-grained amphibolites have been interpreted as metasomatically enriched products of volcanic arc magmatism (*e.g.*, boninites, Thalhammer, 1987), although the coarse-grained amphibolites most likely derived from metagabbros. A 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 age of the coarse-grained amphibolites is not constrained.

5.3. Pre-Variscan orthogneisses

Intermediate to felsic orthogneisses occur as several meters thick intercalations in the more mafic host rocks (Figs. 7d–e; Fig. 11h). Petrographically, a wide spectrum of gneiss types is distinguished including biotite-albite gneiss, epidote-biotite-albite gneiss, hornblende gneiss, muscovite-albite gneiss etc. These gneisses contain variable amounts of major 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 are the intermediate to felsic members of the Early Palaeozoic arc system; they show chemical similarities with calc-alkaline I-type volcanic arc granites (Fig. 15a, Höll & Eichhorn, 2000). These gneisses were interpreted as metavolcanics but intrusive contacts and age data rather support a plutonic origin for at least some of the gneisses. The leucocratic albite-muscovite gneiss (Ostfeldgneiss; Figs. 7d–e) underlying the laminated scheelite–quartz ores in the Eastern Ore Zone was dated at 529 ± 17 Ma (Eichhorn *et al.*, 1999a). Orthogneisses (Older and Younger K2 gneiss) of intrusive origin were also discovered in the Western Ore Zone near the K2 orebody. These gneisses are associated with a metabreccia ("eruption breccia"; see Section 4.2). Gneiss clasts from the breccia were dated at 529 ± 18 Ma, the Younger K2 gneiss at 529 ± 17 Ma (Eichhorn *et al.*, 1999a).

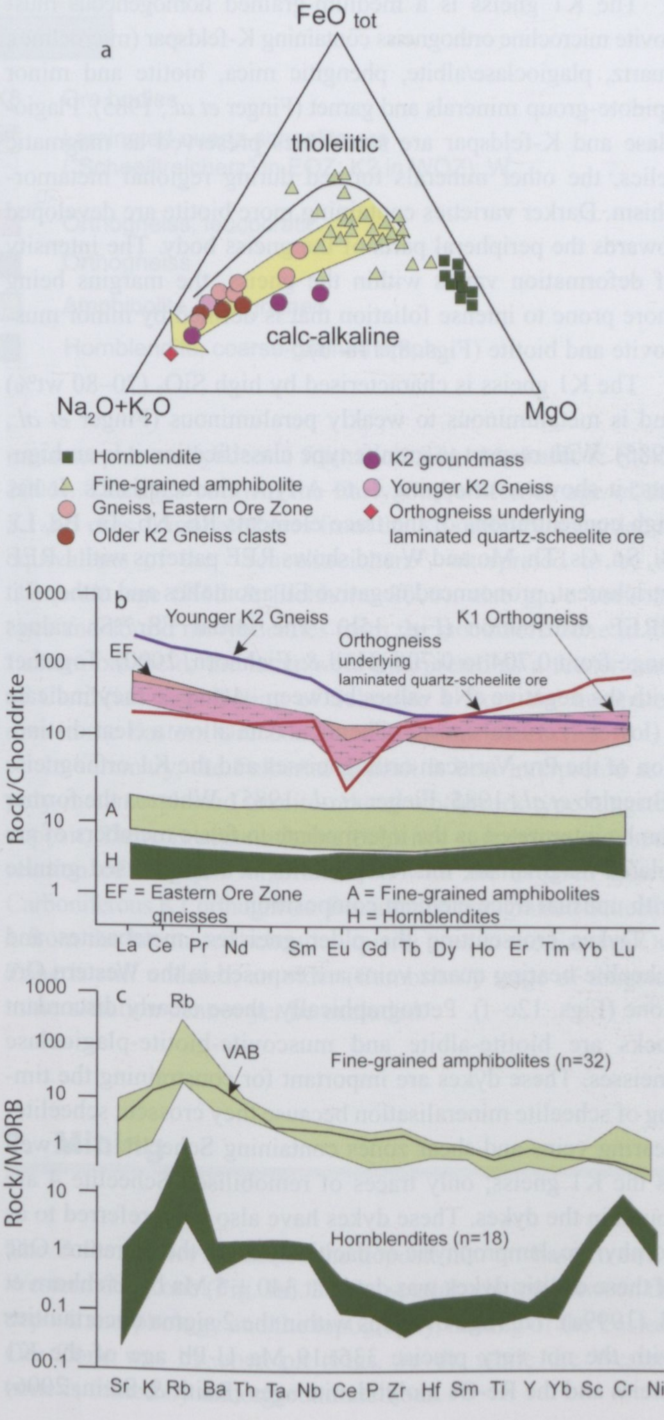

Fig. 15. Diagrams illustrating the chemical composition of rocks of the Habach Complex and the Lower Carboniferous K1 orthogneiss (from Höll & Eichhorn, 2000). **a)** Most rocks of the Habach Complex follow a calc-alkaline trend typical for arc-related magmatism. A few fine-grained amphibolites are tholeiitic 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 Lower Carboniferous (K1) orthogneisses show more evolved LREE enriched patterns. The orthogneiss underlying the laminated scheelite-quartz ores is enriched in HREE and depleted in LREE with a marked negative Eu anomaly resulting in a wing shaped REE pattern. **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 metasomatic processes.

5.4. Variscan orthogneisses

Metagranitoids (Central Gneisses) related to the Variscan orogeny are also common in the Habach Complex (see Section 3.3). At Felbertal, the several hundred meter long and several tens of meters wide K1 orthogneiss that is only exposed underground 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 Variscan 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

The K1 gneiss is a medium-grained homogeneous muscovite microcline orthogneiss containing K-feldspar (microcline), quartz, plagioclase/albite, phengitic mica, biotite and minor epidote-group minerals and garnet (Finger *et al.*, 1985). Plagioclase and K-feldspar are sometimes preserved as magmatic relics, the other minerals formed during regional metamorphism. Darker varieties containing more biotite are 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 that is defined by minor muscovite and biotite (Figs. 8, 11a–b).

The K1 gneiss is characterised by high SiO_2 (70–80 wt%) and is metaluminous to weakly peraluminous (Finger *et al.*, 1985). With respect to granite type classification it is ambiguous; it shows overlapping I- to A-type characteristics. 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 rather flat HREE distribution (Fig. 15b). The initial $^{87}Sr/^{86}Sr$ values range from 0.704 to 0.708 (Höll & Eichhorn, 2000). Together with the negative εNd values between –4 and –6 they indicate a (lower ?) crustal source. Chemical data allow a clear distinction of the Pre-Variscan orthogneisses and the K1 orthogneiss (Briegleb *et al.*, 1985; Finger *et al.*, 1985). Whereas the former can be interpreted as the intermediate to felsic members of arc related magmatism, the K1 protolith is a specialised 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. 12e–f). Petrographically, these clearly discordant rocks are biotite-albite and muscovite-biotite-plagioclase gneisses. These dykes are important for constraining the timing of scheelite mineralisation because they crosscut scheelite-bearing veins and shear zones containing Scheelite 2 as well as the K1 gneiss; only traces of remobilised Scheelite 4 are found in the dykes. These dykes have also been referred to as porphyritic, lamprophyric or dacitic dykes in the literature. One of these dacitic dykes was dated at 340 ± 5 Ma by Eichhorn et al. (1999a). This age overlaps within the 2 sigma uncertainties with the not very precise 336±19 Ma U-Pb age of the K1 gneiss and the Re-Os molybdenite ages (Raith & Stein, 2006) indicating that emplacement of the K1 gneiss, tungsten mineralisation, emplacement of the dykes and regional metamorphism occurred within a rather short time interval during the Variscan orogeny. The available age data are not precise enough to allow resolution of these events.

6. Genetic models for the ore deposit

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 Maucher and Höll (Maucher, 1965; Höll, 1966; Höll & Maucher, 1968; Höll, 1977). The main postulates of this genetic model were (Maucher, 1965; Höll, 1977): (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 exploration in the Eastern Alps, based on this new model, led to the discovery of many scheelite showings in the Eastern Alps including the discovery of the world-class Felbertal tungsten deposit (see Chapter 2, Höll, 1969, 1971, 1975, 1998). The main target of mining in the Eastern Ore Zone was the laminated scheelite–quartz ores ("Scheelitreicherz"; Figs. 6, 7a–b) and the associated stockwork ores (Fig. 7c). 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 precitated tungsten on or very close to the seafloor. Metabreccias associated with the similar K2 ores in the Western Ore Zone were also explained with eruptive volcanic processes (Höll & Schenk, 1988). Ubiquitous discordant mineralised quartz veins were regarded as metamorphic mobilisation products and larger scheelite porphyroblasts (Scheelite 2), common in the Western Ore Zone, were also explained with metamorphic mobilisation processes.

Another model (Thalhammer, 1987; Thalhammer *et al.*, 1989) 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.

All these authors rejected any genetic link to granites, which were discovered in the Western Ore Zone (*i.e.*, K1 gneiss) in the early eighties. After the recognition of this gneiss as an intrusive metagranitoid of Carboniferous age (Pestal, 1983)

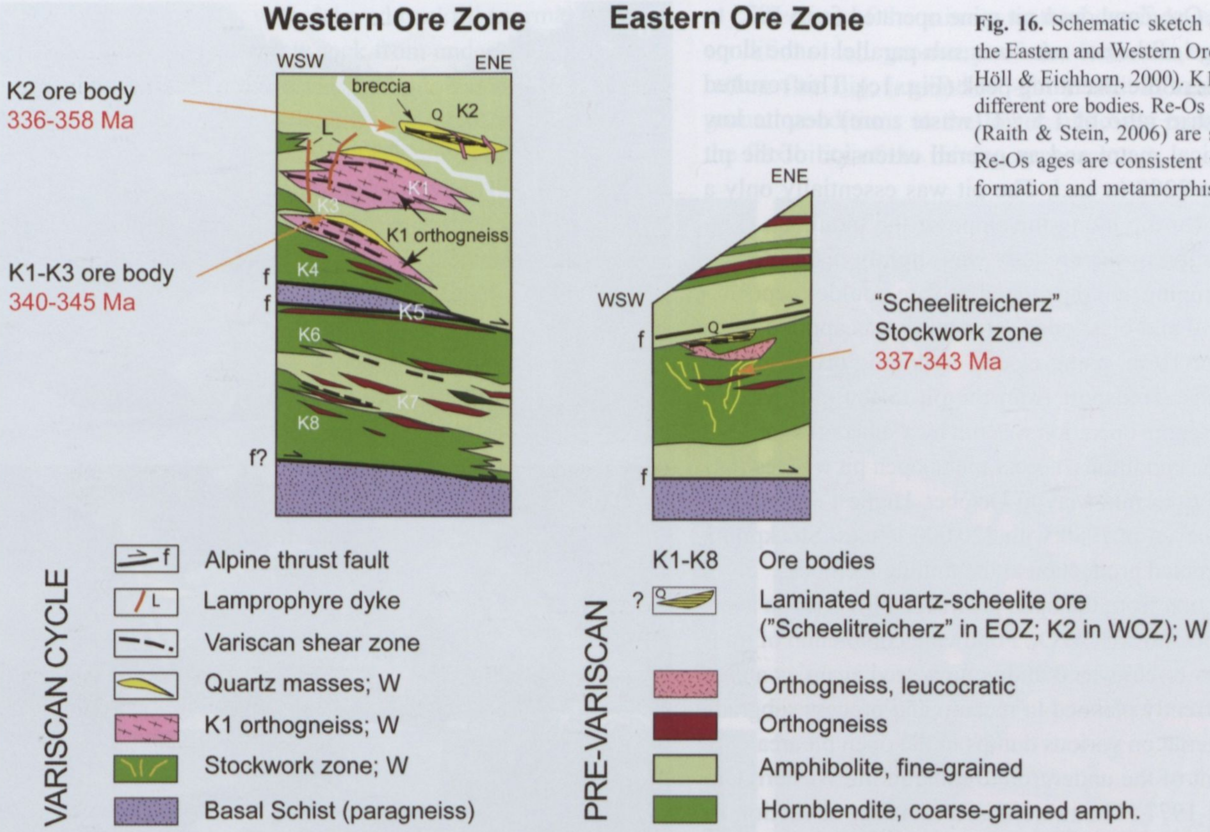

Fig. 16. Schematic sketch of the geology of the Eastern and Western Ore Zones (based on Höll & Eichhorn, 2000). K1 to K8 refer to the different ore bodies. Re-Os molybdenite ages (Raith & Stein, 2006) are shown in red. All Re-Os ages are consistent with Variscan ore formation and metamorphism.

and its close spatial association with high-grade ores (K1-K3 ore bodies) granite-related genetic models were postulated (Pestal, 1983; Briegleb *et al.*, 1985; Finger *et al.*, 1985; Trudu & Clark, 1986; Briegleb, 1991).

The epigenetic model was especially propagated by Briegleb (1991), 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; Figs. 12f–h).

More recently, the epigenetic model and the granitic relationship was also accepted by Eichhorn *et al.* (1999a). However, these authors argue for a *two-stage* formation of the Felbertal deposit; a first stage of Cambrian ~520 Ma, and a second stage of Lower Carboniferous age (~340 Ma). Scheelite 1 from the laminated ores in the Eastern Ore Zone and the K2 ores in the Western Ore Zone are still thought to be of Cambrian age whereas a Lower Carboniferous age of Scheelite 2 and its genetic link with the K1 orthogneiss is now accepted by Eichhorn *et al.* (1999a).

Re-Os dating of molybdenite only confirmed the Early Variscan event. The ages range between ~358 Ma and ~336 Ma and record several pulses of magmatic hydrothermal and metamorphic molybdenite formation (Fig. 16, Raith & Stein, 2006). The ages confirm the Early Carboniferous age of the K1-K3 ores. Laminated ores from the K2 orebody, regarded as equivalents of the "Scheelitreicherz", interpreted to be of Cambrain age (Höll & Eichhorn, 2000), also gave Variscan ages and so did molybdenites from the stockwork zone in the Eastern ore field; the latter were interpreted as a feeder zone of Cambrian age. Dating of Scheelite 1 from the laminated ores in the Eastern Ore Zone was so far not successful.

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 the evolved Lower Carboniferous K1 orthogneiss. Because the fine-grained Scheelite 1 from the laminated scheelite–quartz ores in the Eastern Ore Zone is still undated, an older (Cambrian?) stage of tungsten mineralisation cannot yet be excluded.

7. Mining

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

The Eastern Ore 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. 1c). This resulted in a very low strip ratio of 1.5 : 1 (waste : ore) despite low tonnes per vertical metre and an overall extension of the pit 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. 1c). A large portion of the orebody was slightly dislocated by post-glacial slumping and developed as "ore boulder deposit".

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. It is currently planned to reclaim and process subgrade mineralised material on various dumps in the open pit area.

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 725 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 seven 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. 17–18). 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 (Figs. 17a; 18a–b). Standard section of drifts and ramps is around 20 m². By 2008, some 45 km of drifts and ramps had been developed. 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

Fig. 17. a) Portal of the Felbertal underground mine. **b)** Drilling with modern computer-controlled two-boom jumbo.

capacity close to the portal and than 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 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. Recently, 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 2008, active stoping reached the interval from 750 mL to 775 mL, while development drifting advanced towards 725 mL.

For an underground environment, mined ore grades are fairly low, around 0.4 wt% WO_3. Thus, large-scale low-cost mining methods have to be employed to allow economic extraction. The main mining method is now sublevel caving, using 25 m sublevel interval and stope dimensions of up to 80 by 80 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.

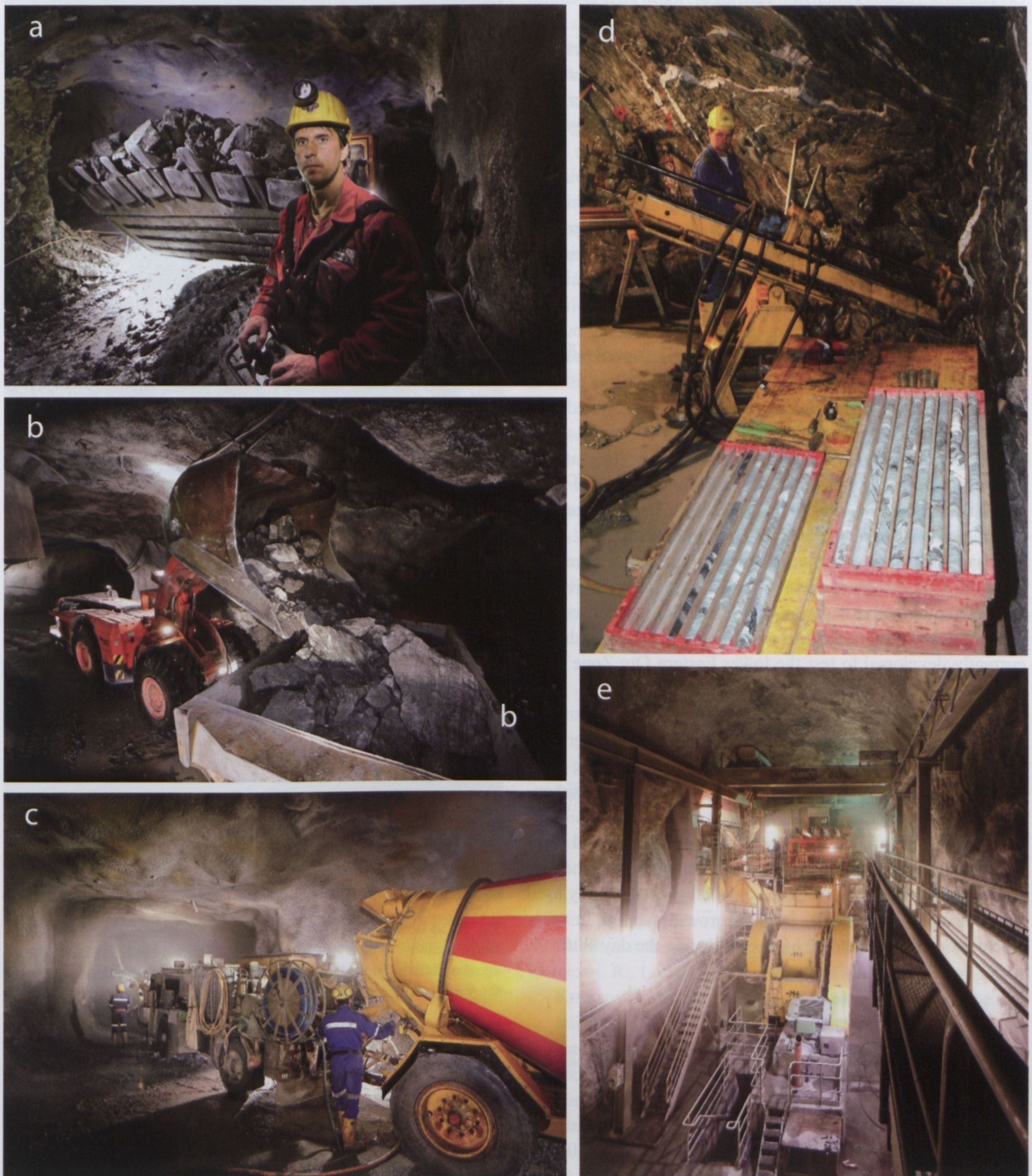

Fig. 18. a) Remote-controlled scooptram with 15 tonnes capacity. **b)** Mucking into an ADT truck for underground haulage from the lower sublevels. **c)** Shotcreting of development drifts. **d)** Underground diamond drilling. **e)** Primary jaw crusher in the underground crushing station.

Drilling equipment at the Felbertal mine includes two-boom jumbos for drifting (Fig. 17b) 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 (Fig. 18d).

Blasting employs emulsion cartridges, loose ANFO explosives and NONEL detonators.

Mucking and haulage to ore passes or truck loading bays is by 15-tonne scooptrams. Mucking from open stopes is undertaken with remote control. Ore produced on the lower sublevels is transported by 25-tonne ADT 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 1800 m of drifting, installation of 6000 rock bolts (split sets and cable bolts) and 3000 mt of shotcrete with steel fibres (Fig. 18c). Backfill requirements are between 60,000 and 120,000 t (Gaul, 2008).

Diamond drilling and sludge hole drilling is undertaken for exploration and stope definition in the underground environment. Due to geometrical constraints, drilling cannot test the down-plunge continuity of the orebody. An exploration drift is currently developed to test the lower Eastern Ore Zone from underground.

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 50 persons including maintenance and service personnel are employed in the mine that operates generally on a 5-day / one-shift basis. A second shift is occasionally used for dedicated service tasks such as ground support in areas where production would be hampered during the day shift.

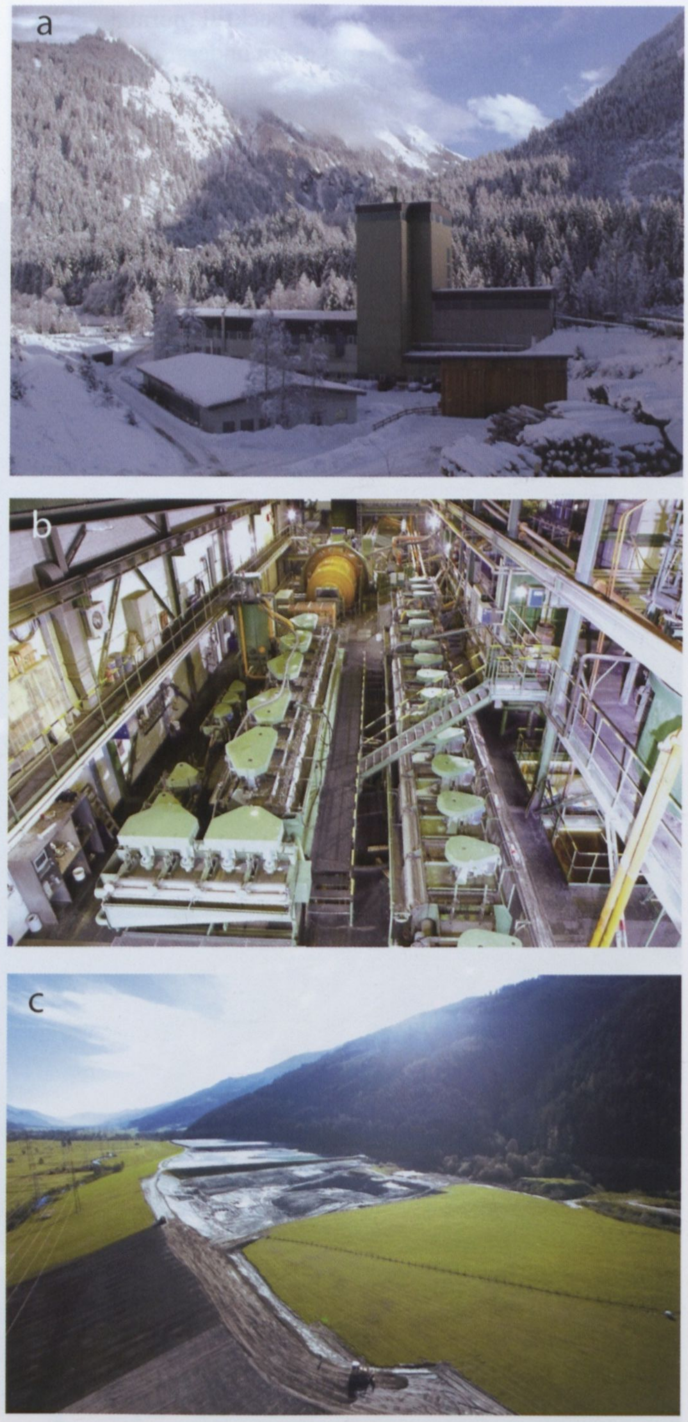

Fig. 19. a) Beneficiation plant 3 km north of the mine, directly at the Felbertauern highway. **b)** Overview of milling and flotation circuit. **c)** Tailings management facilities in the Pinzgau valley near Stuhlfelden showing the extent of the re-cultivation measures that occur concurrently with the operation.

8. 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. 19a–b). The capacity was initially 250,000 tpa, but was increased to the current capacity of some 500,000 tpa by the early 1980s. Crushing facilities at the plant have been dismantled after the underground crusher became operational. 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.

Currently, mill feed is 72 t per hour, with a head grade of 0.35 to 0.45 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. 19b). 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. Spirals and two shaking tables have recently been added to the circuit in order to decrease the load of the flotation circuit itself. Gravity concentrates and flotation concentrates are mixed to provide a homogeneous final product.

Another recent development is the introduction of X-ray sorting, which on the longer term is thought to allow further lowering of the cut-off grade in the mine by constant output of the flotation plant by removal of a sterile fraction before milling.

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. 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. 19c).

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. Similarly, the 4-km tailings pipeline with 200 m head to supply the mine with tailings for backfilling purposes is operated.

Since 1983, some 10 Mt of tailings was 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. Re-cultivation of the tailings ponds is an ongoing measure, and the older portions of the facilities are now used again as pasture (Fig. 19c).

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 of 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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Appendix – Itinerary for IMA2010 AT3 Field trip

Wednesday, August 18, 2010 (Day 1)

15.00	Meeting of the participants at Salzburg main railway station
15.00–17.00	Travel to Mittersill (110 km, by bus)
	Accommodation in Mittersill
	Introduction into the geological background and the Felbertal scheelite deposit

Thursday, August 19, 2010 (Day 2). Visit to the Felbertal scheelite deposit

09.00–12.00	Visit of the operating underground mine in the Western Ore Zone
13.00-17.00	Visit of the former open pit area in the Eastern Ore Zone
	Accommodation in Mittersill

Friday, August 20, 2010 (Day 3)

09.00–12.00	Visit of the beneficiation plant in the Felber Valley (~3 km N of the mine) and tailings management facilities near Stuhlfelden
12.30–21.00	Travel to Salzburg main railway station (by bus) and to Budapest, Keleti railway station (by train)