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PRESENTATION NOTES

TITLE: Structural setting and age of syn- and post-orogenic gold and Zn-Pb-Ag vein deposits, Variscan slate belt, Germany

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ABSTRACT

The veins described are controlled by structures in the Carboniferous Variscan slate belt of central Europe exposed in the Rhenish Massif, Harz block, and Ruhr coal district in Germany. Two syn-orogenic deposits formed during folding at ca. 305 Ma in the overturned NW-limbs of regional anticlines. In the Eisenberg anticline, flexural slip at the contacts of thin limestone beds with black slate led to the crack-seal deposition of laminated calcite veins. Bonanza-style dendritic gold is associated with hematite, chalcopyrite, clausthalite (PbSe) and accessory bornite and naumannite (Ag_2Se). The Ramsbeck Zn-Pb-Ag deposit consists of veins controlled by the axial plane cleavage and by flat reverse faults. Stacked pinch-and-swell veins in slate and thick breccia veins in quartzite were mined over a vertical extent of 700 m, filled with quartz, pyrite, sphalerite, galena (900 g/t Ag), and accessory siderite, chlorite, tetrahedrite and PbSb-sulfosalts. Zones of quartz-sericite ± ankerite alteration bordered veins in slate and diabase. The deposit is located at the margin of a thermal anomaly defined by illite crystallinity, vitrinite reflectance and Bouguer gravity interpreted to indicate a buried granite pluton.

Two post-orogenic deposits formed after folding at or prior to 260-240 Ma, either in normal faults reactivated during fold-belt uplift or in wrench faults of the Elbe strike-slip zone generated during the westward movement of Gondwana relative to Laurussia after continental collision in the Upper Carboniferous. The Auguste Victoria Zn-Pb-Ag deposit is controlled by a 15-60 m wide normal fault, which offsets coal measures in an anticline 700 m SW-block down. Stage 1 breccia ore composed of quartz, sphalerite, galena (1000-1200 g/t Ag), accessory siderite, ankerite, sericite and chalcopyrite is confined to the normal fault, which is offset by both dextral and sinistral wrench faults. The dextral faults contain Stage 2a quartz-sphalerite ore. The sinistral faults contain minor Stage 2a ore overprinted by Stage 2b calcite-barite-marcasite veins. Continuous Zn-Pb mineralization constrains the hiatus between normal and wrench faulting to a short time interval.

In the Harz block, uplifted 3-4 km at the North Boundary Fault during Cretaceous and Cenozoic Alpine stress, WNW-striking wrench faults west of the Brocken granite (283±2 Ma) host Zn-Pb-Ag veins. The two largest deposits (11-19 Mt of ore) are controlled by a dextral extensional system at Clausthal-Zellerfeld, and by a sinistral extensional duplex at Bad Grund. Lateral displacement on the main faults was 500-800 m. Crosscutting relationships indicate that dextral preceded sinistral movement. Stage 1 hematite-pyrite mineralization was associated with dolomite-quartz-illite replacement at fluid temperatures of about 300°C. The formation of banded and breccia veins progressed from Stage 2 quartz-calcite-sphalerite-galena to Stage 3 siderite-barite-galena, fluid temperature falling from about 360°C to 220°C with time. Stage 3 galena was silver-rich (1000-2000 g/t) due to inclusions of tetrahedrite, pyrargyrite, argentite and native silver. Rb-Sr ages of adularia (263±4 Ma) from veins in the aureole of the Brocken granite, and of 2M-illite from Stage 1 alteration at Bad Grund (240±17 Ma) indicate ore formation in the Permian or Triassic. Isotopic resetting suggests reactivation (30-100 m offset) of some faults at ca. 180, 140 and 90 Ma.

1 INTRODUCTION

These explanatory notes accompany color slides illustrating the structural setting of syn- and post-orogenic vein deposits in the Rhenish Massif, Harz and Ruhr coal district, part of the Variscan slate belt in Germany. Both this text and the slide presentation (in tablet 4:3 format and Adobe 1998 color) are available free of charge as Adobe pdf-files from the SGA website. They are designed as open access teaching tools for projection and the study on-screen. This text explains each slide step-by-step.

Four well-documented deposits were selected as structural type localities out of a much larger group based on the personal experience of the author: **(1)** the Eisenberg gold deposit, bedding-parallel veins in an anticline; **(2)** the Ramsbeck Zn-Pb-Ag deposit, veins controlled by the axial plane cleavage and reverse faults in an anticline; **(3)** the Auguste Victoria Zn-Pb-Ag deposit, breccia ore in a normal fault displacing the folds; and **(4)** the Clausthal Zellerfeld and Bad Grund Zn-Pb-Ag deposits in the Upper Harz, banded and breccia veins in wrench faults displacing the regional folds. Much of the published literature is in German and not easily accessible to the international public. A comprehensive review of vein deposits in the Variscan orogen is beyond the scope of this study.

The term “syn-orogenic” is used as a time constraint, when structural relations indicate vein formation during Variscan folding, and “post-orogenic” when the host structures postdate folding. Local stratigraphic nomenclature (Westphalian, Stephanian) is retained but correlated with U-Pb ages listed in the chart of the International Commission on Stratigraphy (ICS 2018). The Westphalian is equivalent to the Moscovian (315-307 Ma), and the Stephanian to the Kasimovian and Gzhelian stages (307-299 Ma) of the Carboniferous. The Lower Permian is dated at 299-273 Ma (Cisuralian series), and the Upper Permian at 273-252 Ma (Guadalupian and Lopingian series) in the ICS chart. The radiometric ages quoted are based on the decay constants of Steiger and Jäger (1977), recently revised for the K-Ar (Renne et al. 2011) and Rb-Sr systems (Villa et al. 2015). The revisions will result in slightly younger K-Ar and older Rb-Sr ages (3-5 Ma at 300 Ma). Two key Rb-Sr ages have been recalculated using Isoplot 3.75 of Ludwig (2012) and the new decay constant. Mineralogical, fluid inclusion and isotope data are summarized in the context of the structural framework. In the Appendix, genetic models for the Upper Harz, the subject of most specialized studies are briefly reviewed.

2 SLIDES DESCRIPTION

2.1 *Slide 1. SGA disclaimer and recommended citation*

2.2 *Slide 2. Title slide.*

Contents

2.3 *Slide 3. Europe: Cratons and orogenic belts*

The tectonic map of Europe (modified from Meinhold 1971) shows the present-day tectonic setting. The Cenozoic Alpine orogen in southern Europe (red, metamorphic massifs dark red), part of the Neo-Tethyan fold belt extending into Turkey and Iran, formed during the collision of the African-Arabian and Eurasian continents leaving the Mediterranean sea as a remnant oceanic basin. Most of Europe is underlain by the Precambrian Baltic craton (Baltica), shown in dark pink where outcropping, light pink where under thin sedimentary cover, and in yellow where covered by deep sedimentary basins. The craton is bounded by the Cambrian-Silurian Caledonian (dark violet) and by the Devonian-Carboniferous Variscan (green) orogenic belts.

The Variscan basement in central and western Europe is transected by two sets of Permo-Carboniferous faults: (1) NW- to WNW-striking dextral strike-slip faults with 20-150 km displacement including the Tornquist-Teisseyre Zone (TTZ), the Elbe Zone (EZ), the Bray Fault (BF), and the Amorican Faults (AF), and (2) subordinate north- to NNE-striking sinistral faults such as the Sillon Houiller (SH) with a lateral offset of 70 km in the Massif Central, France (Arthaud and Matte 1977; Holder and Leveridge 1986; Ziegler 1990). These faults are interpreted as part of a Riedel-type mega-shear zone, which developed along the suture between Gondwana and Laurussia shortly after Carboniferous folding in Europe ceased (Arthaud and Matte 1977).

The TTZ is a broad fault zone marking the boundary between the consolidated Baltic craton and the fold belts to the southwest. The Oslo Graben (OG) at the termination of the TTZ has been interpreted as a pull-apart structure related to dextral strike-slip (Ro et al. 1990; Ziegler 1990). The U-Pb ages of rift-related basalt, syenite and granite constrain TTZ strike-slip to the Permo-Carboniferous (310-260 Ma; peak at 300-270 Ma; Corfu et al. 2017). Subsequent movements include Mesozoic normal faulting during the formation of the Danish sedimentary basin, and basin inversion during the Upper Cretaceous and Tertiary (Walter 1995). The inversion was caused by Alpine-Tethyan far-field stress during the NE-directed subduction of oceanic crust at the southern margin of the Eurasian continent. Stress culminated in the Eocene to Miocene during the collision with the African-Arabian plate (e.g. Moritz and Baker 2019).

2.4 *Slide 4. Orogenic belts in central Europe*

The geologic map of central Europe (modified from Schriel 1930) shows the outcrop area of the Variscan fold belt, limited by the German-Polish Basin in the north and by the Cenozoic Alpine fold belt and its molasse basin in the south. The Tornquist-Teisseyre (TTZ) and Elbe fault zones (EZ) are boundaries to the German-Polish basin, where the Variscan basement is buried under Permo-Carboniferous volcanic and red-bed clastic rocks 2-4 km thick, and Upper Permian to Cenozoic sedimentary rocks up to 8 km thick (Breitkreuz and Kennedy 1999; Henningsen and Katzung 2002).

South of the Elbe Zone, the basement crops out in the Rhenish Massif (RM) and in the Harz block (HZ), both part of the Rhenohercynian slate belt of folded Devonian sandstones and shales (dark brown) and Carboniferous greywacke turbidites and coal measures (grey). The Taunus suture (TS) separates the slate belt from the metamorphic part of the orogen, exposed at the shoulders of the Rhine Graben (RG) and in the Bohemian Massif (BM). The terranes south of the suture (Saxothuringikum, Moldanubikum) represent the rifted margin of Gondwana, accreted and metamorphosed to granulite facies during the collision with the Laurussian continent in the Upper Carboniferous (Linnemann 2004). Syn- to post-tectonic granites (red) were emplaced at 340-290 Ma (Walter 1995; Sebastian 2013).

Like the TTZ, the Elbe Zone (EZ) and parallel faults (blue lines) record two main phases of movement: strike-slip in the Carboniferous to Permian, and Alpine-Tethyan uplift in the Upper Cretaceous and Tertiary. At the Flechtingen basement horst (FH), seismic reflection data indicate that the uplift amounts to 6 km (Scheck et al. 2002). A minor phase of dextral reactivation took place at some EZ faults during Atlantic rifting in the Upper Jurassic and Lower Cretaceous (Ziegler 1990).

In the Elbe valley near Dresden, the EZ is represented by faults (EF) with a total dextral offset of 60-120 km (Scheck et al. 2002). The Saxony Fault in the southwest, a zone of cataclasite and mylonite in gneiss and granite moved at 330 to 300 Ma. The older age is constrained by the Meissen volcano-plutonic complex emplaced into an extensional fault stepover basin, and the younger age by rhyolite tuff at the base of the Döhlen molasse. After 300 Ma, the Döhlen molasse basin deepened due to a normal component of movement on the bounding faults. In contrast, the reactivated Lausitz Fault in the northeast overrides Upper Cretaceous sandstone 1 km NE-block up (Sebastian 2013).

East of the Elbe, the EZ is represented by the Sudetic faults (SF) subdivided into the main Intra-Sudetic Fault and the subsidiary Sudetic Boundary Fault. At the Intra-Sudetic Fault, dextral displacement on the scale of several 10 km in the Carboniferous was reversed in the Permo-Carboniferous by sinistral movement, which postdates the emplacement of the Karkonosze pluton (Cloos 1922; Aleksandrowski et al. 1997). The Karkonosze granites are dated at 312±3 to 307±3 Ma, and a sulfide-bearing rhyolite dyke emplaced into the fault zone is dated at 300.7±2.4 Ma (U-Pb zircon; Mikulski et al. 2020). A left-lateral offset of 10 km is estimated by correlating NNE-striking mylonite zones north (Niemcza) and south (Skrzynka) of the Intra-Sudetic Fault, which both have a sinistral sense of shear. At the Sudetic Boundary Fault, reactivation in the Tertiary lifted Cretaceous rocks 600 m NE-block up (Cloos 1922; Aleksandrowski et al. 1997). Faults at the southwest boundary of the Bohemian Massif include the Bavarian Pfahl (BP), a 200 km long quartz-veined zone of mylonite in gneiss and granite linked by a step-over basin to the Frankish Line (FL). Note the position of the KTB drill hole, which intersected fluid-filled faults of the Frankish Line at 9.1 km depth (Wöhrl 2003).

2.5 *Slide 5. Rhenish slate belt: Syn- and post-orogenic veins*

The geologic map (modified from Walther and Zitzmann 1973) shows the location of three Variscan ore deposits described below: the syn-orogenic Eisenberg (EB) and Ramsbeck (RB), and the post-orogenic Auguste Victoria deposit (AV). The folded stratigraphic units in the Rhenish Massif comprise a Lower Devonian quartzite-sandstone ± shale succession (dark red-brown), a Middle Devonian sequence of sand-banded and calcareous shales (brown-grey), minor basaltic spilites (dark green) and limestone reefs (blue), Lower Carboniferous black shale and greywacke turbidites (grey), and Upper Carboniferous deltaic sand- and siltstones with coal measures (grey). In the Ruhr coal district, part of the Variscan foreland basin at the northern margin of the Rhenish Massif, 9 billion metric tons of black coal was mined until closure in 2018.

The regional folds strike N50-60°E, have axial planes inclined towards the northwest, and horizontal to gently plunging fold axes. The NW-limbs of some anticlines are overturned. The Eisenberg and Ramsbeck veins are controlled by structures related to the main phase of Carboniferous folding at ca. 305 Ma. Ramsbeck represents a mineralization style common in the Rhenish slate belt: Zn-Pb-Ag veins controlled by the axial plane cleavage and by reverse faults. Such veins were also mined in a 60 km long zone extending from Holzappel (HO) southwest across the river Rhine to Werlau (WL) and the city of Trier. The main quartz-siderite-sphalerite-galena vein at Holzappel was mined over a strike of 3.4 km and >1 km down dip. In the Zn-Pb districts centered on Bad Ems (BE), Lüderich (LD) and Velbert (VB), fault zones crosscutting the folds controlled vein and breccia ore (Beyschlag et al. 1916; Schneiderhöhn 1941). The Zn-Pb-Ag deposits at Ramsbeck, in the Holzappel-Trier zone and at Auguste Victoria are characterized by Variscan uranogenic ($^{206}Pb/^{204}Pb$ = 18.206-18.330) and thorogenic ($^{208}Pb/^{204}Pb$ = 38.093-38.341) lead isotope ratios (Large and Schaeffer 1983; Diedel and Baumann 1988; Krahn and Baumann 1996; Wagner and Schneider 2002).

2.6 *Slide 6. The Eisenberg vein and Eder placer gold deposits*

The gold-bearing Eisenberg anticline in Lower Carboniferous black slate, chert and limestone is located 5 km southwest of Korbach. The deposit is the principal source of gold placers, which extend via tributary streams to the Eder over a distance of 50 km (Beyschlag and Schriel 1923). The placers surrounding the 562 m high Eisenberg occur in Permian fluviatile red beds and marine shore conglomerates, and in Pleistocene gravels. The gold in these proximal placers consists of rounded detrital grains, and of newly formed dendritic crystals precipitated by acidic groundwater (Kulick et al. 1997). The detrital gold in Permian Zechstein 1 marine conglomerate indicates that the primary deposit is older than 260 Ma (Lopingian series; ICS 2018). The gold content of the proximal placers is estimated at 0.5-2 g/m^3. The distal placers in the Eder valley contain 0.16-0.95 g/m^3 in fine gold flakes (Beyschlag and Schriel 1923; Kulick et al. 1997).

The Meissen chronicle of 1250 AD is the oldest record of mining at the Eisenberg. In 1480, duke Phillip of Waldeck regulated the mines. Until 1585, when the main drainage adit collapsed, 8-10 km of drifts, 80 adits, and more than 50 shafts were developed or sunk. Grades of 137-384 g/t gold in hand-sorted bulk ore were recorded in the local mint. The total gold in the ore mined underground is estimated at 2.5 metric tons, of which about 40% were recovered by amalgamation. Intermittent placer mining lasted until the 19th century (Beyschlag and Schriel 1923; Kulick et al. 1997).

2.7 *Slide 7. Stratabound gold veins in the Eisenberg anticline*

The Eisenberg anticline (map modified from Kulick et al. 1997) consists of a core of Upper Devonian silt- and sand-banded grey slate, and outer bituminous rocks of the Lower Carboniferous Kulm succession. Illite crystallinity in the anticline indicates metamorphic temperatures of about 250°C (Weber et al. 1987). The auriferous Kulm succession is subdivided into (Kulick et al. 1997):

(1) The Kulm 1 Lower Aluminous Slate (30-40 m) composed mainly of quartz, illite, chlorite, and bitumen (up to 4.3 wt.% C_{org}), and marked by thin beds of illite-rich felsic tuff. The upper half is enriched in framboidal pyrite (3-10 vol.%) associated with chalcopyrite and trace bornite. Background copper contents are 100-500 ppm but spaced horizons are enriched ten-fold (0.27-0.45 wt.% Cu over 80 cm). Lead, zinc (both 10-50 ppm) and gold (0.01-0.05 ppm) contents are low.

(2) The Kulm 2 chert-limestone-slate succession, the lower part (10-24 m) composed of black radiolarian chert and siliceous slate, and the upper part (40 m) of grey-green slate alternating with siliceous limestone and a marker bed of lithic tuff 1-10 m thick.

(3) The Kulm 3 Upper Aluminous Slate (8-15 m) consists of black bituminous slate (25 vol.% C_{org} + pyrite), siliceous-calcareous slate (3-12 vol.% C_{org} + pyrite) and limestone intercalated on a decimeter- to meter-scale. Felsic tuffs (0.5-5 cm beds) are composed of illite, kaolinite, quartz, and remnant orthoclase, plagioclase, chlorite and biotite.

(4) The Kulm 3 slate-greywacke succession (> 250 m), grey silt-banded slates low in bitumen grade upwards into slate with thicker and more abundant greywacke beds, which form the core of the syncline northwest of the Eisenberg anticline.

Gold mineralization: The Upper Aluminous Slate southeast of Goldhausen is the host unit of bedding-parallel veins confined to the overturned NW-limb of the anticline. The workings in this unit, accessible from the Georg and Preussag (PS) shafts, are continuous over a strike of more than 1 km. Scattered mines further northeast extend stratabound mineralization to 2 km. Minor production came from strike-parallel reverse faults in the core of the anticline. Two barren fault systems crosscut the ore: (1) strike-slip faults (N65-90°W/60-85°S) with dextral movement north block east; and (2) normal faults (N40°W/65-90° NE or SW) oriented perpendicular to the fold axis (Kulick et al. 1997).

2.8 *Slide 8. Eisenberg anticline: Mine workings in cross section*

The cross sections A-B and C-D (see Slide 2.7), modified from Kulick and Theuerjahr (1983), show selected mine workings. The supergene copper ore at Victor is unrelated to gold, and derived from diagenetic sulfides in the Lower Aluminous Slate. Copper dissolved in groundwater during sulfide oxidation precipitated as malachite, azurite and chalcocite in adjacent limestone. In 1545, production amounted to 24 t Cu (Beyschlag and Schriel 1923; Kulick et al. 1997).

Section A-B: The Water Adit (Wasserstollen) intersects strike-parallel reverse faults of the Schlossberg system, which dip 40-60°SE at surface but steepen to 65-80° at depth. Grade in the 1.6-m-thick main fault decreased from 19 g/t in the Wasserstollen to 0.5 g/t Au in an adit 27 m below. The faults consist of cataclasite cemented by gold-bearing carbonate and quartz. Near surface, the carbonate cement was leached and the faults contained red clay suggesting secondary enrichment. The Schlossberg faults in the Kulm 2 succession were mined over a strike length of 380 m and vertical depth of 38 m (Kulick et al. 1997).

Section C-D: The St Georg mine, drained via the Urstollen adit 56 m below shaft collar, represents the bedding-parallel veins southeast of Goldhausen. The collapse of the Urstollen in 1585 caused the shutdown of most mines. In 1919-1929, the shaft and other medieval workings were refurbished (Rauschenbusch and Rauschenbusch 1929). In 1932, the Preussag sunk a 70 m deep new shaft to access ore below these workings and in 1974-1978, the Geological Survey of Hessen carried out underground sampling and diamond drilling. On the 70 m level, scattered grades ≤ 5.5 g/t gold were detected (Kulick et al. 1997).

2.9 *Slide 9. Eisenberg anticline: Bedding-parallel veins*

Photographs A to C show late medieval workings from 1585 or earlier in the St Georg and St Sebastian mines southeast of Goldhausen.

(A) St Georg mine model, Korbach museum, section looking northeast. At least 5 sets of bedding-parallel veins (Lager 1 to 5), spread over a horizontal distance of 7 m in the Kulm 3 Upper Aluminous Slate, were selectively mined down to the Urstollen adit. One "Lager" comprised laminated veins (5-10 mm thick) at limestone-slate contacts plus crackle and ladder veins crossing the limestone in between. The ore handpicked by the medieval miners consisted of: (1) a single veined limestone bed 10-15 cm thick or (2) several closely spaced beds grading 24-35 g/t gold over a width of 30-80 cm (Ramdohr 1932; Kulick et al. 1997).

Crosscutting relationships in the St Georg mine (Kulick et al. 1997) constrain the timing of structures from the oldest to the youngest: **(1)** laminated Lager veins controlling main-stage gold; vertical striations indicate flexural slip at limestone contacts, **(2)** flat thrust faults subparallel in strike to bedding, which dip 10-25° SE and displace the HW-block up to 20 cm northwest, some mineralized at the intersection with Lager veins, and **(3)** barren normal or oblique-slip faults perpendicular in strike to bedding, which dip 65-90° NE or SW.

(B) St Sebastian mine, the stope above the -33 m level is 0.8-1.0 m wide. The grey illite-rich tuff in the center of the crown pillar was removed first to break black slate into the open space. The Lager 5 ore, a 10-mm-thick calcite-hematite vein in contact with limestone was mined last.

(C) St Sebastian mine -33 m level, crosscut driven with hammer and chisel into black slate of the Upper Aluminous Kulm 3 formation, the hammer is 32 cm tall.

2.10 *Slide 10. Eisenberg St Georg: Bedding-parallel veins*

The ore samples in photographs B to E are from Lager 1 on the Georg shaft -38 m level.

(A) Georg shaft -34 m level, crown pillar 15 m southwest of the shaft, looking northeast: the Lager 1 ore consists of three laminated, hematite-stained calcite ± quartz ± dolomite veins bound to the contacts of grey siliceous limestone (white arrows); the laminated veins are linked by thin veins (white) crossing the limestone bed, most mineralized with native gold. The black bituminous slate contains light grey illite-rich tuff. The hammer is 32 cm long.

(B) Footwall part of Lager 1: the laminated calcite ± quartz ± hematite vein is bound to the contact slate-limestone, the limestone stained red by dispersed hematite. One of the cross-cutting calcite veins contains native gold. Note the thin marker band of sand-sized felsic tuff (quartz, orthoclase, plagioclase, biotite) at the bottom of the specimen. The matchstick is 4 cm long, collection Rauschenbusch / Kulick.

(C) Hanging wall part of Lager 1, sketch modified from Ramdohr (1932). Laminated crack-seal veins mark the flexural slip surfaces. In the laminations, the carbonate is recrystallized and the quartz brecciated, whereas the gangue in crackle and ladder veins is unstrained. Multiple stages of calcite ± quartz ± Fe-dolomite ± hematite fill are evident. Gold was deposited late. The felsic tuff is the same as in (B).

(D) Lager 1 ore: aggregates of native gold fill part of a laminated calcite-quartz vein at the contact slate-limestone. Some of the white calcite is stained pink by dispersed hematite. The calcite laminations are separated by stylolites of illite, and by thin lenses of slate and limestone. The scale bar is in millimeter, collection Rauschenbusch / Kulick.

(E) Lager 1 ore: aggregates of native gold in a ladder vein crossing a laminated calcite-quartz vein at the contact slate-limestone. The ladder vein has thin red rims of hematite, and is filled with calcite and Fe-dolomite (collection Rauschenbusch / Kulick).

2.11 *Slide 11. Eisenberg St Georg: Oxidized Au-Cu-Pb-Se ore*

The ore mineralogy is based on samples from the St Georg mine described in Ramdohr (1932), Maucher and Rehwald (1961), and Kulick et al. (1997). The native gold is very fine-grained (0.5-5 mm). Needles and flakes of gold (11 wt.% Ag) occur disseminated in the gangue, form felted or branching dendritic aggregates, and flower- or moss-shaped masses, which fill up to half the volume of a crackle vein or crack-seal lamination. Many grains are zoned to thin silver-rich rims. Associated oxides, sulfides and selenides are less abundant than gold (Ramdohr 1932): chalcopyrite, clausthalite, goethite-lepidocrocite, hematite, bornite, pyrite, sphalerite, digenite and magnetite, in the order of abundance. Chalcopyrite, clausthalite and gold form myrmekitic aggregates. Bornite contains oriented lamellae of chalcopyrite and fills the interstices in digenite trellis, textures interpreted to indicate >200°C fluid temperature (Ramdohr 1932). Primary fluid inclusions in vein quartz homogenized at 180-230°C (Sohl 1990). Crystalline goethite and lepidocrocite are early hypogene oxides, whereas hematite occurs in both early- and late-stage veins, locally in specular crystals.

(A) Georg shaft -34 m level, crown pillar 15 m southwest of the shaft, Lager 1 ore: moss-shaped and branching dendritic aggregates of native gold on the surface of a crackle vein crossing siliceous limestone. The calcite gangue was dissolved in acid. The matchstick is 3 cm long, collection Kulick.

(B) Georg shaft -34 m level, crown pillar 15 m southwest of the shaft, Lager 1 ore: dendritic aggregate of native gold on the surface of a bedding-parallel laminated vein at the limestone contact. The calcite was dissolved in acid. The aggregate is about 10 mm long, collection Kulick.

(C) Georg shaft -38 m level, Lager 1 ore: Syn-kinematic, snowball-shaped aggregates of clausthalite (PbSe) with inclusions of darker naumannite (Ag_2Se) in contact with native gold (white), tiny crystals of gold are disseminated in the gangue. Reflected light photomicrograph modified from Maucher and Rehwald (1961), collection Rauschenbusch.

Ramdohr (1932) concluded that the deposit formed from an ascending hydrothermal fluid. A source-distal setting is consistent with the presence of selenides, the estimated fluid temperature (about 230°C), and lack of visible wall-rock alteration, except perhaps for illite ± kaolinite in tuff close to the veins. The assemblage native gold + hematite in the bitumen-rich Upper Aluminous Slate indicates that the hydrothermal fluid was oxidized. Fluid reduction probably contributed to the bonanza-style precipitation of dendritic gold.

2.12 *Slide 12. Saddle Reefs in folds: Type locality Bendigo*

The bedding-parallel veins at spaced limestone-slate contacts in the overturned limb of the Eisenberg anticline are structurally identical to those formed by flexural slip during folding (Ramsay 1974; Tanner 1989). The type locality for gold deposits of this "Saddle Reef" style is the Bendigo goldfield in the Paleozoic Lachlan fold belt, southeast Australia (map A), where the Re-Os isochron age (438±6 Ma) of arsenopyrite and pyrite (n=5, MSWD=1.7) links gold mineralization to Silurian folding (Arne et al. 2001; Hough et al. 2007).

(A) Geologic map of the Bendigo area in the Lachlan fold belt, Australia, modified from Willman (2007). The Devonian Harcourt granodiorite-granite batholith separates the Bendigo and Castlemaine gold deposits. Syn-orogenic vein formation preceded the emplacement of the post-folding batholith at ca. 375 Ma. Granite-related Au-Bi-Te quartz breccia and pyroxene skarn in hornfels were mined at Maldon (67 t Au). The inset map of southeast Australia shows the Bendigo Zone (BZ) separated by regional faults from the Stawell (SZ) and Melbourne (MZ) Zones. Age and production data: Cherry and Wilkinson (1994), Bierlein et al. 2000, Arne et al. (2001), Willman (2007).

The Bendigo deposits (1851-2007: 697 t Au incl. 157 t from placers) are hosted by an Ordovician slate-greywacke succession folded into north-trending tight anticlines and synclines of shallow plunge. A sub-vertical axial plane cleavage is widely developed (Cox et al. 1991; Willman 2007). Mesothermal gold quartz veins (reefs) form stacked ore bodies in anticlines mined to a depth of 1400 m, whereas the synclines are poorly mineralized. Three structural types of vein are common: **(1)** bedding-parallel laminated "leg reefs" in anticlinal limbs, often associated with tensional spur veins extending into competent beds; **(2)** thick "saddle reefs" in the dilated anticlinal hinge, some extending into "neck reefs" crosscutting the beds; and **(3)** "fault reefs" with footwall tensional veins in strike-parallel reverse faults, which develop at steeply dipping bedding planes but flatten where they crosscut the fold hinge (Cox et al. 1991; Cherry and Wilkinson 1994; Leader et al. 2013).

(B) Looking north at a cross section through a Bendigo anticline illustrating the structural types of gold quartz vein, modified from Leader et al. (2013).

(C) Stacked saddle reefs (red) in workings of the Hustlers mine, Bendigo, cross section looking north (modified from Baragwanath 1930). The post-ore lamprophyre dyke (blue) is Jurassic (159±6 Ma K-Ar; Cherry and Wilkinson 1994).

Eisenberg: Bedding-parallel veins formed in the overturned NW-limb of the Eisenberg anticline during folding in the Stephanian, constrained by the K-Ar age of metamorphic illite at 297±9 Ma (Ahrendt et al. 1983). Erosion of the Variscan mountain chain took place in the Lower Permian (ca. 295-275 Ma), when the "saddle reef" position of the Kulm 3 slate-limestone succession was removed. Some reverse faults of possible "fault reef" geometry (Schlossberg system) were preserved. The anticline remained above sea level in the Upper Permian at 260 Ma but was covered by more than 400 m of sediment during the Mesozoic. Uplift began in the Upper Cretaceous and continued during the Tertiary (Kulick et al. 1997).

2.13 *Slide 13. Ramsbeck Zn-Pb-Ag veins: Setting in a regional anticline*

The Ramsbeck mine (1840-1974: 16.7 million metric tons at 4.4% Zn, 2.1% Pb and 50-60 g/t Ag; Behrend and Paeckelmann 1937; Bauer et al. 1979) closed in 1974 but remains open to tourists via the Eickhoff tunnel (www.sauerlaender-besucherbergwerk.de).
The geologic map of the northeast Rhenish Massif (modified from Weber 1977) shows the Ramsbeck vein system (white double arrow) relative to the Givetian Meggen sedimentary-exhalative Zn-Pb-Ba deposit (Mueller 2019), which outcrops in a subsidiary syncline (red) at the northwest limb of the East Sauerland Anticline (ESA). The coordinates are latitude and

longitude. The inset shows the map area relative to German and Dutch cities.

The Ramsbeck veins are located at the margin of a thermal anomaly defined by the crystallinity of illite (white lines 105-115) in 633 polished slate samples measured by X-ray diffraction at the half-height of the 10Å {001} peak relative to quartz (Hb-illite$_{001}$ x 100 / Hb-quartz$_{100}$). Lower values correspond to increased illite crystallinity (Weber 1972a; 1972b; Werner 1988). This anomaly coincides with a regional high of vitrinite reflectance (magenta line V = 6%) and with a low in Bouguer gravity most likely caused by buried granite. Peak temperatures of 300-350°C at 304±10 Ma (n=4) in the aureole of this pluton are constrained by actinolite-pumpellyite assemblages in basaltic dykes and by illite K-Ar ages, respectively (Ahrendt et al. 1983; Werner 1988). The thermal anomaly is displaced 1000 m NE-block down at the Altenbüren Fault (AF; Weber 1977).

Primary inclusions in Ramsbeck vein quartz and sphalerite contain NaCl-KCl-H_2O fluids of low to moderate salinity (3-14 wt.% $NaCl_{eq}$), which homogenize into liquid at 140-210°C (Langhoff 1997). The correction to trapping temperature is plus 80-90°C (Behr et al. 1987) given at least 3 km burial depth and a lithostatic pressure of about 100 MPa (1 kbar) during ore formation (Bauer et al. 1979). The composition of late-stage chlorite (in Behrend and Paeckelmann 1937) indicates a fluid temperature of 306±50°C using the Al^{IV} thermometer of Cathelineau (1988). Early-stage sphalerite and galena have $d^{34}S$ values of +6.5 to +7.7‰, whereas late-stage sphalerite (+2.4 to +8.7‰) and boulangerite (-0.5 to +7.7‰) display a greater range (Wagner and Boyce 2001). These values overlap those of sulfides in mantle-derived magmatic rocks (0±3‰) but are close to the average $d^{34}S$ (+7‰) of the present-day crust suggesting assimilation of country rock sulfur, a feature of granitoids in Nova Scotia, Tasmania and Japan (Ohmoto 1986).

2.14 *Slide 14. Ramsbeck Zn-Pb-Ag veins in foliated quartzite and slate*

The geologic map (modified from Behrend and Paeckelmann 1937) shows the N60-70°E striking Devonian quartzite-slate succession at the NW-limb of the East Sauerland Anticline (ESA), the host formation of the mines in the district: Alexander (AX), Bastenberg (BA), Wilibald (WB), Dörnberg (DB), Aurora (AR), Juno (JN) and Pluto (PL). The Ramsbeck succession, shown in lithologic units, separates the ESA from the Nuttla Syncline. Veins of economic thickness (2-4 m) and grade were confined to the 80-100 m thick Main Quartzite, which persists for more than 7 km across the district, and to the 40-80 m thick Footwall Quartzite restricted to the Dörnberg area. Both quartzite units are highlighted bright green. In the Dörnberg area, stacked veins were mined over a vertical extent of 700 m. Diamond drilling before closure in 1974 indicated resources of 2.8 million metric tons below sea level (Podufal and Wellmer 1979). The Ramsbeck succession forms a hard quartzite-rich range in monotonous Middle Devonian grey to black slates 3000 m thick, which vary from calcareous to sandy and contain felsic tuffs and diabase sills or dykes (Weber 1977). Two trends of Zn-Pb veins parallel to the slaty cleavage occur 1.0 and 1.5 km southeast of the Ramsbeck range. These veins were mined up to 1911 in the Ries system (RS).

Post-ore faults: NW- to NNW-striking joints and faults (blue lines) cross the Ramsbeck succession. Dips vary from 45-80° SW or NE. In the Bastenberg mine, a 1.5-m-wide joint extending SSE from the main cleavage-parallel vein was mined over a distance of 100 m indicating that some cross joints / faults developed prior to ore formation, initially as tensional surfaces perpendicular to the fold axes (Behrend and Paeckelmann 1937). However, most NW-faults offset the cleavage-parallel veins, locally up to 300 m down as in the graben separating the Bastenberg and Dörnberg mines. Some normal faults contain vein fill up to 2 m thick, which is subdivided into: Stage 1 barite with minor gersdorffite, and Stage 2 calcite + Fe-dolomite with minor pyrite, marcasite, chalcopyrite, low-Ag galena, low-Fe sphalerite, and accessory pyrargyrite, stephanite, acanthite and millerite (Bauer et al. 1979).

The post-ore faulting and mineralization has been attributed to Tertiary reactivation (Bauer et al. 1979). Alternatively, it took place during post-folding uplift in the Permo-Carboniferous, as constrained by normal plus strike-slip faulting in the Auguste Victoria area (see below). At Ramsbeck, WNW-striking dextral strike-slip faults with up to 60 m apparent offset occur in the Dörnberg area. NNE-striking sinistral faults with up to 400 m apparent offset contained limonite iron ore grading into pyrite at depth (Behrend and Paeckelmann 1937).

2.15 *Slide 15. Ramsbeck Zn-Pb-Ag veins in slaty cleavage and faults*

Cross-section through the Bastenberg mine (Section "e" in Slide 2.14; modified from Behrend and Paeckelmann 1937) illustrating folds in the Ramsbeck quartzite-slate succession at the NW-limb of the ESA. In the overturned limb, which dips 20-30° SSE, the Main Quartzite is thrust over the Crinoid Slate. In the subhorizontal normal limb below, the lithologic units face the right way up. Folds of this geometry step down to >1.5 km depth, as the hinge of the regional Nuttla Syncline was not intersected in the 1.1 km deep Valme drill hole 3 km southeast of Ramsbeck (Bauer et al. 1979). The Bastenberg is the site of the 130 m long Venetian adit (1.4 m high, 0.2 m at top, 0.7 m at base), which may date back to the Bronze Age. Most of the mining took place in the Bastenberg Vein at the faulted contact of the Main Quartzite with the Crinoid Slate (Behrend and Paeckelmann 1937).

2.16 *Slide 16. Ramsbeck Zn-Pb-Ag veins: Dörnberg section*

Cross-section through the Dörnberg mine looking east (modified from Podufal 1977) showing stacked Zn-Pb-Ag veins in the folded Main Quartzite below the Eickhoff adit, the main drainage tunnel. A limestone bed (blue) marks the stratigraphic top of the quartzite unit, which strikes N60-70°E. Overturned fold limbs dip 30-50° SSE and alternate with normal limbs dipping flatly south. The fold axes plunge 5-10° SW (Podufal and Wellmer 1979).

Like the slates, the quartzite displays a cleavage sub-parallel to the axial plane of the folds, which is moderately fanned in thick beds (Weber 1977; Bauer et al. 1979). Cleavage planes reactivated as reverse faults are the principal structures controlling the veins. They strike N65-75°E, dip 10-45° SSE (average: 30°), and have offsets varying from a few meters to more than 100 m (FW Vein 1). Striations are ± parallel to the dip direction (Podufal and Wellmer 1979). Not all veins are located in faults. The correlation of beds across veins and the jig-saw fit of wall-rock fragments suggest that some cleavage planes were simply forced open by fluid pressure and filled with gangue and sulfides (Behrend and Paeckelmann 1937).

The veins are offset by numerous flat reverse faults, which moved the hanging wall block NNW and dip 15°SSE to 10° NNW (average: 5° SSE). Some are dome-shaped in cross section. The offsets vary from a few decimeters to tens of meters. Most flat faults are barren or weakly mineralized between the sections of vein displaced. The exception is the Aurora Fault, which offset the Dörnberg, Aurora and three minor veins up to 80 m and contained high-grade ore over a distance of 140 m (Behrend and Paeckelmann 1937; Podufal 1977).

The third syn-mineral structures are normal faults (not shown), which are parallel in strike to the veins but dip steeply SSE. They persist several ten meters in strike, have offsets of up to 5 m, and are locally mineralized with sphalerite and galena. They are interpreted as related to the relaxation of Variscan compression (Weber 1977).

2.17 *Slide 17. Ramsbeck: Veins in the axial plane cleavage and in flat reverse faults*

The syn-orogenic mineralization at Ramsbeck took place in stages separated by periods of reverse faulting (Behrend and Paeckelmann 1937; Scherp in Bauer et al. 1979; Wagner and Cook 1998). STAGE 1 is confined to the cleavage-parallel veins and faults, and consists of quartz, minor siderite (6-8 wt.% Mn), pyrite, and accessory arsenopyrite.

STAGE 2 fills both the cleavage-parallel veins and some of the flat reverse faults and consists of quartz, sphalerite (6.1-9.6 wt.% Fe), minor galena, and accessory chalcopyrite. The sphalerite contains inclusions of chalcopyrite and, rarely, stannite and pyrrhotite. The silver content of galena varied from 400 to 1400 g/t and averaged 900 g/t (Bauer et al. 1979).

STAGE 3 is separated in time from Stage 2 by the formation of ore mylonites in both the cleavage-parallel veins and the flat faults close to the intersection of both structures. The mylonites consist of rounded or corroded clasts of vein quartz, quartzite, and lesser Fe-rich sphalerite cemented by recrystallized sphalerite and galena. Many ore mylonites are enriched in silver (250-492 g/t) and antimony (up to 0.25 wt.%) indicating the presence of tetrahedrite, bournonite and boulangerite. These sulfosalts and late sphalerite (1.7-4.5 % Fe), chalcopyrite, galena and quartz also form weakly strained vein fill. Late minor minerals also include pyrite, arsenopyrite, calcite, ankerite, chlorite, kaolinite and dickite.

(A) Looking east at the Dörnberg Vein oriented parallel to the axial plane cleavage (dip 30°SSE) in grey quartzite with partings of dark grey phyllite. Striations on the footwall vein surface pitch 80-90° consistent with dip-slip. The vein is composed of white quartz, minor dark brown sphalerite and accessory chlorite, and is offset 1-2 m south-side down at a strike-parallel fault dipping 70°SSE (broken white line). Dörnberg mine, stope above the Eickhoff level close to the internal shaft 1, the hammer is 32 cm tall.

(B) Footwall Vein 1 composed of Stage 1 massive pyrite, minor quartz and accessory siderite oriented parallel to the axial plane cleavage in dark grey phyllite. A second vein of Stage 2 sphalerite and white quartz, oriented parallel to a flat reverse fault, crosscuts the cleavage planes and the pyrite vein. Display specimen in the Ramsbeck visitor center collected from the 300 to 360 m level of the Dörnberg mine, stope between crosscuts 2 and 6, the Swiss knife is 8.5 cm long.

(C) Looking northeast at a cross section through the Aurora Vein oriented parallel to cleavage planes in the Main Quartzite (modified from Bornhardt 1912). The angular quartzite fragments are quartz-veined and bordered by sparse sulfide seams (in bottom right corner) indicating repeat fracturing and sulfide deposition. The fragments are cemented by Stage 2 quartz and accessory sphalerite, which form a banded vein at the hanging wall contact, where they are crosscut by Stage 3 galena-rich mylonite marked by quartz clasts. Galena and minor sphalerite form replacement aggregates below the mylonite. Exposure in the stope above the Willibald 3 adit, photographed and colored by Bruno Baumgärtel, August 1910.

2.18 *Slide 18. Ramsbeck: Vein-fault system in plan section*

Projection of the Footwall Vein 4 within the Main Quartzite unit to a horizontal plane (modified from Podufal and Wellmer 1979) illustrating the structure of the vein-fault system: steeper cleavage-parallel vein segments are linked by flat reverse faults. The average dip of the mineralized surface is 23° SSE between +3 m above (360 m mine level) and -300 m below sea level. Mineable ore was defined by a composite thickness of ≥ 15 cm sphalerite equivalent. In the stopes below the Eickhoff adit, barren or weakly mineralized flat faults amounted to 25-30 vol.% diluting the grade of the crude ore extracted.

2.19 *Slide 19. Ramsbeck: Vein-fault system in cross section*

(A) North-south section of the Aurora vein-fault system in Main Quartzite west of the Aurora shaft between the Christian and Willibald 4 adits (not to scale; modified from Behrend and Paeckelmann 1937). The cleavage-parallel

Aurora Vein is offset at a reverse fault mineralized with 1-10 cm thick ore mylonite in its steeper parts and with unstrained Zn-Pb ore in its central flat part, which opened during movement. Flat reverse faults were only mineralized between the veins they offset. They lack Stage 1 pyrite but contain Stage 2-3 sphalerite and galena as well as Stage 3 bournonite, boulangerite and tetrahedrite (Behrend and Paeckelmann 1937; Bauer et al. 1979).

(B) Steel-grey ore mylonite, rounded and embayed clasts of white quartz are cemented by fine-grained galena and sphalerite. Note the irregular replacement front in older vein quartz. Dörnberg mine, Footwall Vein 1, 300 to 360 m level, stope between crosscuts 2 and 6, the lens cap is 52 mm across, collection Podufal.

(C) Looking northeast at a cross section of the Aurora Vein oriented parallel to cleavage in the Main Quartzite (modified from Bornhardt 1912). The banded vein is composed of Stage 2 iron-rich sphalerite, quartz, minor galena and rare chalcopyrite. Exposure in the stope above the Willibald 3 adit, photographed and colored by Bruno Baumgärtel, August 1910.

(D) Stage 2 sphalerite (ZnS), white quartz and rare calcite in veins parallel to the axial plane cleavage in phyllite. The pinch-and-swell quartz veins are interpreted to reflect the incremental opening of the cleavage planes due to supra-lithostatic fluid pressure. Dörnberg mine, Footwall Vein 1, 300 to 360 m level, stope between crosscuts 2 and 6, the matchstick is 42 mm long, collection AGM.

2.20 *Slide 20. Ramsbeck: Zn-Pb grade, vein textures, alteration*

LEFT: The map shows the contoured Zn-Pb grade (as sulfide thickness in ZnS equivalent) of the Footwall Vein 1 between crosscuts 2 and 4 on the 360 m level of the Dörnberg mine (modified from Podufal and Wellmer 1979). Note the scissor-type movement on some of the flat faults, which are barren at this location indicating that the reverse faulting outlasted mineralization.

(A) Footwall Vein 1: breccia in the Main Quartzite, angular fragments of fine-grained quartzite are cemented by Stage 2 white quartz, brown iron-rich sphalerite, and minor galena and pyrite. Quartz is the oldest vein mineral rimming the fragments. Dörnberg mine, 300 to 360 m level, stope between crosscuts 2 and 6, the Swiss knife is 8.5 cm long, collection Podufal. Wall-rock alteration: Quartzite adjacent to the veins was partly silicified and contained sparse disseminated pyrite (Scherp in Bauer et al. 1979).

(B) Footwall Vein 1: composite vein parallel to the axial plane cleavage in dark grey phyllite (Upper Crinoid Slate): Stage 1 massive pyrite with accessory quartz is separated from Stage 2 iron-rich sphalerite by a thin band (arrow) of brown siderite. Quartz ladder veins segment the siderite band indicating extension. The cleavage-parallel pinch-and-swell veins are composed of Stage 2 quartz and minor sphalerite. Dörnberg mine, 300 to 360 m level, stope between crosscuts 2 and 6, the Swiss knife is 8.5 cm long, collection Podufal. Wall-rock alteration: At vein contacts, the slate was altered to quartz-sericite ± pyrite schist 1-2 cm thick replacing metamorphic illite, chlorite, and rare feldspar (Scherp in Bauer et al. 1979).

Alteration in diabase: Vesicular diabase dykes rotated parallel to the axial plane cleavage occur locally in the Dörnberg mine (Weber 1977). They consist of metamorphic chlorite, albite and calcite. Along the contact with veins, the dykes are foliated and altered to a light grey sericite-quartz-ankerite ± leucoxene assemblage. Altered diabase contains 2.03-4.06 wt.% TiO_2, 1.71-9.98 % CO_2, and 2.02-4.59 % K_2O. K_2O/Na_2O ratios of 5:1 to 20:1 suggest that the alteration mica is muscovite (Scherp in Bauer et al. 1979).

2.21 *Slide 21. Ruhr coal district: Zn-Pb-Ag ore in normal faults*

The Ruhr coal-mining district in North Rhine Westphalia contains three Zn-Pb-Ag deposits controlled by post-orogenic faults. The Auguste Victoria deposit produced 5.2 million metric tons (Mt) of ore at 7% Zn, 4% Pb, 0.04% Cu and 65 g/t Ag (1938-1962), and the Christian Levin deposit 0.35 Mt at 10.7% Pb, 0.3% Zn and 26 g/t Ag (1938-1958). The Klara/ Graf Moltke deposit (2 Mt at 8% Zn, 2% Pb) was developed but not mined due to low metal prices in 1958 (Buschendorf et al. 1957; Pilger et al. 1961; Krassmann 2019).

LEFT: Bedrock map of the western Ruhr district (modified from Pilger et al. 1961). The Ruhr and Lippe are tributaries of the river Rhine. Upper Permian, Triassic, and Upper Cretaceous sedimentary rocks cover the erosion surface in the Carboniferous coal measures (dip: 2-6° N). The cover rocks pinch out along a line connecting the cities of Essen and Bochum but increase northward to a thickness of 800 m in the Lippe valley. Oligocene sandstones and shales in the west represent the east boundary of the Tertiary succession in the Rhine Basin (Henningsen and Katzung 2002). The 3.8 km thick Upper Carboniferous coal measures overlie 1-2 km thick Lower Carboniferous slate, greywacke and limestone without coal. On the map, the Namurian C and Westphalian A units up to coal seam Katharina delineate NE-striking tight anticlines (grey), whereas the Westphalian B and C delineate broad open synclines. The folds have gently plunging axes and vertical to steeply inclined axial surfaces. They are displaced by four sets of faults, from the oldest to youngest: **(1)** syn-orogenic reverse faults with up to 2000 m displacement, some re-folded during progressive deformation; **(2)** post-orogenic NW-striking normal faults (local term: Sprung) with up to 1000 m displacement; **(3)** WNW-striking dextral strike-slip faults, and **(4)** north-striking sinistral strike-slip faults subordinate to the dextral set (Hesemann and Pilger 1951; Henningsen and Katzung 2002). The Auguste Victoria (AV), Christian Levin (CL), Klara (KL), and the Zn-Pb deposits in the Velbert district (VB) to the south are controlled by normal faults perpendicular in strike to the fold axes.

CENTER: Stratigraphic column of the Upper Carboniferous (Pennsylvanian) coal measures in the Ruhr district (modified from Henningsen and Katzung 2002) showing prominent coal seams (black) and sandstones (yellow) in the fluviatile-deltaic siltstone-shale succession (ca. 320-305 Ma) of the Variscan foredeep. The coal measures are subdivided into the Namurian C and Westphalian A to C units keyed to type localities at local cities. Coal comprises 4-5% of the succession in the southern and about 2% in the northern part of the district. Out of 266 coal seams, 108 seams 0.5-2.8 m thick (Flöz in German) were mined. The unconformity at the end of the Westphalian C marks the main phase of Variscan folding in the Stephanian at ca. 305 Ma.

RIGHT: Column illustrating the sedimentary rocks in one cycle of coal formation (modified from Drozdzewski 2011). The coal seams are not strictly stratigraphic markers, as they are traversed at low angles by thin layers of volcanic ash altered to kaolin clay. Sandstone associated with the Westphalian A Finefrau coal seam contains detrital zircons eroded from metamorphic rocks (410-2590 Ma) and granites (327±3 Ma, U-Pb) in the Variscan terranes southeast of the Rhenish Massif (Linnemann et al. 2019). Some Westphalian B sandstones contain clasts of low-volatile coal eroded from exposed Namurian C seams. The high coal rank at clast deposition is attributed to elevated heat flow, probably caused by granite plutons emplaced at depth (Henningsen and Katzung 2002).

2.22 *Slide 22. Ruhr district: Folded coal measures*

(A) Cross section at Christian Levin looking east (modified from Buschendorf et al. 1957) showing folded and thrust-faulted major coal seams (e.g. Katharina, Finefrau) in the Upper Carboniferous basement (grey). The intensity of folding decreases to the north and up the stratigraphic section. The basement is overlain by flatly north-dipping Upper Cretaceous sand- and marlstones (green), and by Pleistocene glacial sediments (orange). The vertical scale is 4-times that of the horizontal.

(B) Looking northeast at the unconformity between folded Upper Carboniferous and flat-lying Upper Cretaceous sedimentary rocks. The Westphalian A beds consist of fine-grained mica-bearing sandstone, exposed below a reverse fault (white arrow), and sand-banded grey siltstone with a slaty cleavage. The poorly sorted transgression conglomerate with goethite and sandstone pebbles at the unconformity grades upwards into glauconitic sandstone. Geological Garden in the city of Bochum, exposure in the former open pit of the Friederica mine, which produced coal and black-band ironstone from 1750-1907.

(C) Looking NNW at a section sub-parallel to strike in coal measures forming the wall of the Dünkelberg quarry, Mutte valley south of the river Ruhr. The coal seam Gleitling 3 (black-brown) is overlain by the Finefrau conglomeratic sandstone, and underlain by slates comprising (top to bottom): carbonaceous mudstone with plant roots (2 m), siltstone (8-10 m), mudstone with plant roots (3-4 m), sand-banded siltstone (8-10 m). The coal seam is displaced at two normal faults (white arrows). The wall is about 35 m high. Muttental open-air museum at the former Nachtigall coal mine, Ruhr valley in the city of Witten.

(D) Looking north at the position of seam Dickebank, mined for coal and siderite, which is overlain by the cross-bedded Dickebank sandstone and underlain by brown carbonaceous mudstone with plant roots grading downward into grey sand-banded siltstone. The coal-bearing mudstone contains yellow-brown siderite nodules and lenses up to 20 cm long. From 1851-1912, about 9 million metric tons of "black-band" siderite were mined as iron ore (25-40% Fe) in the Ruhr district (Wrede 2006). Geological Garden in the city of Bochum, exposure in the former open pit of the Friederica mine. The open Swiss knife is 16 cm tall.

2.23 *Slide 23. Auguste Victoria: Faults in plan and cross section*

LEFT: Plan of Level 3 (743 m below surface) showing the principal structures in the Auguste Victoria mine (modified from Hesemann and Pilger 1951). Crosscutting relationships indicate, from the oldest to youngest: **(1)** the upright Auguste Victoria anticline (AVA) outlined by the coal seams mined; **(2)** the AV reverse fault (AVRF) with > 600 m displacement; **(3)** the post-orogenic Blumenthal normal fault (BNF) controlling the William Köhler Zn-Pb-Ag deposit (black), **(4)** the mineralized AV dextral strike-slip fault (AVF) with 210 m horizontal and 15 m vertical offset, and **(5)** the mineralized Hüls sinistral strike-slip fault (HUF). The AV strike-slip fault, marked by cataclasite up to 5 m thick, contained uneconomic sphalerite-quartz cemented breccia and barite-calcite-marcasite veins attributed to the late stages of sulfide mineralization (Pilger et al. 1961). The drift linking the production shafts 1/2 to the man-and-supply shafts 4/5 was chosen as the Zero line crosscut in the ore deposit.

RIGHT: Section through the Blumenthal normal fault (blue) at crosscut Zero, parallel in strike to the coal seams (black), sandstones, sand-banded siltstones (both yellow) and mudstones of the Westphalian A beds. The stopes (red) projected from crosscut 2 south average 15-18 m in width. The ore extends to the uppermost mine level. Galena was intersected in a drill hole 1 m below the Cretaceous unconformity (Hesemann and Pilger 1951; Pilger et al. 1961).

The Blumenthal Fault consists of a stepped zone 15-60 m wide, which dips 60-70° SW. The vertical displacement at the mine is 700 m SW-block down, as indicated by the correlation of Carboniferous strata across the fault, the upward drag of coal seams in the SW-block, and vertical striations (pitch 75-90°) on fault planes. Half the displacement is attributed to the footwall boundary fault, one quarter to the hanging wall boundary fault, and the remainder to faults within the zone. A diamond hole (DDH) drilled from the uppermost mine level into the Cretaceous sandstone showed that the erosion surface on the fault is 55 m higher than elsewhere on the mining lease. About 20-25 m is due to a paleo-high formed by the silicified fault zone, and 30-35 m to post-Cretaceous reverse reactivation caused by far-field stress in the foreland of the Alpine-Tethyan fold belt. The deposit is thus older than the Cenomanian sandstone cover (ca. 100 Ma; ICS 2018), and probably older than the flat-lying Permian Zechstein 1 conglomerate and black shale (ca. 260 Ma) on adjacent mining leases (Hesemann and Pilger 1951).

2.24 *Slide 24. Auguste Victoria Zn-Pb ore: Structural controls*

TOP: Looking southwest at the longitudinal projection of the Zn-Pb-Ag ore bodies in the Blumenthal Fault onto the AV anticline (modified from Hesemann and Pilger 1958; Pilger et al 1961). The top of the Northern Orebody was eroded prior to the Cretaceous marine transgression. The apparent inclination of the axial plane to the southeast is caused by the change in strike of the projection line. The Zn-Pb deposits and most prospects in the Ruhr district occur where NW-striking normal faults cross NE-striking anticlines.

BOTTOM: Structural plan of Level 3 (-743 m) showing the Stage 1 sphalerite-galena ore in the Blumenthal normal fault (black), the Stage 2a sphalerite ore controlled by the North Zone of dextral strike-slip faults (red), and the Stage 2b barite-calcite-pyrite-marcasite mineralization in the Hüls system of sinistral strike-slip faults (green; modified from Hesemann and Pilger 1958; Pilger et al 1961).

The 150-m-wide North Zone consists of 3-7 shear zones, which strike N75°W, dip 70-85° SSW, and displace the Blumenthal Fault and Stage 1 ore 10-20 m north block east. Striations on fault planes are horizontal or pitch at shallow angles. Stage 2a replacement is confined to the intersection with the Blumenthal Fault, and extends along normal fault planes. Some 2a sphalerite zones with minor dextral offsets trend N55°W across the Blumenthal Fault, a Riedel orientation relative to the North Zone shown in the Southern Orebody.

The Hüls system has an overall strike of N60-65°W, and consists of en-echelon subvertical faults (N70-75°W) and fissures (N90°W), the latter forming open spaces up to 5 m wide. The faults displace the south block east and have horizontal to moderately east-pitching striations. In the Southern Orebody, in particular, they offset both Stage 1 and Stage 2a ore. In aggregate, these offsets cause the sigmoidal deflection of the Blumenthal Fault in strike separating the ore bodies. Stage 2b fault fill consists mainly of calcite, pyrite and marcasite (Pilger et al. 1961).

2.25 *Slide 25. Auguste Victoria: Ore formation during faulting*

TOP: Geologic map of the Northern Orebody on Level 3a (-833 m) of the Auguste Victoria mine showing the mineralization stages controlled by the Blumenthal normal fault, the North Zone dextral strike-slip faults, and the Hüls sinistral strike-slip faults (modified from Hesemann and Pilger 1951). Main stage ore was confined to the Blumenthal Fault, and comprised wall-rock silicification plus low-grade quartz breccia along the footwall boundary fault (Stage 1a), sphalerite-rich breccia in the central part (Stage 1b), and galena-rich breccia in the hanging wall part (Stage 1c). Fragments of Stage 1a in Stage 1b and of Stage 1b in Stage 1c indicate syn-tectonic sulfide deposition, and the stepwise widening of the Blumenthal Fault from early movement on the footwall boundary to later movements on its hanging wall faults (Hesemann and Pilger 1951).

The North Zone is part of the WNW-trending strike-slip system represented by the AV Fault (Slide 2.23). In the Northern Orebody, the dextral faults offset both the Blumenthal Fault and the Stage 1 ore. They controlled Stage 2a silica replacement and sphalerite-quartz ore. The sphalerite in both Stage 1b and 2a had low iron contents of 1.62-1.75% and 1.35-1.60%, respectively (Pilger et al. 1961).

The Hüls sinistral strike-slip faults (Huels A to C) control Stage 2b mineralization composed of barite, calcite, pyrite and marcasite. Sparse sphalerite (1.32% Fe) and rare galena are interpreted as remobilized from older ore (Hesemann and Pilger 1951). Some Stage 2b veins extend along normal faults, which were reactivated as indicated by horizontal striations overprinting steeply pitching ones. Note the deflection of the Blumenthal Fault in strike by stepped sinistral offsets at the southeast end of the Northern Orebody.

(A) Stage 1a fault breccia: angular to subrounded fragments of silicified black slate and older breccia (above the coin) are cemented by white sugary quartz and by sparse brown sphalerite. Small open vugs are lined with quartz crystals. Sample 55, Auguste Victoria mine collection. The Swiss knife is 8.5 cm long.

(B) Stage 1b breccia ore: fragments of fine-grained brown sandstone, black slate and white Stage 1a quartz are cemented by dark brown crystalline sphalerite and by minor fine-grained galena (at knife). The clear grey quartz of the top lines an open vug. Sample 15, Auguste Victoria mine collection. The Swiss knife is 8.5 cm long.

(C) Stage 1c breccia ore: wall-rock fragments (dotted) are cemented by galena and accessory sphalerite (black), which are partly replaced by Stage 2b calcite and marcasite (yellow) adjacent to a Hüls fault. Drawing of an exposure on Level 3, Crosscut Zero, in the hanging wall part of the Blumenthal Fault (modified from Hesemann and Pilger 1951).

2.26 *Slide 26. Auguste Victoria: Stage 1 ore in the normal fault*

Stage 1 sphalerite and galena in the Blumenthal normal fault and less abundant Stage 2a sphalerite in and adjacent to the North Zone strike-slip faults are the principal ore minerals. In both stages, the sequence of deposition is quartz - sphalerite - chalcopyrite - galena - quartz, repeated several times in the fault breccia. The abundance of quartz relative to hydrothermal sericite, siderite, ankerite and late dickite is reflected in the average composition of the ore (71 wt.% SiO_2; 3.8% Al_2O_3; 1.3% CaO). Pyrite and millerite are absent in Stage 1.

In 1950, the sphalerite flotation concentrate contained 57-60% Zn, 31.5% S, 1.75% Fe, 0.8-1.2% Pb, 0.25% Cu, 0.15% Sb (trace As), 95-135 g/t Ag, 590 g/t Ga, 150 g/t Ge, 300 g/t In, 50 g/t Cd, 40-80 g/t Sn, 40 g/t Mn and 24 g/t Hg, and the galena concentrate 73-78% Pb, 13.4% S, 0.8-2% Zn, 0.4% Cu, 0.25% Sb (trace As, no Bi) and 1000-1200 g/t Ag (Hesemann and Pilger 1951; Pilger et al. 1961). The total metal recovered amounted to 277,000 t Zn, 169,000 t Pb and 250 t Ag (1938-1962; Gewerkschaft Auguste Victoria 1997).

LEFT: Longitudinal projection of Stage 1 ore in the Northern Orebody looking southwest (modified from Hesemann and Pilger 1951). The gradual change from sphalerite-rich ore at depth to galena-rich ore at the top is similar to the inner-outer Cu to Zn to Pb zonation in other hydrothermal ore deposits, controlled by chloride solubility in an H_2S-bearing fluid and by temperature at about constant pressure (Hemley and Hunt 1992). The upward zonation of Zn to Pb in Stage 1 ore indicates an ascending fluid. Application of the empirical sphalerite geothermometer of Frenzel et al. (2016) to the flotation concentrate composition results in an estimated fluid temperature of 259±17°C during sulfide deposition, which may be rounded to 260±20°C.

(A) Stage 1b Zn-Pb cockade ore: fragments of silicified black siltstone and quartz-sphalerite breccia ore are mantled by concentric grey layers of fine-grained galena and quartz forming round to elliptical cockades, which are cemented by dark brown sphalerite and white quartz crystals lining interstitial vugs. Sample 40, Auguste Victoria mine collection, the Swiss knife is 8.5 cm long.

(B) Stage 1b/c lead cockade ore (25 wt.% PbS): closely packed, fine-grained grey galena-quartz cockades with central fragments of silicified siltstone or Stage 1b ore, which are cemented by quartz and interstitial yellow-white clay. Note the light brown sandstone at the knife. Sample 38, Auguste Victoria mine collection, the Swiss knife is 8.5 cm long.

(C) Transmitted light photograph of a round cockade surrounding an angular fragment of siltstone. The concentric shells are composed of galena-rich (black) and quartz-rich layers (white), modified from Stolze in Pilger et al. (1961).

Stage 1 cockade ore was confined to the lower half of the Northern Orebody and common on level 3a (Slide 2.25), where it filled fissures in breccia ore up to 1 m wide and 28 m long. The cockades are interpreted as gel structures recrystallized into radially oriented thin quartz crystals with micron-sized galena inclusions and interstitial galena grains (0.1-0.3 mm). The consistency of fine galena-quartz layering in adjacent spheres and soft-layer indentations indicate that the cockades grew suspended in a viscous SiO_2-PbS colloidal solution, probably during periods of tectonic quiescence in the Blumenthal Fault (Stolze in Pilger et al. 1961).

2.27 *Slide 27. Auguste Victoria: Stage 2 ore in strike-slip faults*

LEFT: Longitudinal projection of Stage 2 ore in the Northern Orebody looking southwest. The distribution of syn-tectonic Stage 2 mineralization indicates the successive opening of the strike-slip faults during a short period of time (Hesemann and Pilger 1951). Stage 2a sphalerite-quartz ± ankerite ± siderite ore was deposited early from a fluid ascending in the North Zone faults, which infiltrated first the Hüls A and then the Hüls B fault at progressively higher levels in the ore body. Minor galena, pyrite and millerite were deposited with sphalerite on and above Level 2.

Stage 2b barite-calcite-pyrite-marcasite mineralization overprints Stage 2a and fills all three Hüls strike-slip faults in the lower part of the ore body. In the upper part, Stage 2a sphalerite-quartz ore restricted the ascent of the Stage 2b fluid in the Hüls A and B but not in the Hüls C fault, which opened last and was mineralized with marcasite and pyrite to the uppermost level. Calcite and barite are sparse above Level 2. Late marcasite is 2- to 3-times more abundant than pyrite, and forms colloform aggregates with pyrite and minor sphalerite. Galena (200-250 g/t Ag), chalcopyrite and millerite are accessory.

(A) Fragments of light brown Stage 2a sphalerite and of quartz-sphalerite breccia ore are cemented by white Stage 2b barite, which contains interstitial marcasite (right margin). Sample 49, Auguste Victoria mine collection, the Swiss knife is 8 cm tall. Marcasite (0.03% As), calcite (0.3-0.4% Mn) and barite (0.5% Sr) are the most abundant minerals in Stage 2b (Stolze in Pilger et al. 1961).

(B) Fault breccia composed of white barite fragments in yellow-grey marcasite cement crosscuts massive Stage 2b barite indicating that mineral fill in the Hüls faults was syntectonic. Sample 22, Auguste Victoria mine collection, the Swiss knife is 8.5 cm long.

Age constraints: Hesemann and Pilger (1951) interpret the relationship between faulting and syn-tectonic mineralization to indicate a short-lived magmatic-hydrothermal system, which operated after Variscan folding but before significant erosion in the Lower Permian. Ore formation took place at 3-4 km depth based on stratigraphic reconstruction. Normal faults initiated during folding were reactivated causing 700 m offset at the Blumenthal Fault, followed by 100-m-scale dextral strike-slip on the Auguste Victoria system, and then by sinistral strike-slip on the Hüls system interpreted as stress release after dextral displacement.

This interpretation is consistent with the regional pattern of Permo-Carboniferous strike-slip faults in Europe (Slides 2.3 and 2.4), and with the lead isotope ratios in AV galena (Krahn and Baumann 1996), which match those at Ramsbeck where thermal and geophysical anomalies delineate the related pluton. In contrast, the radiogenic lead isotope ratios in galena from the barite-rich ore at Christian Levin are more compatible with post-orogenic basement-brine mineralization (Diedel and Baumann 1988; Wrede 2006).

2.28 *Slide 28. Harz Block: Zn-Pb-Ag ore in wrench faults*

Ore production from the Upper Harz district west of the Brocken granite amounts to 37.8 million metric tons (Mt) at recovered grades of 5.1% Pb, 3.9% Zn and 135 g/t Ag (1524-1992) equal to 1.910 Mt of lead, 1.463 Mt of zinc, and >5000 t silver (Stedingk 2012). After a period of shallow shaft and open-cut mining in 1200-1350 AD, systematic underground development began in 1524 initiated by duke Heinrich the Younger of Wolfenbüttel (Buschendorf et al. 1971).

RIGHT: Geologic map of the Harz block uplifted and tilted SSW at the North Boundary Fault in the Cretaceous and Cenozoic (modified from Hinze et al. 1998). The Variscan slate belt is in light grey, and the raft of basement Ecker gneiss is black. The Devonian anticlinorium (brown) south of Goslar, NE-striking folds in Devonian basaltic spilite (dark green), and Devonian limestone reefs (dark blue) are highlighted. Also colored are the post-folding Harzburg norite-gabbro intrusion (G), the Brocken (B) and Ramberg (R) granite plutons and the Harz dyke swarm (HD), all considered part of an underlying batholith. The dykes are feeders to Permian rhyolite, minor andesite and basalt flows intercalated with red beds at the south rim of the Harz block. The Brocken and Ramberg granites (283±2 Ma and 283±3 Ma U-Pb zircon; Zech et al. 2010) are younger than the quartz porphyries of the Halle Volcanic Complex (HVC; 307±3 to 294±3 Ma U-Pb zircon; Breitkreuz and Kennedy 1999). The Permo-Carboniferous volcanic and red bed sedimentary succession is overlain by the Permian Zechstein formation (blue), represented by marine limestone, anhydrite and dolomite at the Harz rim, and by up to 2000 m of salt in the basins to the north and south covered by Triassic (pink), Jurassic (light blue), Cretaceous (light green) and younger sedimentary rocks.

LEFT: Geologic map of the Upper Harz (modified from Hinze et al. 1998) highlighting the post-folding wrench faults sub-parallel to the Harz North Boundary Fault (HNBF). The N50-60°E striking folds are outlined by Lower to Upper Devonian (LD to UD) sandstones and slates in the anticlinorium south of Goslar, and by Middle Devonian (MD) diabase-spilite anticlines. All folds have axial surfaces inclined towards the northwest. The Carboniferous greywacke succession hosts the major fault-controlled Zn-Pb-Ag deposits centered on the mining towns of Clausthal-Zellerfeld (CLZ), Bad Grund (BG) and Lautenthal (LT). The silver deposit at St Andreasberg (StA), famous for its collector-item minerals (Stedingk et al. 2016), is controlled by the dextral Edelleuter Fault (ELF), which offsets tight folds in Devonian diabase 750 m north block east. Post-folding intrusions include the ultramafic-mafic Harzburg gabbro (G), the Brocken diorite-granite pluton (B), and the north-striking kersantite dyke (K). Lamprophyres in the Erzgebirge block of the Bohemian Massif are dated at 328±0.5 to 294±6 Ma (K-Ar and Ar-Ar phlogopite; Seifert 2008). The emplacement depth of the Brocken pluton prior to erosion is estimated at 3-6 km according to melt-inclusion data (80-200 MPa; 740-560°C) from post-orogenic granites in the northern Bohemian Massif (Thomas and Klemm 1997).

2.29 *Slide 29. Elbe Zone: Harz North Boundary Fault*

(A) The Variscan slate belt in the Harz block was uplifted 3-4 km at the WNW-striking and 70° south dipping Harz North Boundary Fault (HNBF), which is part of the Elbe Zone (Scheck et al. 2002). The onset of Alpine-Tethyan far-field stress is constrained by angular unconformities in the Mesozoic sedimentary rocks, which were tilted up and overturned at the front of the basement block (Wagenbreth and Steiner 1990). In the Upper Permian to Middle Triassic, the NE-trending Hunsrück-Eichsfeld-Oberharz paleo-high influenced sedimentation (Mohr 1993). In the Upper Triassic (ca. 210-201 Ma; ICS 2018), parts of the Harz were above sea level, perhaps elevated at the HNBF, and shallow-marine oolitic iron ore beds suggest a

WNW-trending shoreline in the Jurassic. The first unconformity (15°) is at the base of the Lower Cretaceous Hauterivian sandstone (ca. 135 Ma), and the main unconformity (up to 90°) at the base of Santonian conglomeratic sandstone (ca. 85 Ma). Granite clasts indicate that the Brocken complex was unroofed at this time. Major phases of uplift also took place in the Miocene and Pliocene (Mohr 1993).

(B) In the Harz block, the N50°E-striking folds in the Devonian and Carboniferous sedimentary rocks are marked by a slaty cleavage: Looking northeast at Upper Devonian calcareous slate forming the vertically dipping SE-limb of a syncline in Middle Devonian black slate. Leached limestone nodules trace the vertical bedding. The axial plane cleavage dips 50-60° SE. Margaretenklippen outcrop in the Granetal near Goslar, the Swiss knife is 18 cm tall.

(C) While most folds are upright, overturning of the strata and thrust faulting occur locally, for example in the Devonian slates at the Rammelsberg mine, Goslar. The diagram (after Abt 1958) illustrates an isoclinal syncline in Wissenbach black slate looking northeast. Structures include: subsidiary drag folds in ductile beds (black), the axial plane cleavage, fanning of the cleavage in competent limestone and sandstone beds, and the thinning of these beds on the fold limbs due to bedding-parallel flexural slip.

2.30 *Slide 30. Harz Block: Post-orogenic wrench faults*

LEFT: Structural map of the Upper Harz district (modified from Jacobsen and Schneider 1950; Sperling and Stoppel 1981) showing the wrench faults parallel to the Harz North Boundary Fault (HNBF), and the mining towns of Goslar, Lautenthal (LT), Clausthal-Zellerfeld (CLZ), and Bad Grund (BG). The faults offset the N50-60°E striking Variscan folds. Stahl (1920) recognized that the movement was either strike- or oblique-slip. Richter (1941) suggested that the movement was dextral with a minor component south side down. Faults transecting the Devonian anticlinorium SSW of Goslar offset a sub-vertical kersantite dyke (K) by a cumulative amount of 2 km north block east. In contrast, sinistral strike-slip of 800 m south block east has been established at the Silbernaal Fault (SNF; Stedingk and Ehling 1995). Faults branching off the SNF, termed the Charlotter (CRF) and Burgstätter Ruschel (BRF), crosscut the dextral Zellerfeld-Rosenhof-Burgstätter fault system (ZEF-RHF-BUF). Apparently, the wrench faults progressed from early dextral to late sinistral movement, the dominant phase evident in the offset of marker folds and dykes. The three faults bounding the Devonian anticlinorium to the SSE have a south-side-down component, constrained by stratigraphic correlation to 400-500 m at both the sinistral Lautenthal (LTF) and the dextral Bockswiese (BOF) faults. Mineralized faults include the dextral ZEF-RHF-BUF system at Clausthal-Zellerfeld (10.8 Mt at 3.8% Zn + 4.6% Pb), the dextral oblique-slip BOF (2.15 Mt at 1.4% Zn + 5.7% Pb), the sinistal SNF at Bad Grund (19.1 Mt at 3.9% Zn + 5.8% Pb), and the sinistral oblique-slip LTF at Lautenthal (4.2 Mt at 6.7% Zn + 2.3% Pb; Sperling and Stoppel 1981; Stedingk 2012).

(A) Looking at thin-bedded black slate and greywacke of the Lower Carboniferous Kulm 3 stratigraphic unit, the most common host rock in the Upper Harz vein district. Exposure in the adit to the New Main shaft, Lautenthal museum and visitor mine (www.lautenthals-glueck.de). The hammer is 32 cm tall.

(B) Looking northeast at folded Lower Carboniferous greywacke: sandstone turbidite beds (35-45% quartz, 15-35% feldspar, 5-20% chlorite, 1-5% sericite, 3-10% clay) are separated by thin black-grey siltstone. Quarry in the Innerste valley near the Meding shaft.

Relative age constraints: The Goslar segment of the HNBF extends east into the Harz block towards the Ilsestein, the NW-striking 11 km long border granite of the Brocken pluton interpreted as emplaced into the fault zone (Mohr 1993). The north-striking kersantite dyke (K) terminates at the Lautenthal Fault but another kersantite was emplaced into this fault (Schulze 1968). Thus, the wrench faults postdate Variscan folding at ca. 305 Ma but are older than 283±2 Ma, the U-Pb zircon age of the Brocken pluton (Zech et al. 2010). On the other hand, the Weisser Hirsch Fault (WHF) offsets the Oker granite 600 m in a dextral sense, the Edelleuter Fault at St Andreasberg offsets hornfels, and other faults offset the feeder dykes to Permian volcanic rocks indicating large-scale (500-800 m) faulting coincident with Permian magmatic activity at 300-280 Ma.

The Silbernaal (SNF) and Weisser Hirsch faults extend west into the Upper Permian Zechstein limestone and dolomite, which unconformably overlie the Variscan basement and dip 5-10° west. At both faults, the limestone was replaced by tabular siderite-barite ore, barren of base metals but mined for iron (limonite) and barite in open cuts (Sperling and Stoppel 1979). At the Silbernaal Fault, the Permian cover rocks are offset 30-40 m south block up. Dextral reverse oblique-slip of 50-100 m is indicated by post-sulfide faults in the ore bodies below the unconformity. These faults had reverse offsets (0.2-5 m), were confined to the SNF and rotated anticlockwise in strike (Sperling 1973). The Permian Zechstein 1 limestone correlates with the base of the Lopingian formation dated at 259±0.5 Ma (ICS 2018; Oszczepalski et al. 2019) indicating fault reactivation, probably during Alpine-Tethyan far-field stress. In contrast to the SNF and WHF, other wrench faults have not been traced into the Upper Permian cover rocks. In particular, there is not evidence for post-Permian fault movement on the ZEF-RHF-BUF system at Clausthal-Zellerfeld.

2.31 *Slide 31. Clausthal-Zellerfeld: Zn-Pb veins in dextral faults*

LEFT: The structural map (modified from Stedingk 2012) shows the steeply dipping wrench faults controlling the Clausthal-Zellerfeld deposit, which produced 10.8 million metric tons of ore at recovered grades of 3.8% Zn, 4.6% Pb and >100 g/t Ag (1524-1930; Sperling and Stoppel 1981). The Zellerfeld (ZEF) and Rosenhof (RHF) boundary faults are linked by the Burgstätter Fault (BUF), oriented 40° clockwise in strike, close to the empirical direction of extension in a dextral strike-slip system (Sylvester 1988). At both boundary faults, folds in Devonian diabase are offset 600 m south block west, the strike-slip complemented by a minor normal component. The Rosenhof Fault branches into the Kranicher Fault (KRF) and other strands at the Ottiliae shaft (OT) forming a complex fault pattern near Clausthal. The Silbernaal Fault (SNF) south of the dextral system moved in the opposite direction, and offsets marker conglomerates 800 m south block east (Stedingk and Ehling 1995). The Charlotter Ruschel (CRF) displaces the Zellerfeld Fault 250 m, and the Burgstätter Ruschel (BRF) the Burgstätter Fault 50 m in a sinistral sense (Sperling and Stoppel 1979).

The ore bodies were initially developed from inclined shafts (St Lorenz: SL) replaced in the 19th century with the vertical New Johannes (NJ), Meding (MD), Ottiliae (OT), Kaiser Wilhelm II (WH) and Königin Marie (KM) shafts. Ore was mined from outcrops down to 600 m in the Zellerfeld, 800 m in the Rosenhof, and 1000 m in the Burgstätter faults. The Tiefer Georg (+307 m; 1777-1799 AD) and the Ernst August drainage adits (+190 m; 1851-1864) still dewater the mines to about 400 m depth (Sperling and Stoppel 1979; 1981). The wooden wheels used to hoist the ore and pump mine water to the lowest adit were powered by water stored in 149 artificial lakes connected by 500 km of ditches. This system (Upper Harz Water Regale) protected by royal right (regale) in the 16th to 19th centuries became UNESCO world heritage in 2010 (www.oberharz.de).

RIGHT: Vein from the Burgstätter Fault: Stage 2 banded ore enclosing sulfide-rimmed vein fragments, coarse-grained (2-5 mm) dark brown sphalerite and grey galena (60 vol.% of total sulfide) in white-grey quartz and minor calcite. Museum collection, Technical University of Clausthal, Adolph Römer Strasse 2a, Clausthal-Zellerfeld, the Swiss knife is 8.5 cm long.

2.32 *Slide 32. Clausthal-Zellerfeld: Burgstätter dextral fault*

Syn-tectonic banded and breccia veins up to 5 m thick and 300 m long in the Burgstätter Fault account for 70% (7.46 Mt at 4.4% Zn + 3.6% Pb) of the total ore mined at Clausthal-Zellerfeld. About one third of the fault surface contained ore. Composite veins were mined over a width of up to 10 m on the Wilhelm 19 level (Sperling and Stoppel 1979).

(A) Structural plan of the Burgstätter Fault (modified from Stedingk 2012) at two mine levels 660 m apart showing the junctions with the Kranicher (KRF) and Rosenhof (RHF) faults, the sinistral displacement at the Burgstätter Ruschel (BRF), and the locations of the St Lorenz (SL), Kaiser Wilhelm II (WH), Königin Marie (KM), and Caroline (CL) shafts. Sinistral movement on the barren BRF postdates mineralization in the dextral Burgstätter Fault.

(B) Cross section illustrating the steep SW-dip (75°) of the Burgstätter (BUF) and Kranicher (KRF) faults at the Kaiser Wilhelm II shaft, and the development of Zn-Pb-Ag ore down to the 24 level about 1000 m below surface.

(C) Longitudinal projection of Zn-Pb-Ag ore in the Burgstätter Fault (modified from Stedingk 2012) showing the Wilhelm (W), Margarethe (M) and Dorothea (D) ore bodies, the intersection lines with the Kranicher (KRF) and Rosenhof (RHF) dextral faults, and the sub-vertical intersection with the post-ore Burgstätter Ruschel (BRF) strike-slip fault. Note the Tiefer Georg and Ernst August drainage adits.

STAGE 1 hematite-dolomite-pyrite (+ illite?) alteration and silicification in zones up to 1 m wide was prominent on the Wilhelm 23 level but extended up to the Tiefer Georg adit, mainly along the footwall and hanging wall boundary faults. Associated quartz-chalcopyrite veins increased in thickness with depth. On the Tiefer Georg level, Stage 1 ankerite veins in altered greywacke NW and SE of the St Lorenz shaft contained hematite, clausthalite (PbSe), tiemannite (HgSe), minor naumannite (Ag_2Se), pyrite and chalcopyrite. Hematite-dolomite ± talc alteration occurred in the Kranicher Fault (Sperling and Stoppel 1979).

STAGE 2 sphalerite, galena, accessory chalcopyrite, quartz and calcite constituted the Zn-Pb-Ag ore. Stage 3 siderite and barite were rare or absent. Sphalerite (1.4-5.3% Fe) was the most abundant sulfide below the Wilhelm 17 level indicating an upward zonation ZnS to PbS in the ore bodies. Galena $d^{34}S$ values increased with depth from -1.4‰ on the Wilhelm 3 level to +3.5‰ on 16 level and +4.7-5.8‰ on 20-23 level (Nielsen 1968), perhaps reflecting a temperature gradient. Galena from the upper levels in the Dorothea ore body had higher Ag-Sb contents (>0.23% Ag, 0.32-0.65% Sb) than galena from the lower levels (0.07-0.09% Ag, 0.17-0.33% Sb) due to inclusions of jamesonite, boulangerite, stibnite, tetrahedrite (9% Ag), pyrargyrite, stephanite and native silver. Stage 2 ore was also dominant in the Zellerfeld and Rosenhof boundary faults. Galena concentrates from the Burgstätter Fault (0.06-0.20% Ag) were rich in silver relative to those from the Zellerfeld (0.03-0.10% Ag) and Rosenhof faults (0.05-0.08% Ag; Wilke 1952).

(D) Burgstätter Fault, Kranicher vein: Stage 2 banded vein composed of sphalerite (dark brown), calcite (yellow) and minor galena (blue), the wall rock (grey) is quartz-flooded (white). Wilhelm ore body, 23 level southeast of the Kaiser Wilhelm II shaft, between cross-cuts 1 and 2. The scale bar is 1 m long. The hand-colored photograph taken by Mascher in 1930 shows zinc-rich ore on the deepest active mine level shortly before closure.

(E) Stage 2 breccia composed of angular fragments of grey sandy slate cemented by brown sphalerite (2-5 mm) and white-grey quartz. Some fragments are rimmed by sphalerite and quartz but others are not. Zinc-rich ore from the Margarethe ore body, lower Burgstätter Fault. Museum collection, Technical University of Clausthal, Adolph Römer Strasse 2a, Clausthal-Zellerfeld, the Swiss knife is 8.5 cm long.

2.33 *Slide 33. Bad Grund: Zn-Pb veins in a sinistral extensional duplex*

In contrast to other deposits in the district, the ore bodies at Bad Grund were blind except for small outcrops at the Achenbach (AB) and Meding (MD) shafts. The mine "Silberner Nagel" (silver nail) near the Meding shaft was in operation from 1570 to 1733. From 1831 to 1992, 19.1 million metric tons of ore at recovered grades of 5.8% Pb, 3.9% Zn, 0.07% Cu and 117 g/t Ag were mined. Zinc remained insignificant until 1930 (Stedingk 2012). The galena concentrate averaged 76.5% Pb, 1.0% Zn and 1500 g/t Ag, and the zinc concentrate 59.1% Zn, 1.7% Pb, 40 g/t Ag, 140 g/t In, 20 g/t Ge, 100 g/t Sn and 600 g/t Hg (Sperling 1973).

(A) Structural map of the Silbernaal fault system (SNF) showing the 500-m-wide extensional duplex at Bad Grund (modified from Stedingk 2012), and the Charlotter Ruschel branch fault (CRF). The SNF contains ore bodies over a length of 6.5 km between the West (WS), Achenbach (AB), Knesebeck (KB), Wiemannsbucht (WB) and Meding (MD) shafts. The strands of the SNF dip 60-80° south at surface. Many steepen to sub-vertical at depth. The main fault is 15-20 m wide on average but widens to 70 m at the West shaft and to 50 m east of the Achenbach shaft. The other faults vary in width from 2-12 m (Sperling 1973; Sperling and Stoppel 1979). The offset at the Silbernaal Fault is 800 m south block east (Stedingk and Ehling 1995). The dextral Rosenhof Fault (RHF) has a 200-m-down component at the Devonian limestone reef, whereas movement at the Laubhütte Fault (LHF) is 700 m south block west and < 50 m down (Sperling 1973).

(B) Longitunal projection of Zn-Pb-Ag ore bodies in the main Silbernaal Fault (Westfeld II and I, 800/900W, Achenbach, Ostfeld, Wiemannsbucht, Silbernaal) excluding those in other faults of the system (modified from Stedingk 2012). Stage 1 hematite-pyrite mineralization is particularly widespread in the west but Stage 1 dolomite-illite wall-rock alteration extends east to the Meding shaft. Stage 2 sphalerite-galena-calcite ore is predominant in Westfeld II and partly overprinted by Stage 3 galena-siderite-barite in all other ore bodies (Sperling and Stoppel 1979; Stedingk 2012).

2.34 *Slide 34. Bad Grund Westfeld: Stage 1 hematite + pyrite*

TOP LEFT: Longitudinal projection of Variscan folds in Carboniferous greywacke at the footwall boundary of the Silbernaal Fault (dip 65-70° SW), unconformably overlain by Permian limestone (Zechstein 1/2) at the West shaft (modified from Stedingk and Ehling 1995). The correlation of slate marker horizons and conglomerate beds (C1 and C2) in the footwall and hanging wall of the fault indicates strike-slip and a lateral offset of 800 m south block east. Stage 1 hematite-pyrite ± chalcopyrite mineralization and associated dolomite-quartz-illite alteration is widespread in and adjacent to the fault enveloping the Westfeld ore bodies. Red hematite staining, extensive on level 1 of the West shaft, does not persist into the Permian limestone cover. The Stauffenburg drill holes intersected barren dolomite-ankerite, siderite and anhydrite veins 4 to 300 cm thick in greywacke west of the Zn-Pb ore bodies (Sperling and Stoppel 1979).

BOTTOM LEFT: Level plans illustrating the distribution of Stage 1 hematite-pyrite ± chalcopyrite mineralization and dolomite-quartz-illite alteration associated with the Silbernaal Fault (modified from Sperling 1973). Wall-rock alteration was pervasive in greywacke and mostly fracture- and bedding-controlled in silt-banded slate. The Westfeld I ore body extended from 900-1550 m W and Westfeld II from 1450-2060 m W counted from the Achenbach shaft. Silica replacement up to 30 m wide was mainly confined to Westfeld II. Hematite occurred dispersed in dolomite but also formed specular aggregates. Ankerite and Mg-rich siderite were late Stage 1 (Sperling 1973).

(A) Looking east at quartz-illite altered greywacke crosscut by dark red hematite-stained dolomite veins (1-10 mm) containing 1-2% disseminated pyrite (Stage 1). White Stage 2 veins of calcite-sphalerite-chalcopyrite ore crosscut the altered wall rock and the brown ankerite-siderite vein at the bottom. Westfeld II ore body, Achenbach shaft 20 level, main vein 10-20 m SW of the footwall boundary fault, cut 4 in east drive at 1600 m W, the hammer is 32 cm long.

(B) Stage 1 altered greywacke southwest of a thick Stage 2 calcite-sphalerite ± galena vein: crackle breccia composed of grey dolomite-quartz-illite altered wall-rock fragments (70-80 vol.%) and dark red, hematite-stained dolomite cement containing 1% disseminated pyrite. Quartz, ferroan dolomite and well crystallized 2M-illite were identified by X-ray diffraction. Stage 2 veinlets (1-2 mm) are filled with quartz, white calcite, and chalcopyrite. Westfeld II ore body, Achenbach shaft 20 level, footwall branch of the main vein, cut 11 in west drive at 1600 m W, the matchstick is 4 cm long.

Illite temperature estimates: Illite crystallinity has been used to estimate temperature in low-grade metamorphic rocks at Ramsbeck (Slide 13). At Bad Grund, a study was carried out on drill core intersecting the southern and main faults of the extensional duplex at 960 m E on level 15 of the Achenbach shaft, and sampling least altered wall rock in the south crosscut at 1460 m E (Schmidt 1991). The host rocks at both locations are greywacke and slate of the Kulm 3b unit. The clay fraction (2-6 mm) was separated and analyzed by X-ray diffraction using quartz as an internal standard. Illite in the fault zone had a half-height (Hb = $illite_{001}$ x 100 / $quartz_{100}$) peak width averaging 130 (n = 27; maximum 110-120, n = 7), whereas illite in the least-altered rocks to the south had a mean of 195 (n = 7; Schmidt 1991). The higher illite crystallinity in the Silbernaal fault zone corresponds to a temperature of about 300°C (Schmidt 1991). Hb-values of 135 in pure illite are equivalent to Hb = 105 in polished rock samples (Werner 1988). The Stage 1 estimate of 300°C is thus supported by the case study at Ramsbeck.

Illite Rb-Sr ages: Seven bulk samples of altered greywacke enclosed in Stage 2 calcite-sulfide veins of the Westfeld II ore body, and five drill core samples of unaltered slate and greywacke were analyzed for their Rb-Sr isotope ratios, mineral modes, and major oxide compositions (Boness et al. 1990). The unaltered samples consisted of quartz, albite, chlorite, minor calcite and illite, and had low K_2O/Na_2O ratios (0.48-0.64) representative of Harz greywacke (Visean: 346.7±0.4 to 330.9±0.2 Ma; ICS 2018).

The altered greywacke consisted of quartz, illite and carbonate (dolomite, siderite, calcite). The K_2O/Na_2O ratios of the whole rocks (mean 18.8; n=7) were much higher than those of unaltered greywacke indicating intense potassium metasomatism. The clay consisted of 99% 2M-illite and 1% 1M-illite, the latter residing in the fine grain fractions (100% 0.1-0.2 mm; 45% 0.2-0.6 mm). SEM imaging showed that the 2M-illite formed discrete crystals, whereas the 1M-illite formed aggregates composed of < 0.1 mm grains (Boness et al. 1990). The 2M-illite had an interlayer charge of K = 1.564-1.600 and Na = 0.113 (for 22 oxygens), comparable to muscovite from the prehnite-pumpellyite to greenschist facies boundary (Hunziker et al. 1986), and gave Rb-Sr isochron ages of 242±28 Ma and 247±20 Ma using the whole rock, grain fraction (>0.6 mm), HCl leachate and residue isotope ratios of two samples. As the regression-line intercepts agreed within error with the $^{87}Sr/^{86}Sr$ ratio measured in Stage 2/3 galena (0.7138 ± 0.0007), the Triassic ages were interpreted to date sulfide mineralization. The Rb-Sr data of the 1M-illite fractions (0.1-0.2 mm; 1% of the total clay) were regressed separately. The ages of 180±9 Ma and 176±8 Ma, and the $^{87}Sr/^{86}Sr$ intercept ratios of 0.7152 ± 0.0013 and 0.7168 ± 0.0008 date an event unrelated to ore formation (Boness et al. 1990).

The critical 2M-illite ages have been recalculated using Isoplot 3.45 of Ludwig (2012) and the ^{87}Rb decay constant in Villa et al. (2015). The $^{87}Sr/^{86}Sr$ intercept ratios obtained by Model 3 regression are 0.7127 ± 0.0024 (n=7, MSWD=35) and 0.7136 ± 0.0018 (n=7, MSWD=21). Both agree within error with the measured $^{87}Sr/^{86}Sr$ ratios in calcite and barite (0.7133 ± 0.0005; n=45; Voigt 1984; Lévêque and Haack 1993a) from Zn-Pb-Ag ore, confirming the conclusion of Boness et al. (1990) of strontium derivation from a homogenous reservoir during sulfide deposition (Stages 1-3). If the average calcite-barite $^{87}Sr/^{86}Sr$ ratio is included in the Model 3 regression, the 2M-illite ages are 241±20 Ma (n=8, MSWD=30) and 238±17 Ma (n=8, MSWD=17). They correspond to the Middle Triassic (247-237 Ma; ICS 2018), when the Upper Harz was part of the NE-trending Hunsrück-Eichsfeld-Oberharz paleohigh, an area of condensed Permian and Triassic sedimentation (Mohr 1993).

2.35 *Slide 35. Bad Grund Westfeld: Stage 2 Zn-Pb ore*

The Westfeld II ore body contained 5-6 t Zn+Pb / m^2 vein surface between level 12 and 14, the highest base-metal grade in the Bad Grund mine. Stage 2 ore was zoned from a broad sphalerite-rich core to a 20-40 m wide galena-rich rim. Chalcopyrite increased below the Achenbach shaft level 18 indicating a vertical Cu-Zn-Pb zonation. Sphalerite veins were 1.5-2.0 m thick on average, and up to 7 m thick on level 13 forming quartz-calcite banded and breccia ore 500 m long and 20 m wide close to the footwall boundary of the Silbernaal Fault (Sperling 1973; Stedingk 2012).

LEFT: Thin Stage 3 siderite and barite veins, probably formed during small-scale SW-block down movement, crosscut Stage 2 sphalerite-calcite ± quartz veins with galena margins and barren calcite veins. Similar relationships caused by tectonic movement were used to subdivide Stage 2 into four and Stage 3 into three sub-stages (Sperling 1973). Post-mineral reverse faults offset all veins. Westfeld I, stope between the Achenbach shaft 11 and 12 levels at 1400 m W.

(A) Looking west at the footwall part of a 6-m-thick vein composed of Stage 2b chalcopyrite crosscut by Stage 2c calcite-sphalerite ± galena ore. The host rock is brecciated, dolomite-quartz-illite altered greywacke stained red by disseminated hematite and pyrite. Westfeld II ore body, Achenbach shaft 20 level, crosscut through the main vein 10-20 m SW of the footwall boundary fault, cut 11 in west drive at 1600 m W. Photograph courtesy Wolfgang Werner, January 1992, showing the author (left) and mine geologist Klaus Stedingk (right).

(B) Looking east at the transition from Stage 2c banded calcite-sphalerite-galena into breccia ore: fragments of Stage 1 dolomite-quartz-illite altered greywacke are cemented by calcite and sphalerite. A post-mineral reverse fault offsets the banded vein in the upper left corner (arrow). Hanging wall part of the 6-m-thick vein in (A), the hammer is 32 cm tall.

(C) Stage 2 banded and breccia ore: angular fragments of Stage 1 dolomite-quartz-illite altered greywacke (left), and older bands of white-grey quartz, yellow chalcopyrite, and dark brown sphalerite are overgrown by massive white quartz and pale yellow calcite. The quartz-calcite gangue encloses 20-cm-thick cockade ore composed of grey galena and minor brown sphalerite cementing fragments of altered greywacke, massive chalcopyrite, and quartz-chalcopyrite. Westfeld II ore body, Achenbach shaft 20 level, the pink pen is 14 cm long. Display at the mine museum Clausthal-Zellerfeld (www.oberharzerbergwerksmuseum.de).

Mineralogy: The principal gangue minerals in Stage 2 veins are quartz and calcite. Calcite contains 1.5% $FeCO_3$ and 2.6-3.5% $MnCO_3$ and is strained due to fault movement. Least-strained quartz crystals and geopetal ZnS-quartz layers fill cavities in the center of veins and represent the final Stage 2d. Sphalerite in the Westfeld II ore body has higher iron contents (3.0-4.7% Fe) than Stage 2 sphalerite in all other ore bodies (1.2-2.4% Fe). Silver and antimony in galena (0.08-0.15% Ag; 0.46-0.61% Sb) are related to inclusions and attached grains of tetrahedrite (Sperling 1973; Sperling and Stoppel 1979).

Temperature estimates: In the Westfeld II ore body, the Ga/Ge ratios in sphalerite indicate fluid temperatures of 270-240°C. When plotted in longitudinal projection, the ratios outline vertical fluid ascent branching laterally (Möller and Dulski 1993; Stedingk 1993). The $d^{34}S$ values of sphalerite (+6 to +10‰) and galena (+4 to +7‰) in Westfeld II are higher than those in all other ore bodies (+4 to +6‰ sph; +2 to +4‰ gal). Sphalerite-galena pairs display consistent isotope fractionation $d^{34}S_{ZnS}$ > $d^{34}S_{PbS}$ averaging 1.8‰ (Sperling and Nielsen 1973), which equates to sulfide deposition at 360±25°C using the calibration in Ohmoto and Rye (1979). These results were confirmed by Zheng and Hoefs (1993a), who analyzed an additional 21 sphalerite-galena pairs, established equilibrium, and obtained Stage 2 temperatures of 400-220°C using the same calibration.

Fluid inclusions: Primary 2-phase fluid inclusions in euhedral Stage 2d quartz (n=20) had salinities of 15.0-25.1 wt.% $NaCl_{eq}$, and homogenized into liquid at T_h = 147-160°C. Inclusions in Stage 2c sphalerite had similar salinities and T_h (Adeyemi 1982). Schmidt (1991) analyzed fluid inclusions (n=136) forming planar arrays in quartz and calcite filling veins in the central Silbernaal fault system. In strained calcite, secondary 2-phase (2-10 vol.% gas) and 3-phase inclusions with solids all homogenized into liquid at 80-105°C. Secondary and primary (?) inclusions in quartz homogenized at 105-130°C, 140-165°C, 175-200°C, and 210-225°C, perhaps trapping different generations of fluid (Schmidt 1991). First melting (T_e = -65 to -60°C) and final melting temperatures (T_m = -35 to -25°C) indicated that the aqueous phase contained $CaCl_2$ and NaCl (26-32 wt.% $NaCl_{eq}$). There was no evidence for phase separation or the presence of CO_2. Rare single-phase inclusions contained methane (Schmidt 1991).

2.36 *Slide 36. Bad Grund East: Stage 3 Pb-Ag ore*

Underground mining at Bad Grund began in 1570 near the Meding shaft following the 1.8 km long Silbernaal ore shoot down-plunge until the 1920s. Production from 1831-1899 is estimated at 1.6 million metric tons at 9% Pb and 230 g/t Ag. The silver grade still averaged 240 g/t in 1924-1932 (Sperling 1973; Stedingk 2012). Bituminous slate was abundant in the greywacke hosting this ore body. Stage 1 carbonate-quartz-pyrite ± illite (?) replacement, locally stained by hematite, was extensive in greywacke (König 1923). The ore body consisted of Stage 3 galena and trace sphalerite. Barite formed veins up to 4 m thick in the upper part (above level 10), and gave way to siderite and quartz at depth. Barite textures varied from cataclastic to crystalline, and colors from white (pure) to grey or red due to dispersed galena or hematite, respectively. Quartz replaced barite locally (König 1923). Stage 2 sphalerite was restricted to the lower western part of the ore body (Stedingk 2012).

LEFT: Stage 3 crackle-breccia Pb-Ag ore in altered greywacke, Silbernaal ore body 1700 m W of the Meding shaft, back of a stope 25-30 m above level 10 (modified from König 1923). Galena is intergrown with minor chalcedony and quartz but also rims barite, which locally cuts across its galena margin. Siderite formed symmetric rims to barite veins in other exposures. Small open vugs were common.

(A) Achenbach Pb-Ag ore: Stage 3a in the center is composed of fine-grained galena, minor sphalerite (1.2-3.0% Fe) and chalcopyrite cemented by white quartz and calcite. Stage 3b (bottom) consists of siderite, calcite and sulfide bands, a siderite vein crossing Stage 3a. Stage 3c (top) is represented by crystalline (5-10 mm) yellow-white barite. Achenbach shaft level 19, Vein H at 120 m W, the red pen is 14 cm long.

(B) Westfeld I Pb-Ag ore: Stage 3b/c breccia composed of angular fragments of hematite-stained altered greywacke (Stage 1) rimmed by brown siderite and blue-grey galena. White barite fills the interstitial space. Achenbach shaft level 19 at 1560 m W, Vein L, the specimen is 30 cm long.

Mineralogy: The Silbernaal hanging wall fault south of the Wiemannsbucht shaft contained a 400 m long and 250 m high ore body, which extended from levels 12 to 17 and consisted of a zoned Stage 3 galena vein 0.5 m thick. Galena was intergrown with calcite in the central part, and with siderite and lesser barite at the margin. The silver in galena decreased from 0.23-0.41 wt.% at the periphery to 0.12-0.19 % Ag in the inner and lower parts (Sperling and Stoppel 1979).

Common Stage 3 gangue minerals are Mn-rich siderite and barite (2.7-10.5% $SrSO_4$). In places, barite contained cm-thick bands of tetrahedrite (4.3% Ag). Chalcopyrite was partly replaced by tetrahedrite and bournonite. Silver-rich galena enclosed grains of bournonite, boulangerite, tetrahedrite, pyrargyrite, argentite and rare native silver. Cavities in Stage 3 veins were lined with quartz, siderite, barite, calcite, colloform marcasite, and rare stibnite, native antimony, cinnabar, amalgam and native mercury (Sperling 1973).

Temperature estimates: The $d^{34}S$ values of Stage 3 sphalerite (+2 to +4‰) and galena (± 0‰) are lower than in Stage 2. Sphalerite-galena pairs display an average isotope fractionation of 3‰ (Sperling and Nielsen 1973), which equates to sulfide deposition at 220±25°C using the calibration in Ohmoto and Rye (1979). Zheng and Hoefs (1993a) analyzed an additional 14 sphalerite-galena pairs, established equilibrium, and obtained Stage 3 temperatures of 240-140°C using the same calibration. Stage 3 barite $d^{34}S$ values have a modal maximum at +13 to +15‰ (n=35). Isotope fractionation between barite and coexisting sulfides was not in equilibrium suggesting that most barite precipitated after the galena (Zheng and Hoefs 1993a). Fluid inclusions in early Stage 3a quartz and in late quartz lining vugs record decreasing homogenization temperatures (early 115-124°C to late 107-96°C) coupled with decreasing salinity (early 17 to 12; late 12 to 0 wt.% $NaCl_{eq}$), values lower than in Stage 2 (Adeyemi 1982).

2.37 *Slide 37. St Andreasberg veins: Wrench fault reversal*

The St Andreasberg silver deposit is famous for its collector-item crystals of zeolite, tetrahedrite, pyrargyrite and dyscrasite (Stedingk et al. 2016). Metal production (1521-1910) amounts to 313 t Ag, 12500 t Pb and 2500 t Cu from crude ore estimated at 5-8% Pb, 1-3% Zn, 1% Cu, 0.03-0.1% Ag, 1% Co + Ni and 1% As + Sb (Wilke 1952). The shaft buildings and water-driven hoist and pumping wheels of the Samson mine (www.grube-samson.de), and the 16th to 19th century underground workings of the Roter Bär mine are popular tourist attractions (www.lehrbergwerk.de). The structural setting of the veins illustrates the reversal of movement from early dextral to late sinistral on the Edelleuter wrench fault.

TOP: Block diagram of the bounding faults, main veins and inclined shafts projected onto the level of the Grüner Hirschler adit 130 m below the Samson shaft collar (modified from Wilke 1952). The Brocken granite underlies the mine area at > 850 m depth. The succession of Devonian sandstone, calcareous and black slate, diabase, and Carboniferous greywacke is contact metamorphosed to hornfels, skarn and cordierite knotted schist. The folds are displaced by barren reverse faults (Neufanger, Abendröther), which strike N75°E, dip 50-75° SSE, and are indurated to hornfels. The reverse faults are in turn displaced by wrench faults of the Edelleuter system, which strike N70-80°W, dip 60-80° S or N, and contain 0.3 m thick fault-fill veins. Diagonal extension veins oriented N20-50°W/70-80°NE branch off the Edelleuter and its subsidiary faults. The extension veins, 0.3-1.0 m thick (Felicitas, Samson, Dorothee), are marked by open vugs and vertical striations at their walls (Wilke 1952). The clockwise angle in strike (40°) between the Edelleuter faults (av. N75°W/70°S) and the diagonal veins (av. N35°W/75°NE) indicates vein-fill during dextral strike-slip (see Sylvester 1988). This sense of movement, however, is inconsistent with the sinistral offset of the Abendröther reverse fault interpreted to indicate a late phase of strike- or oblique-slip reversal on the wrench faults.

Vein-fill stages (Wilke 1952): STAGE 1 comprises early hematite + quartz, siderite + ankerite + Fe-Mn calcite, and accessory pyrrhotite, pyrite and chalcopyrite. Locally, late calcite-quartz-hematite veins contain clausthalite (PbSe), tiemannite (HgSe) and guanajuatite (Bi_2Se_3) associated with chalcopyrite, cobaltite, native gold (12-14 wt.% Ag), Pd_8Sb_3 alloy and

$PdCuBiSe_3$ (Geilmann and Rose 1928; Cabral et al. 2015).

STAGE 2 consists of an early Pb-Zn quartz-sulfide assemblage (galena, Fe-rich sphalerite, minor chalcopyrite, tetrahedrite, accessory bournonite, jamesonite) and a late Ag-Co-Ni calcite-arsenide assemblage (mainly safflorite-rammelsbergite, colloform native arsenic, dyscrasite, pyrargyrite).

STAGE 3 comprises early andradite, zeolites (stilbite, heulandite, analcime), hematite, quartz and calcite containing pyrrhotite, pyrite, galena, low-Fe sphalerite, millerite, niccolite and late pyrargyrite, stephanite, polybasite, native silver, argentite, and realgar.

The stages record pulses of ascending fluid cooling from an initial high temperature, which may be estimated for the Stage 3 assemblage andradite + quartz + wollastonite in contact with Stage 2 calcite (Wilke 1952). Quartz + calcite react to wollastonite at 500°C, and quartz + calcite + hematite to andradite at 400°C (P = 50 MPa, X_{CO2} = 0. 1; Einaudi 1982). On the other hand, analcime + quartz is stable relative to albite at less than 180°C (P = 50-100 MPa), and stilbite-Ca relative to heulandite-Ca at less than 150°C (P = 100 MPa; Deer et al. 2004). Minor fluorite occurred in all stages, barite in Stages 2 and 3, and anhydrite in Stage 3 at >600 m depth (Wilke 1952). Nielsen (1968) determined negative $d^{34}S$ values in Stage 2/3 galena (-7 to -23‰; n=29) suggesting sulfide-sulfate co-precipitation (Rye 1993).

(A) Early Stage 2 vein filled with bands of galena, comb-textured quartz, and minor calcite. The vein wall at the pen (14 cm long) is sharp. The opposite wall is marked by a 2 cm thick breccia cemented by grey silica and sheared galena. The host rock is indurated, silty slate. Jacobsglück vein, Samson shaft level 8.

(B) Late Stage 2 vein filled with calcite enclosing native arsenic (As; medium grey) and dyscrasite (Ag_3Sb; tarnished black) rimmed by silver-white Co-Ni arsenides. Note the Stage 1 breccia of hornfels fragments cemented by brown carbonate and quartz. The host rock is carbonate-altered hornfels. Samson mine, the matchstick is 4 cm long.

(C) Stage 3 pseudo-hexagonal crystals of calcite coated with galena and silver minerals, perhaps pyrargyrite, stephanite and polybasite. The pen is 14 cm long. Samson shaft 33 level, open vug in the Samson vein measuring 3.5 m long, 2 m high, and 20-30 cm wide (Wilke 1952). Samples A, B and C are from the museum collection of the Technical University of Clausthal, Adolph Römer Strasse 2a, Clausthal-Zellerfeld.

Adularia K-Ar and Rb-Sr ages: Andreasberg adularia associated with Stage 3 zeolites gave a total fusion $^{40}Ar/^{39}Ar$ age of 135.7±2.6 Ma (2s), and a 2-point calcite-adularia Rb-Sr model age of 123.9±1.2 Ma (Mertz et al. 1989). A comparable study involved adularia from quartz-calcite veins in faults at Hasserode, which offset hornfels and granite at the NE-margin of the Brocken pluton. These veins also contain zeolites, hematite, Zn-Pb sulfides and Co-Ni arsenides (Wilke 1952). The Hasserode adularia (0.5-2 mm) had 77-80% triclinic Si-Al order. Using calcite $^{87}Sr/^{86}Sr$ as the initial ratio (0.71033 ± 0.00020), 2-point Rb-Sr isochrons gave Permian (260±7 Ma, n=3) and Triassic ages (223±4 Ma, n=4; Hagedorn and Lippolt 1993). The critical Permian age has been re-calculated using Isoplot 3.45 of Ludwig (2012) and the ^{87}Rb decay constant in Villa et al. (2015). Regression of the Hasserode calcite and adularia isotope data results in a Model 1 Rb-Sr age of 263±4 Ma (n=4, MSWD=1.3).

In contrast, the K-Ar method yielded total and $^{40}Ar/^{39}Ar$ plateau ages of 141.5±2.2 to 138±3.0 Ma at Hasserode. Adularia from a chalcopyrite-actinolite vein in the aureole of the Ramberg granite, located at Gernrode close to the Harz North Boundary Fault, gave a K-Ar age of 92.5±2.0 Ma. An argon diffusion study of the turbid vein adularia indicated closure temperatures as low as 100°C. In addition, progressive Si-Al ordering may have caused argon loss (Hagedorn and Lippolt 1993).

2.38 *Slide 38. Variscan veins: Key genetic features*

Structural setting: Syn-orogenic in bedding-parallel "saddle reefs" and in the axial plane cleavage of anticlines (Eisenberg, Ramsbeck). Post-orogenic in normal and wrench faults displacing folds in the Variscan slate belt (Auguste Victoria, Upper Harz). Normal faulting during fold-belt uplift preceded wrench faulting along the WNW-striking Elbe Zone. The hiatus was short as syn-tectonic breccia ore formed in both structures at Auguste Victoria. The mineralization in wrench faults took place during the transition from early dextral and late sinistral lateral movement.

Absolute age: The syn-orogenic Eisenberg and Ramsbeck veins formed at ca. 305 Ma during main-stage Variscan folding. Post-orogenic mineralization in the normal fault at Auguste Victoria and in the wrench faults of the Upper Harz probably took place before the Zechstein 1 marine transgression at ca. 260 Ma. However, there are no radiometric age constraints at Auguste Victoria and few in the Upper Harz, where Rb-Sr illite and adularia ages indicate ore formation at or before 260-240 Ma. The reactivation of regional faults at 140-135 and 90-85 Ma during Alpine far-field stress was minor (30-100 m) relative to the Lower Permian movement (500-800 m), and did not affect all wrench faults in the Harz.

Ore deposits: Gold-hematite-chalcopyrite-clausthalite (PbSe) in carbonate veins (Eisenberg), and sphalerite-galena ± chalcopyrite in quartz-carbonate ± barite veins and breccia (Ramsbeck, Auguste Victoria, Upper Harz). The Eisenberg deposit represents a group of oxidized gold-selenide ± PdSb alloy veins in the Variscan slate belt including occurrences preceding Zn-Pb-Ag mineralization at Clausthal-Zellerfeld and St Andreasberg. The silver-rich galena in the Zn-Pb veins (900-2000 g/t Ag in concentrates) contrasts with the silver-poor galena in the Mississippi Valley-type Zn-Pb deposits (200-500 Mt of ore) related to the discharge of brines from the German-Polish basin: Mechernich-Maubach in Triassic sandstone (80-140 g/t Ag; Behrend 1950), and Upper Silesia in Triassic limestone (64-260 g/t Ag; Stappenbeck 1928).

Ore formation: At the Eisenberg, oxidized native gold and Cu-Pb sulfide-selenide deposition at >200°C in reduced black slate, probably distal to the fluid source. At Ramsbeck, Zn-Pb-Ag sulfide mineralization at >300°C, the source granite outlined by anomalies in illite crystallinity, vitrinite reflectance and Bouguer gravity. At Auguste Victoria, Zn-Pb-Ag sulfide mineralization at 260°C in reduced coal measures. In the Upper Harz, early oxidized Fe ± Cu-Pb sulfide-selenide mineralization at 300°C followed by main-stage Zn-Pb-Ag sulfide deposition during fluid cooling from 360 to 220°C (>400 to 150°C at St Andreasberg). The fluid temperatures estimated by mineral and isotope thermometry are higher than those measured by phase homogenization in inclusions (110-180°C; max. 225°C at Bad Grund).

Appendix: Harz veins, discussion of fluid sources

The Zn-Pb-Ag veins in the Upper Harz district remained in production until 1992, and thus have been subject to more specialized chronological, isotope and fluid inclusion studies than the other deposits described above. Early genetic models related vein formation to magmatic fluids sourced in the Brocken and Ramberg plutons (Schneiderhöhn 1941; Buschendorf et al. 1971; Mohr 1993). Both granites represent feeder intrusions to the Lower Permian volcanic rocks and, perhaps, cupolas and laccoliths of a deeper batholith. In the German-Polish basin, deep drill holes intersected Permo-Carboniferous rhyodacite flows, ignimbrites, minor andesite and basalt up to 2.5 km thick, part of a "large igneous province" comprising 70,000-80,000 km^3 of volcanic products (Paulick and Breitkreuz 2005). More recently, mineralization has been related to basin-derived brines circulating in the faults during Mesozoic reactivation (Behr et al. 1987; Lüders et al. 1993; de Graaf et al. 2020). For those interested, the alternative models are discussed below given ongoing research on similar Zn-Pb deposits elsewhere (Yu et al. 2020).

K-Ar and Rb-Sr ages: The chronological studies at Bad Grund, St Andreasberg, Hasserode and Gernrode resulted in a wide range of possible vein-formation ages: 263±4 Ma, 240±17 Ma, 223±4 Ma, 180±9 Ma, 141.5±2.2 Ma, 135.7±2.6 Ma, 123.9±1.2 Ma and 92.5±2.0 Ma. Some interpreted these results to record multiple episodes of sulfide, barite and fluorite deposition lasting from Triassic to Cretaceous time (Lüders et al. 1993). Others selected a specific age. Haack and Lauterjung (1993) applied a mixing model to the data of Boness et al. (1990) from Bad Grund. They regarded the 2M-illite as inherited and the 1M-illite as crystallized during ore formation mixing wall rock and fluid strontium. Consequently, the Triassic age defined by 99% of the clay fraction (240±17 Ma) was considered inherited from the Carboniferous greywacke, and the Jurassic age (180±9 Ma) defined by the remaining 1% of ultra-fine 1M-illite (< 0.1 mm) was interpreted to date sulfide deposition.

K and Rb are lattice-bound in illite and adularia crystals, whereas the daughter products of ^{40}K and ^{87}Rb decay are not. The daughter isotopes (^{40}Ar and ^{87}Sr) may leave the crystal due to thermally activated volume diffusion, which is grain size dependent, or due to lattice restructuring. Both processes generate younger ages. Illite K-Ar ages are completely reset at 260±30°C and illite Rb-Sr ages at about 300°C, low-grade metamorphic conditions eliminating 1M-illite (Hunziker et al. 1986). In fault zones, argon and strontium retention in illite is also controlled by neo-crystallization during movement (Kirschner et al. 1996).

In the Silbernaal Fault, the high illite crystallinity, Stage 1-2 temperature estimates of 300-360°C, and the predominance of K-rich 2M-illite/muscovite (99 vol.%) suggest that the Triassic Rb-Sr age records Zn-Pb mineralization. However, as neither the Stage 1 hematite-pyrite nor Stage 2 sphalerite-galena mineralization persists into the Zechstein cover rocks, ore formation is probably older than 260 Ma, the stratigraphic age of the Z1 limestone. At St Andreasberg, Hasserode and Gernrode, all K-Ar and some Rb-Sr adularia ages are reset due to Si-Al ordering to a triclinic symmetry, and because argon diffusion did not close until the terrane cooled below about 100°C. The younger ages of ca. 140-124 and 92 Ma may be related to uplift at the Harz North Boundary Fault recorded by unconformities (at 135 and 85 Ma) in the Cretaceous sedimentary succession. The Permian and Triassic Rb-Sr adularia ages, too, might be minima given 3-4 km burial before the un-roofing of the Brocken granite at 85 Ma, and heat flow in the wake of the Lower Permian "large igneous province".

Magmatic fluids: The hematite-pyrite assemblages at Bad Grund, Clausthal-Zellerfeld and St Andreasberg contrast with the reduced nature of the Devonian-Carboniferous host rocks, mainly sandstone, greywacke and bituminous shale, which cannot buffer fluid to such high oxidation state. Little is known about the crystalline basement. Uplifted rafts such as the Ecker gneiss are not marked by widely dispersed iron oxides. Most Brocken granites are grey but the NW-striking, late Ilsestein granite at the north rim is bright red due to hematite in abundant K-feldspar (Mohr 1993). Sericite-quartz alteration and hematite-pyrite ± fluorite mineralization are present in parts of the Brocken roof granite (Friese and Haack 1993).

Additional evidence is based on strontium, lead and stable isotope data. Strontium substitutes for Ca in carbonate (60-350 ppm Sr) and for Ba in barite (>1 wt.% Sr). As these minerals contain little Rb (most < 0.6 ppm), they preserve the initial $^{87}Sr/^{86}Sr$ ratio of the hydrothermal fluid. Stage 1 dolomite (0.7132 ± 0.0018), and Stage 2/3 calcite and barite (0.7133 ± 0.0005; n=45; Voigt 1984; Lévêque and Haack 1993a) at Bad Grund have homogenous ratios indicating a common source for Sr, Ca and Ba in an evolving hydrothermal system. The St Andreasberg (0.7118 ± 0.0024; n=9) and Hasserode veins (0.7103 ± 0.0002; n=1) at the periphery of the Brocken have slightly lower ratios. All values agree within 2-sigma error with the initial $^{87}Sr/^{86}Sr$ ratio defined by diorite and granite whole rock samples from the pluton (0.713 ± 0.002; Schoell 1986).

Non-radiogenic Pb-rich minerals are interpreted to preserve the initial lead isotope composition at the time of formation. Stage 3 galena at Bad Grund has average ratios (n=10) of $^{206}Pb/^{204}Pb$ = 18.463 ± 0.042 (2s), $^{207}Pb/^{204}Pb$ = 15.535 ± 0.044 and $^{208}Pb/^{204}Pb$ = 38.486 ± 0.136 (Wedepohl et al. 1978; Lévêque and Haack 1993b). These ratios agree with those of Stage 2 galena and are close to those in least-radiogenic K-feldspar (n=7) of the Brocken granite: $^{206}Pb/^{204}Pb$ = 18.540 ± 0.036 (2s), $^{207}Pb/^{204}Pb$ = 15.531 ± 0.018 and $^{208}Pb/^{204}Pb$ = 38.423 ± 0.064 (Wedepohl et al. 1978; Friese and Haack 1993). The K-feldspars analyzed were acid-washed but not leached in hydrofluoric acid to remove unsupported ^{206}Pb derived from the migration and accumulation of the radioactive daughters of ^{238}U (Ludwig and Silver 1977). The lowest $^{206}Pb/^{204}Pb$ measured in granite K-feldspars was 18.519 suggesting that these ratios, too, approach those measured in Bad Grund galena.

Zheng and Hoefs (1993b,c) determined the stable isotope composition of Stage 2/3 vein calcite (n=130; $d^{13}C_{PDB}$ = -8.8 to -4.9‰; $d^{18}O_{SMOW}$ = +16.4 to +21.7‰) and Stage 3 siderite (n=20; $d^{13}C$ = -7.5 to -3.7‰; $d^{18}O$ = +18.7 to +23.0‰) at Bad Grund. The data define tightly clustered positive correlation trends in $d^{13}C$ versus $d^{18}O$ space. Stage 2 calcite-sulfide veins had a narrower range ($d^{13}C_{PDB}$ = -8.8 to -7.8‰; $d^{18}O$ = +16.4 to +17.7‰). Samples across thick (2.2-3.6 m) veins in the Westfeld I and Wiemannsbucht ore bodies showed an increase in $d^{13}C$ and $d^{18}O$ from the center to both margins, trends not consistent with carbonate deposition during the mixing of NaCl-$CaCl_2$-KCl brine with meteoric water or with CO_2 degassing. Instead, the correlated isotope data represent fractionation during calcite and siderite precipitation from an H_2CO_3-dominant magmatic or deep crustal fluid ($d^{13}C$ = -7‰; $d^{18}O$ = +10‰) cooling from 280°C to 170°C. Changes in fluid composition during wall-rock interaction (Stage 1) triggered vein formation (Zheng and Hoefs 1993b,c).

Basin and basement brines: The barite-siderite replacement in Zechstein 1 limestone at the Silbernaal Fault, and the present-day precipitation of barite and aragonite close to the Wiemannsbucht shaft are proof of post-Permian mineralization, albeit one free of sulfides (Stedingk 2012). Studies of fluid inclusions filled with NaCl-$CaCl_2$-KCl brine in altered parts of the Brocken granite and in veins of the Upper Harz provided the basis of the "basinal brine" model for Zn-Pb-Ag ore formation in the Upper Harz (Behr et al. 1987; Lüders and Möller 1992; Lüders et al. 1993; de Graaf et al. 2020). The low homogenization temperatures (T_h = 110-180°C) of most inclusions, similar to those measured in MVT deposits (100-150°C, rarely 210°C; Leach et al. 2005) were considered critical evidence. The model requires the gravity-driven descent of brines derived from salt in the German-Polish sedimentary basin into the faults during Mesozoic-Cenozoic reactivation, the leaching of Ca, Sr, Ba and base metals due to hydrolysis reactions in the metamorphic basement at 8-12 km depth, and the subsequent ascent of the evolved brines during seismic activity. At crustal levels of 1-2 km below surface, the ascending brine was diluted during mixing with groundwater, which introduced H_2S or SO_4^{2-} during sulfide and barite deposition, respectively, the sulfur sourced from Permian Zechstein anhydrite (Lüders et al. 1993). However, such a sulfur source would also introduce significant amounts of strontium, considered unlikely given the low strontium isotope ratios of the Zechstein marine succession ($^{87}Sr/^{86}Sr$ = 0.7068-0.7078; Kramm and Wedepohl 1991). Alternatively, the H_2S required to precipitate sulfide from basement brine may be sourced from the Paleozoic sedimentary succession in the fold belt (de Graaf et al. 2020), an interpretation at odds with the high oxidation state of Stage 1 hematite-pyrite mineralization in the Upper Harz.

The KTB deep drill hole collared at the west margin of the Bohemian Massif intersected a reduced succession of paragneiss and amphibolite, and graphitic cataclasites of the Frankish Line (Slide 4), a Permo-Carboniferous fault zone reactivated in the Triassic (245 Ma) and Cretaceous. Low-salinity groundwater was present until 1.5 km and $CaCl_2$-NaCl brine below 3.1 km depth, the expected stratification according to density. The brine contained significant amounts of dissolved N_2 and CH_4 but little zinc (0.2 mg/litre) and no H_2S, although the faults were mineralized with pyrite and pyrrhotite. Brine influx persisted to the final depth of 9.1 km, where the temperature reached 275°C (Wöhrl 2003). Whether intermittent seismic activity is sufficient to cause basement brine to ascend and form a 6.5 km long ore deposit remains an open question. A local heat source may be required to overcome the density stratification.

The maximum fluid-inclusion homogenization temperatures measured in the Upper Harz district are 225°C in the Silbernaal and 254°C in the Weisser Hirsch faults, which may be increased by a pressure correction of at least 30°C (Schmidt 1991; Lüders et al. 1993). The much lower temperatures (T_h = 110-180°C) in the vast majority of fluid inclusions suggest that most are secondary (Table 2 in Lüders and Möller 1992), trapped during the waning stage of the hydrothermal system or after sulfide deposition, when cooler brine circulated in the faults. At Bad Grund, there is a trend to lower fluid salinity with time approaching zero wt.% $NaCl_{eq}$ in quartz crystals lining Stage 3 open vugs. The hydrogen-oxygen isotope ratios of fluid released from primary and secondary inclusions in crushed vein quartz plot close to the meteoric water line and seawater (de Graaf et al. 2020) suggesting the presence of low-density groundwater in the wrench faults. Laser ablation ICP-MS analyses targeted at primary inclusions, and measurements of their zinc and lead concentrations are needed to resolve outstanding issues.

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