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PRESENTATION NOTES

TITLE: The Devonian Meggen SEDEX deposit, Germany: Vent-distal Fe-Zn-Pb sulfide and barite gel sedimentation in a black shale basin

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SUMMARY

The sedimentary-exhalative Zn-Pb-Ba deposit at Meggen, Germany, produced 26.4 million metric tons (Mt) of pyritic ore for sulfuric acid (1853-1962), 18.2 Mt for sphalerite-galena flotation (at 8.4 % Zn, 1.1 % Pb; 1963-1992), and 9.0 Mt of barite (>94 % $BaSO_4$; 1901-1977). The deposit is located in the Rhenish Massif, a basement block of Devonian-Carboniferous sandstone and slate folded during the Variscan orogeny. The block is separated by a Cenozoic graben from the Harz uplift, the site of the Rammelsberg SEDEX deposit. The Meggen deposit is hosted in Middle Devonian (upper Givetian) black shale of a pelagic rift basin, close to thick limestone reefs marking the former continental shelf. The rift basin contains coeval hematite ironstone deposits (97 Mt at 35-40% Fe; 1830-1983) on submarine ridges of basaltic spilite, and altered lavas and tuffs of subordinate trachyte and alkali rhyolite as part of a bimodal suite.

The Meggen deposit consists of central sulfide ore rimmed by barite margins in the north and south. It outcrops in the doubly plunging Meggen Syncline, and at the overturned SE-limb of the regional Attendorn-Elspe Syncline. Both folds are displaced by strike-parallel thrusts, and by normal faults oriented perpendicular to the fold axes. The succession of bituminous slates hosting the deposit, up to 130 m thick, is thrust over the Givetian Meggen Reef exposed 500-600 m below surface in the regional syncline, which also contains the large Attendorn Reef at its NW-limb. The Givetian Meggen Beds (15-40 m) in the footwall of the ore, composed of pyritic black shale and graded siltstone turbidite beds, are affected by stratabound decalcification, selective silicification, and pervasive alteration to illite. The Givetian-Frasnian Lagerkalk, a pelagic limestone 3-5 m thick overlies the ore conformably, extends 25 km in strike along the SE-limb of the Attendorn-Elspe Syncline, and is marked by a manganese anomaly (1000-2000 ppm) up to 5 km away from the ore body. The Frasnian bituminous and chloritic shale-limestone succession (35-80 m) overlying the Lagerkalk contains two marker horizons of Zn-Pb enriched pyrite nodules. Altered felsic tuffs (MT1 to MT4) are interbedded at the base and at the top of the Lagerkalk, and up to 15 m above in Frasnian black shales.

The sulfide ore averages 3.5-4 m in thickness, and consists of fine-grained pyrite (65 vol.%), sphalerite (13 vol.%; 1% Fe), marcasite (1%), galena (0.5%), barite (0.4%), and a gangue of quartz, chalcedony, illite and carbonate (20%). Gel textures like cauliflower banding, and framboidal, concentrically zoned or radially textured spheroids (20-60 micron) are well preserved in pyrite but not in sphalerite and galena, which are recrystallized. Black illite seams, sphalerite-rich layers, and lamina of packed pyrite spheroids define bedding on a cm- to mm-scale. In intercalated massive zones, bedding is contorted or obliterated, perhaps due to early diagenetic liquefaction of the settled gel. The average ore is enriched in Mn (mean: 1300 ppm), As (572 ppm), Tl (227 ppm), Ni (172 ppm), Sb (164 ppm), and Cu (100 ppm).

Laterally, the sulfide ore pinches out below the barite margins. The average barite ore is 2.5-3 m thick, dark grey and fine-grained, and consists of 95 wt% barite, 1-2% strontium sulfate, and 0.3% pyrite. Layers of radially textured spheroids and shale partings define the bedding but recrystallization is extensive. The sulfur isotope composition of the barite (average $\delta^{34}S = +22.8 \pm 0.2$ ‰) is close to the value of Upper Givetian marine anhydrite ($\delta^{34}S = +22.3 \pm 0.8$ ‰) implicating seawater as the sulfate source. The isotope composition of pyrite (av. $\delta^{34}S = +19.8$ ‰), the sulfide least affected by recrystallization, suggests the thermochemical reduction of anhydrite to hydrogen sulfide in the thick sedimentary succession below the deposit, a process probably catalyzed by organic matter.

Isopach maps and paleo-geographic reconstructions indicate that the Meggen sulfide-barite ore was deposited in a shallow euxinic basin at the faulted margin of the Devonian rift basin, sheltered by the Meggen and Attendorn reefs from turbidite flow down the shelf slope. Hydrothermal fluid ascended at faults carrying dissolved H_2S and Fe, Zn, Pb and Ba chloride. It pooled as high-density brine in the euxinic basin, where the sulfide gels flocculated and settled. Barite precipitated at the basin margin by dilution with seawater above the O_2/H_2S interface. Meggen represents the low-temperature (150-200°C), vent-distal SEDEX type contrasting with the vent-proximal, high-temperature (300°C), high-grade (25-30% Zn+Pb) Rammelsberg deposit.

1 INTRODUCTION

These explanatory notes accompany 33 color slides illustrating the regional geology, structural setting, ore petrology, geochemistry, and Devonian paleo-geography of the Meggen SEDEX deposit in Germany. Both this text and the slide presentation (in I-pad 4:3 format) are available free of charge as Adobe pdf-files from the SGA website. They are designed as open access teaching tools for digital projection and for the study on-screen. This text explains each slide step-by-step. Most of the published literature, including the comprehensive Monograph by Ehrenberg et al. (1954), is in German and not easily accessible to the English speaking international public.

The German term "exhalativ-sedimentär" used by Ramdohr (1928) and Ehrenberg et al. (1954) was translated into English (Carne and Cathro 1982) as "sedimentary-exhalative" (SEDEX), and became the accepted genetic term for this type of base-metal deposit (Leach et al. 2005). The Devonian Meggen and Rammelsberg deposits in Germany are regarded as type localities, Meggen representing the vent-distal low-temperature and the Rammelsberg the vent-proximal high-temperature subtype. At Meggen, the most abundant sulfide is pyrite and depositional gel textures are well preserved. At the Rammelsberg, the high-grade ore is rich in sphalerite, galena and chalcopyrite, and dynamo-thermal recrystallization during folding obliterated most primary textures. The SGA presentations on these deposits are thus complementary.

Publications in English recommended for reading include contributions edited by Kurt von Gehlen (1985): German geological correlation program Part C: Stratabound sulfide ore deposit in central Europe. Geologisches Jahrbuch Reihe D, Heft 70.

Krebs W (1981): The geology of the Meggen ore deposit. In: Wolf KH (editor), Handbook of strata-bound and stratiform ore deposits, Part III, Volume 9: Regional studies and specific deposits. Elsevier, Amsterdam-New York, pp. 509-549.

Werner W (1989): Synsedimentary faulting and sediment-hosted submarine hydrothermal mineralization in the Late Paleozoic Rhenish Basin (Germany). Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Geotektonische Forschungen, Heft no. 71, 305 pp

2 SLIDE DESCRIPTIONS

2.1 *Slide 1. SGA disclaimer and recommended citation*

2.2 *Slide 2. Title slide.*

2.3 *Slide 3. Meggen: Past production and grade*

The total sulfide production amounts to 44.7 million metric tons of heavy-medium separated pyritic ore at estimated grades of 7.7 % zinc and 0.75 % lead. The average copper grade (0.01 %) quoted is based on the value (0.03 %) in Ehrenberg et al. (1954) for the eastern ore body, and on the value (0.004 %) in Thein (1985) for the western part. The silver and gold grades are estimated at 4 g/t and 0.1 g/t, respectively, based on the assays of drill-hole and channel samples of 3.0-8.0 g/t Ag and 0.02-3.4 g/t Au (Ehrenberg et al. 1954; p. 285). Clausen (1978) reports traces of gold (<0.1 g/t).

The total barite mined amounts to 8.98 million metric tons of shale-free ore (1901-1977) at average grades of 95 % barium sulfate, 2 % strontium sulfate, and 1.4 % silica (Ehrenberg et al. 1954; Walther 1986). Most of the barite was supplied to the chemical industry as feedstock for paint pigment.

The Meggen mine operated continuously from 1853 to 1992, and produced a total of 56 million metric tons of crude sulfide and 10 million tons of crude barite ore. The production data quoted above refer to the crushed ore stripped of 20% (sulfide) and 10% gangue (barite), respectively, by water-based heavy-medium separation.

From 1853-1962, about 26.4 million metric tons of fine-grained massive sulfide were mined as a raw material for the industrial production of sulfuric acid. The best estimate of grade is the 1936-1952 average of 40.8 wt.% sulfur, 32.8 % iron, 7.2 % zinc, and about 0.5 % lead (Ehrenberg et al. 1954; p. 138-139). After roasting, most zinc (80-90 %) remained in the hematite residue, from which an unknown quantity was recovered by acid leaching. A pilot flotation plant was commissioned in 1937 to process 10-20 % of the separated pyritic ore (Ehrenberg et al. 1954), producing approximately 105,000 tons of zinc metal until 1962.

From 1960 onward, the flotation plant was expanded until it became fully operational in 1963. After heavy-medium separation, the crushed ore was milled to 80 percent <50 micron for sulfide flotation. From 1963-1992, the plant processed 18.3 million metric tons of sulfide ore at head grades of 8.4 wt.% zinc and 1.1 % lead, recovering 11,866,192 metric tons of pyrite concentrate (46-47 % S), 2,653,461 tons of sphalerite concentrate (53-54 % Zn), and 182,502 tons of galena concentrate (35-50 % Pb). The average recovery was 92 % for sphalerite and about 40 % for galena (Walther 1986; Gaul 1992).

2.4 *Slide 4. Europe: Cratons and orogenic belts*

The tectonic map of Europe (modified from Meinhold 1971) shows the continent-scale geologic units, the present plate-tectonic setting, and the location of the Meggen and Rammelsberg SEDEX deposits. The Cenozoic Alpine orogen (red, metamorphic massifs dark red) in south-central Europe, part of the Tethyan fold belt extending eastward into Turkey and Iran, formed during the collision of the African-Arabian and Eurasian continents leaving the Mediterranean as a remnant ocean basin. Most of Europe is underlain by the Precambrian Baltic craton (Baltica), shown in dark pink where outcropping, in light pink where under thin sedimentary cover, and in yellow where covered by deep sedimentary basins. The craton is bounded to the northwest by the Cambrian-Silurian Caledonian orogen (dark violet), and on all other sides by Devonian-Carboniferous Variscan orogenic belts (green). In Germany and other parts of central Europe, the Alpine orogen overprints parts of the older Variscan one. Neogene volcanic fields, like Iceland on the mid-Atlantic ridge, are shown in black.

2.5 *Slide 5. Geologic map of central Europe*

The geologic map of central Europe (Schriel 1930) shows the outcrop area of the Variscan fold belt, limited by the German-Polish basin in the north, where the Devonian-Carboniferous strata are covered by 2-8 km thick Permian to Cenozoic sedimentary rocks (Ziegler 1990), and limited by the Cenozoic Alpine fold belt and its foreland molasse basins in the south. The Rhenish Massif (RM) and the Harz (HZ) block represent the external part of the Variscan orogen, a folded "slate belt" of Devonian sandstones and shales (dark brown) and Carboniferous greywackes (grey).

The un-metamorphosed slate belt is separated by a suture zone (white dotted line) of medium-pressure phyllites from the metamorphosed internal part of the Variscan orogen, exposed in basement uplifts on both sides of the Cenozoic Rhine graben (RG) and in the Bohemian Massif (BM). Mesozoic platform sediments cover the area between the Black Forrest (BF) and the Bohemian uplifts.

2.6 *Slide 6. Variscan tectonic zones, Germany*

Generalized geologic map (modified from Engel et al. 1983) showing the un-metamorphosed Devonian-Carboniferous slate belt (Rhenohercynikum), exposed in the Rhenish Massif and in the Harz, and the predominantly metamorphic Variscan terranes to the southeast (Saxothuringikum, Moldanubikum), joined by a suture of greenschist-facies schists termed the Northern Phyllite Zone.

The Rhenish Massif and the Harz block, which contain the Meggen (M) and Rammelsberg (R) Zn-Pb-barite SEDEX deposits, consist mainly of Devonian marine sandstones and shales (brown), Devonian-Carboniferous basalt ± trachyte-alkali rhyolite volcanic complexes (green dots), and Carboniferous greywackes (brown). Regional folds are upright, strike northeast, and are vergent to the northwest. The slate-belt succession is largely par-autochthonous and rests on Silurian sedimentary rocks (grey) and on the Cadomian metamorphic basement (650-550 Ma) of Avalonia, a micro-continent accreted to the Baltic craton in the Lower Silurian. Xenocrystic zircons in Permian volcanic rocks suggest that Cadomian crust underlies most of the slate belt (Breitkreuz and Kennedy 1999). Allochthonous units are the Giessen-Selke nappe (GSN), transported at least 60 km to the northwest from a root zone in the Northern Phyllite Zone, and the Hörre-Acker Zone (yellow).

The greenschists of the Northern Phyllite Zone, metamorphosed at 300°C and 300-600 MPa at ca. 325 Ma, include Devonian shelf sediments and igneous rocks of a Silurian-Devonian magmatic arc. Arc-related Silurian and older Cadomian orthogneisses occur also in the amphibolite-facies (800-900 MPa) Mid-German Crystalline Rise, the main source of detritus accumulated in Rhenohercynian greywackes. Both metamorphic zones are bounded by faults and mark the suture of Avalonia with the rifted continental margin of Gondwana, accreted during collision in the Carboniferous and now represented by the Saxothuringian (grey) and Moldanubian (pink) terranes.

These terranes consist of para- and orthogneisses, synforms of Neoproterozoic greywacke (Dörr et al. 2002), Cadomian granites (540-520 Ma), low-grade Cambrian to Carboniferous volcaniclastic strata (brown), and post-tectonic Carboniferous granite batholiths (red). In the gneiss domes, regional metamorphism progressed from the ultra high-pressure (>2 GPa) eclogite facies at 370-350 Ma, to medium-pressure (700-800 MPa) granulite- and amphibolite facies at 350-340 Ma, to low-pressure (200-300 MPa) greenschist facies at 340-300 Ma during batholith emplacement. Klippe structures (black) indicate regionally extensive metamorphic nappes, now largely eroded (Franke 2000; Linnemann et al. 2003).

2.7 *Slide 7. Rhenish Massif: Variscan slate belt*

The outcrop map shown is part of the Geologic Map of Germany (Walther and Zitzmann, 1973). The stratigraphic units in the Rhenish Massif comprise the Lower Devonian quartzite-sandstone-shale succession (dark red-brown), a Middle Devonian sequence of sand-banded and calcareous shales (brown-grey), basaltic spilites (green) and limestone reefs (blue), and a Carboniferous flysch-molasse sequence of black shale, greywacke, and sand/siltstones with coal measures (medium grey). In total, the Devonian-Carboniferous strata are more than 10 km thick. The Carboniferous sedimentary rocks are mainly exposed at the northern and eastern margin of the massif. Most regional folds are upright, trend about N50°E, and display an axial plane slaty cleavage.

The Middle Devonian Meggen sulfide-barite deposit (M) is shown relative to Givetian-Frasnian limestone reefs (blue: ER Eifel, AR Attendorn, BR Brilon), and relative to the Lahn-Dill syncline (LDS), which contains the largest accumulation of coeval submarine basalts (green). Tertiary trachytes (pink) and alkali olivine basalts (purple) are related to Alpine foreland rifts.

A. Strained Lower Devonian quartzite, a shallow-marine shelf sediment, from a quarry in the Taunus range near Usingen. The Swiss knife is 9 cm long

B. Upper Carboniferous near-shore deltaic sedimentary succession. The Dünnebank coal seam (brown), is underlain by grey slate (mudstone) containing coalified plant fragments, root casts, and siderite nodules. The coal seam is overlain by thick-bedded, medium-grained sandstone. The opened Swiss knife is 16 cm tall. Ruhr coal mining district, North Rhine Westfalia, Bochum, Geological Garden in the open pit of the former Friederica mine.

2.8 *Slide 8. Middle Devonian Lahn-Dill Syncline*

The Middle Devonian to Lower Carboniferous volcanic succession in the Lahn-Dill Syncline is 500-800 m thick. Smaller volcanic centers of similar age 150-350 m thick also occur east of Meggen. In the syncline, tholeiitic basalts comprise 99 volume percent, and picrites, alkali rhyolites (quartz keratophyres) and trachytes (keratophyres) about 1 percent of the succession. Basaltic pillow lavas and tuffs are pervasively altered to "spilitic" mineral assemblages (chlorite, albite, calcite, quartz; minor actinolite, epidote, prehnite, pumpellyite), interpreted to result from the hydrothermal circulation of seawater and low-grade metamorphism. The keratophyre suite of altered lavas and tuffs is characterized by albitized phenocrysts of sanidine, minor quartz phenocrysts, chlorite-stilpnomelane pseudomorphs after amphibole and pyroxene, and accessory riebeckite, aegirine, magnetite, and hematite (Wimmenauer 1985; Schmincke and Sunkel 1987).

The volcanic succession is interpreted as bimodal and related to back-arc spreading in a continental rift basin. The mafic spilites vary in trace element composition from LREE-enriched OIB (oceanic island) to LREE-depleted MORB (mid ocean ridge) basalt indicating oceanic crust (Wedepohl et al. 1983; Schmincke and Sunkel 1987).

Most volcanic rocks are folded into anticlines up to 1.5 km long and 0.6 km wide. These anticlines represent submarine ridges elevated above the adjacent basins. Beds of hematite ironstone were deposited on top of altered basaltic ridges, mainly during the transition from the Middle to Upper Devonian (Bottke 1965). These volcanogenic iron ores are contemporaneous with the sulfide-barite ore at Meggen.

A. Pillow of basaltic spilite (1.3 m long) marked by calcite-filled vesicles at the margin.

Quarry at Philippstein, near Braunfels, Lahn area, Hessen.

B. Foliated lapilli tuff of basaltic spilite (Schalstein) containing 20 vol. % disseminated calcite, looking at a cleavage plane in a hand specimen from the footwall of hematite ore on the 150 m level of the Fortuna mine at Oberbiel, west of Wetzlar, Lahn area, Hessen. The Swiss knife is 9 cm long.

C. Coherent lava of quartz keratophyre marked by 2 vol. % grey quartz and by 5 % white-grey feldspar phenocrysts. The pen is 14 cm long, Goergeshausen quarry, Mensfelder Kopf, Lahn area, Hessen.

2.9 Slide 9. Middle Devonian Lahn-Dill iron ore

From 1830 to 1983, mines in the Lahn-Dill district produced a total of 97 million metric tons of ore at 35-40 % iron. The largest mines were the Königszug mine near Oberscheld (8.3 million tons) and the Fortuna mine near Wetzlar (4.7 million tons). The cross section (modified from Bottke 1965) shows the central part of the Königsberg iron ore mine. Volcanogenic hematite ironstone overlies basaltic spilite and is intercalated with Givetian-Frasnian (tm2-to1) grey limestone, which is in turn overlain by a condensed ridge-facies of Frasnian-Famennian (to1-to6) red limestone. Lower Carboniferous tholeiitic lavas and dykes (diabase) cap the succession. The section illustrates the segmentation of volcanic anticlines by thrust faults.

A. Middle Devonian siliceous hematite ironstone (45 % Fe, 20 % SiO_2, 5 % $CaCO_3$) associated with spilitized basalt on a volcanic ridge. The red pen is 14 cm long. Fortuna iron ore mine, Oberbiel, Lahn-Dill area, Hessen.

B. Upper Devonian limestone deposited a volcanic ridge: grey coral fragments in a red micritic matrix, cavities are filled with banded brown-grey sparry calcite. The lens cap is 5 cm across. Decorative stone quarry at Villmar, Lahn valley, Hessen.

Small mines east of Meggen produced 3 million tons of iron ore (Walther 1986; Walther and Dill 1995). Some ironstones are associated with distal rhodonite-rhodochrosite beds and, rarely, with thin (<1m) sulfide beds in tuffaceous black shale. At Adorf, Sauerland, such pyrite beds contain 1500-3000 g/t copper and 11 g/t silver but less than 30 g/t zinc and lead (Werner 1988).

Volcanic-associated sulfide-barite mineralization is rare and appears to be spatially related to rhyolitic rather than basaltic centers. At Lohrheim in the Lahn area, Middle Devonian black shales and cherts intercalated with keratophyre lavas and tuffs (150 m thick) contain beds of pyrite (0.2-3 m; 50-200 g/t Ag; 2.5 g/t Au) and barite (1 m). The barite is intergrown with accessory pyrite, sphalerite, and cinnabar (Werner 1988).

2.10 Slide 10. Meggen: District geologic map

Simplified geologic map of the northeast Rhenish Massif (modified from Behr 1977), note the location of the Givetian Meggen sulfide-barite deposit (MG) and the Givetian-Frasnian limestone reefs (blue). The reefs are up to 1 km thick, and indicate the approximate position of the Middle Devonian shelf margin relative to the pelagic rift basin at Meggen (Krebs 1981).

The sulfide-barite bed outcrops in the Meggen Syncline (red), a subsidiary fold at the northwest limb of the East Sauerland Anticlinorium (ESA), and continues down-dip on the southeast limb of the Attendorn-Elspe Syncline (AES). The Ebbe Anticline (EA) limits the syncline to the northwest. The grid coordinates are latitude and longitude. The inset map shows the map area (black rectangle) relative to German and Dutch cities.

2.11 Slide 11. Meggen: Composite cross section

The composite NW-SE cross-section (modified from Sachtleben mining company 1988) shows the Meggen Syncline at about 400 m grid west, and the overturned southeast limb of the Elspe Syncline at 1900 m west, both separated by the eroded Meggen Anticline (MA). The Meggen limestone reef is exposed on the Sicilia shaft 11 level and below. The folds are delineated by the sulfide-barite ore and by the overlying Lagerkalk limestone (both in red). Note that the footwall blocks of several reverse faults are displaced to the northwest, a fault type termed under-thrust. The bituminous succession (brown) of ore, pelagic limestone, black shale and siltstone turbidite is thrust over the Meggen Reef (W. Fuchs in Clausen 1978). Drill cores indicate that the reef forms an overturned anticline segmented by thrust faults (Krebs 1981).

The Eifelian-Givetian Meggen Reef is a tabular body more than 250 m thick, composed of in-situ stromatoporoidea and peripheral bioclastic limestone. The upper 30 m of the reef consist of dark grey pelagic limestone (middle Givetian) crosscut by sediment-filled fissures (Clausen 1978; Krebs 1981).

Dark grey bituminous siltstones, black shales with pyrite nodules, and minor graded-bed sandstones constitute the Givetian Meggen Beds (brown) in the footwall of the sulfide-barite ore. In the mine, the thickness of the succession varies from 15 to 40 m. The Meggen Beds are separated from the underlying Tentaculites shale by the Odershausen limestone marker (5-40 cm thick; Clausen 1978).

Above the sulfide ore body, the Frasnian bituminous shales (3.4 wt.% C_{org}) in the hanging wall of the Lagerkalk limestone are characterized by thin grey-black limestone beds and nodules, and by marker horizons of felsic tuff and Zn-Pb enriched pyrite bands. In the mine, the bituminous "Büdesheim" succession varies in thickness from 35 to 80 m (Clausen 1978; Krebs and Gwosdz 1985).

2.12 Slide 12. Meggen: Limestone-shale succession

Photographs illustrating the Middle to Upper Devonian sedimentary succession at Meggen:

A. Looking northeast at Upper Devonian calcareous shale forming the southeast limb of a syncline in Middle Devonian Wissenbach black shale. Leached limestone nodules trace the vertical bedding. The axial plane slaty cleavage dips 50-60° southeast indicating a NW-vergent fold. The Swiss knife is 17 cm tall. Outcrop at the path rounding the Hessenkopf peak near Goslar below the Margarete cliff, Harz, Lower Saxony.

B. Bituminous shale of the Givetian Meggen Beds from the footwall of the sulfide ore. Nodular pyrite bands define the bedding, cut by the slaty cleavage at a 60-70° angle. The nodules are composed of fine-grained pyrite (70 %), white-grey barite (soft), and accessory brown sphalerite. The Swiss knife is 9 cm long.

C. Massive Givetian limestone of the Meggen Reef composed of detritus cemented by sparry calcite, rare single corals (2 cm), and thin micritic beds. Note the fault plane lined with white calcite. Sicilia shaft 11 level, close to the shaft platform.

2.13 Slide 13. Meggen: Geology Sicilia shaft Level 1

Geologic plan of the Sicilia shaft Level 1 (+243.6 m above mean sea level) mapped by W. Henke and Ph. Ommer (modified from the colored plate in Ehrenberg et al. 1954). The narrow Meggen Anticline separates the sulfide-barite ore in the Meggen Syncline from the ore in the overturned limb of the Elspe Syncline. The Meggen Syncline is subdivided into doubly plunging minor folds on this level. Note the strike-parallel reverse faults (saw-teeth on upper block), and the steeply dipping (60-80°SW) Nathaller, Halberbracht and Markhahn normal faults (black lines) perpendicular in strike to the fold axes. The lithologic units are in mine terminology. The Meggen Beds in the footwall of the ore were traditionally termed "Lenneschiefer" (Lenne black slate), and the black-grey calcareous shales above the Lagerkalk limestone were termed "Büdesheim" slate. The green and lesser red "Cypridina" slates were mapped as the uppermost stratigraphic unit. Note the mine Zero North and Zero East grid lines.

2.14 Slide 14. Meggen: Sulfide bed in the Elspe Syncline

Series of four cross sections at 1000 m to 700 m mine-grid west illustrating the irregular folding of the sulfide ore and Lagerkalk limestone (both red) in the overturned southeast limb of the Elspe Syncline (mapped by W. Fuchs; modified from Sachtleben mining company 1988). The fold axes plunge about 15° northeast. Note the change in shape of the main subsidiary anticline along strike. The +500 m and +400 m grid north lines are shown for reference. Note the Sicilia shaft 8 (-100 m MSL) and 12 levels (-300 m below mean sea level).

2.15 Slide 15. Meggen: Structural map Level 12

Structural map of the Sicilia shaft Level 12 (AG Mueller 1979), 304 m below mean sea level and 548 m below Level 1. The sulfide ore (red) outlines the folds, separating the black shales and sandy siltstone turbidites of the Givetian Meggen Beds (white) from the Lagerkalk limestone and Frasnian calcareous shales (light blue) in the hanging wall. The fold axes strike about N45°E in the southwest and N55°E in northeast part of the level, and plunge at shallow angles of 2-13° northeast. The folds are displaced by strike-parallel under- and over-thrusts, and by normal faults oriented perpendicular to the fold axes. The Halberbracht Fault has an offset of 45 m southwest-block-down. The cross sections shown in the next slide are marked as blue grid lines.

The shales display an axial plane slaty cleavage dipping 70° southeast. The under-thrusts are sub-parallel to cleavage planes and displace the footwall block to the northwest. The northwestern syncline is tightened and progressively dismembered by over-thrusts increasing in throw to the northeast. The competent Meggen Reef at depth is considered the cause of this irregular fold and thrust pattern. The strata exposed in crosscuts 1 and 3 (XC1, XC3; highlighted in yellow) were mapped at a 1:100 scale (Slide 17).

2.16 Slide 16. Meggen mine: Cross sections Level 12

Looking northeast at cross sections illustrating the structural style of folding and reverse faulting on the Sicilia shaft Level 12 (AG Mueller 1979). The sulfide ore is shown in red relative to the +600 m grid north line, the -304 m level, and the mine workings.

The sections on the left at 1300 m to 1140 m grid west illustrate the progressive overturning and faulting of the southeast limb of the northwest anticline-syncline pair. Note the cleavage-parallel under-thrust in the core of the anticline.

The sections on the right at 1100 m to 900 m west show the broad anticlinorium thrust over the northwest anticline-syncline pair, and the progressive dismemberment of the synclinal limb.

2.17 Slide 17. Meggen: Stratigraphy of the ore horizon

The lithologic units exposed in the northeast face of Crosscut 3 on the Sicilia shaft Level 12 represent the Givetian Meggen Beds in the footwall of the sulfide ore, and those in the face of Crosscut 1 the Frasnian limestone-shale succession in its hanging wall (AG Mueller 1979).

Frasnian strata: In Crosscut 1 at 1325 m grid west, the 5 m thick Givetian/Frasnian Lagerkalk limestone conformably overlies the sulfide ore. The limestone is light grey, micritic, and subdivided by shale partings into 0.5 m thick beds. It is overlain by the "Büdesheim" bituminous succession. The lowermost part consists of thin-bedded (5-20 cm) dark grey limestone marked by black Kellwasser beds, and of intercalated grey to black shale (1-5 cm). The upper part consists predominantly of dark grey calcareous shale.

Along strike, the Lagerkalk overlies the Meggen Beds directly as the ore-equivalent unit (Krebs 1981). Dornsiepen (1985) used drill-core intersections up to 5 km northeast and southwest of the mine, and conodont biostratigraphy to trace lateral facies changes in the Frasnian strata overlying the Lagerkalk. To the top of the Conodont asymetricus zone (top of tuff MT3), the bituminous succession is 10-15 m thick above the sulfide ore but grades laterally into thinner chloritic shales (at the barite margins), and then into distal nodular limestone less than 5 m thick.

Givetian strata: The Meggen Beds in Crosscut 3 at 930 m to 1000 m grid west constitute the core of the broad anticlinorium. Dark grey siltstone turbidites (brown) form an upper and lower unit 7-8 m thick. Both are composed of graded sandy siltstone beds 1-5 cm thick separated by black shale tops. The base of the upper turbidite unit is marked by fine-grained grey sandstone (10-20 cm beds), which is partly silicified (yellow). Two additional marker units, both about 3 m thick, consist of black bituminous shale (dark grey), rare siltstone layers, and pyrite nodules (≤ 7300 ppm Zn). The upper shale forms the footwall of the sulfide ore and the lower one separates the turbidites.

According to Krüger (1973), Gwosdz et al. (1974) and Clausen (1978), the Givetian Meggen Beds are 15-40 m thick beneath the ore body. To the southwest, they increase in thickness to more than 250 m over a distance of 5 km, most of the increase due to the upper and lower turbidite units. To the northeast, the Meggen Beds increase gradually to about 50 m. Laterally away from the ore body, the black shale beds become less bituminous and contain disseminated rather than nodular pyrite.

2.18 Slide 18. Meggen: Manganese in the Lagerkalk limestone

The pelagic Lagerkalk limestone in the hanging wall of the ore has been traced over a distance of more than 25 km along the southeast limb of the Elspe Syncline. Manganese in this limestone defines an anomaly extending about 5 kilometers away from the sulfide-barite ore body (Gwosdz and Krebs 1977). The highest values of more than 2000 ppm occur in limestone above the barite margins, decreasing gradually to 1000 ppm and then to background values of 500 ppm in outcrops to the northeast and southwest. On the inset map, the Attendorn Reef is shown in blue and the limestone marker is traced in red.

2.19 Slide 19. Meggen Level 8: Sulfide ore

The sulfide ore varied in thickness from 1 to 7 m, averaged 3.5 m, and consisted of 65-70 vol.% pyrite, 13% sphalerite, 1% marcasite, 0.6 % galena, and 15-20 % quartz, chalcedony, illite, and minor carbonate and barite (Ehrenberg et al. 1954).

On the right is the standard petrographic section through the sulfide ore on Level 8 of the Sicilia shaft (modified from Gasser 1974). On the left are two photographs of the footwall black shale, and of the lower sulfide zones A1 and A2 in the standard section. Both were taken on the same level. The hammer is 32 cm tall.

Standard ore section: The section shows the vertical distribution of ore types (red) from the Lenne black shale (grey) to the Lagerkalk limestone (blue). Intercalated is a 6 cm thick graded bed of sandstone (yellow). The lowermost ore type A1 is bedded on a 1-2 cm scale and composed of sharply separated layers of pyrite, sphalerite-galena, and black shale. Pyrite beds grade into nodules but most are laterally continuous over decimeters. In the photographs, the beds are gently folded by tectonic slip on the shale layers. The ore type A2 is massive, bedding is poorly preserved and contorted. Pyrite forms cm-thick short layers and nodular aggregates. Sphalerite and galena are recrystallized and fill the interstitial space between pyrite.

Ore type B is thinly bedded on a 0.5 cm scale by black shale seams. Pyrite layers lens out laterally, are broken and deformed, and grade into mm-sized nodules. Sphalerite and galena form interstitial aggregates. Type B is gradational to Type C at the top of the section. Type C is laminated on a 1-2 mm scale, and consists of wispy pyrite lamina separated by paper-thin shale partings, both discontinuous laterally. Sphalerite is enriched in mm-thick diffuse layers and disseminated in the groundmass. Galena is rare (Gasser 1974).

The vertical distribution of ore types was not consistent across the ore body. In places, types A, B and C were rhythmically interlayered. In general, Type A1 formed the lowermost and Type C the uppermost part of the sulfide ore (Gasser and Thein 1977; Thein 1985). In the Meggen Syncline, the vertical sequence A to C was reversed, and the sulfide ore subdivided into a laminated lower and a thick-bedded upper part by an intercalated black-shale bed 10-50 cm thick (Ehrenberg et al. 1954).

2.20 Slide 20. Meggen: Bedding in sulfide ore

A. Type A2 massive ore, Sicilia shaft level 8, sublevel 3, stope 2/west 1. **Top:** A 9 cm-thick zone with discontinuous lenses (1-5 mm) of colloform pyrite. The darker less polished matrix contains numerous streaks of quartz, melnicovite pyrite, and shale up to 1 mm thick. Brown sphalerite (10 %) occurs in disseminated aggregates (0.5-1 mm). **Center:** A 6 cm-thick zone of contorted and agglomerated lamina of pyrite (80 %) and darker melnicovite pyrite cemented by interstitial aggregates of brown sphalerite (7 %), rare galena, calcite (reaction 5% HCl), and quartz. **Bottom:** A 13 cm-thick zone with sparse lamina of colloform pyrite (1-5 mm thick) in a darker less polished matrix of melnicovite pyrite and gangue; the melnicovite pyrite and the quartz-calcite gangue form streaks 0.5-1 mm thick alternating with discontinuous black shale partings. The matrix encloses several pyrite nodules (5-15 mm), which display sharp boundaries and no internal texture. About 15 % brown sphalerite in disseminated 0.5-3 mm interstitial aggregates.

B. Type C laminated ore, Sicilia shaft level 12, cross cut at 790 m grid west, 450 m grid north. The matchstick is 2 cm long. Very thin (0.5-3 mm) wavy lamina, which pinch out laterally. The well-polished yellow seams consist of densely packed pyrite spheroids 20-60 micron in diameter. The darker ones contain very fine-grained melnicovite pyrite, accessory marcasite, and quartz and carbonate. Sphalerite occurs mainly in diffuse brown-yellow layers up to 5 mm thick, where it forms the matrix of pyrite or marcasite spheroids. Black shale partings are absent. The interstitial aggregates to the right of the matchstick consist of recrystallized honey-colored sphalerite, white-grey carbonate, and rare grey galena. Fractures are lined with galena and carbonate.

Melnicovite pyrite is a finely crystalline, arsenic- and thallium-bearing pyrite of colloform texture, dark yellow-grey and poorly polished due to dispersed micron-sized illite (Ehrenberg et al. 1954). It oxidizes in air to iron sulfate.

2.21 Slide 21. Meggen: Gel textures in lower sulfide ore

The photomicrographs in reflected plane-polarized light show pyrite gel textures in type A2 ore collected on level 8 of the Sicilia shaft, sublevel 8.3. The subhedral well-polished pyrite, and sphalerite, galena and carbonate are secondary phases recrystallized during diagenesis and tectonic deformation.

A. Spheroids composed of cores of framboidal pyrite and concentric shells of pyrite and gangue are cemented by sphalerite (Sp) and minor recrystallized pyrite. The gangue (black) consists mainly of illite and quartz.

B. Concentrically zoned, atoll-shaped pyrite-gangue ± sphalerite spheroids in a matrix of sphalerite (Sp) and minor quartz-illite gangue (black). Some of the spheroids have framboidal cores. Note the tendency of the spheroids to agglomerate.

C. Colloform aggregate composed of agglomerated pyrite spheroids, interstitial quartz-illite gangue, and rare interstitial sphalerite (Sp, grey). Where the gangue content is less, the pyrite is partly recrystallized enclosing remnant spheroids.

D. Colloform aggregate of agglomerated spheroids forming "cauliflower" gel textures composed of micron-sized pyrite crystals, minor quartz-illite gangue (black), and interstitial sphalerite (Sp, grey). Pyrite recrystallization is limited to a few subhedral grains.

2.22 Slide 22. Spheroids in upper sulfide ore

The photomicrographs in reflected plane-polarized light show pyrite gel textures in type C ore collected on level 12 of the Sicilia shaft. The subhedral well-polished pyrite, and interstitial sphalerite, galena and carbonate are secondary phases recrystallized during diagenesis and tectonic deformation.

A. Spheroids composed of radially oriented bladed marcasite (anisotropic, tarnished) grown on a core of quartz-illite gangue (black) or framboidal pyrite + gangue. Some spheroids are partly replaced by polished, subhedral pyrite. The marcasite spheroids and smaller ones of framboidal pyrite are cemented by secondary sphalerite (Sp) and carbonate (dark grey).

B. Laminated bedding defined by a layer of closely packed pyrite framboids (right) in contact with a layer of sphalerite (Sp) enclosing larger pyrite-marcasite spheroids, some radially textured. The groundmass consists of recrystallized sphalerite, lesser quartz + illite (black), and rare carbonate (dark grey).

C. Poorly polished, brown-yellow botryoidal aggregate of melnicovite pyrite and marcasite (anisotropic) with remnant concentric gel textures. The aggregate is in contact with a layer of recrystallized pyrite (Py), sphalerite (Sp), carbonate (dark grey), and rare illite and quartz (black). Note the atoll-shaped spheroid (white arrow) composed of a central pyrite framboid and an outer shell of illite + pyrite dust.

D. Recrystallized layer composed of polished pyrite (Py) enclosing remnant radially textured and framboidal spheroids (black arrows). The pyrite is in contact with subhedral carbonate (dark grey), sphalerite (Sp), galena (Ga), and accessory quartz and illite (black).

The population of pyrite spheroids is subdivided into two groups: (1) large spheroids 0.1-1 mm in diameter and always radially textured; and (2) small spheroids 20-60 micron in diameter (median: 30 micron), which are either radially textured or composed of framboidal pyrite. The framboids consist of agglomerated 1-3 micron pyrite crystals and minor interstitial illite (Gasser and Thein 1977).

2.23 Slide 23. Meggen ore: Mineralogy and isotopes

Sulfides: The average sulfide composition of the ore (in vol.%) listed has been calculated using the mineralogical and specific gravity data in Ehrenberg et al. (1954; Tables 25 and 27; p. 281-285). The iron content of sphalerite varied from 1.0 to 1.5 weight percent. Optical microscopy indicates traces of chalcopyrite and tennantite-tetrahedrite (Ehrenberg et al. 1954). Inclusions of boulangerite in galena were identified by electron microprobe analysis (Gasser and Thein 1977).

Gangue: Apart from detrital quartz, the thin graded turbidite beds intercalated with the ore contain accessory sericitized alkali feldspar, zircon, tourmaline, apatite and rutile. Hydrothermal quartz occurs in bi-pyramidal euhedral crystals enclosed in sulfides, and as chert-like cement and chalcedony interstitial to sulfides. X-ray diffraction analysis indicates that the clay fraction (<2 to 20 micron) consists of illite ± sericite. Chlorite was not detected. In contrast, chlorite is common in shale partings of the Lagerkalk limestone. Carbonates (calcite, siderite, dolomite, ankerite) are minor, enriched in manganese, and mostly recrystallized forming interstitial cement and fracture fill. Barite is rare and concentrated in the peripheral sulfide ore close to the overlap with massive barite (Gasser and Thein 1977).

Sulfur isotopes: The sulfur isotope ratios of the barite ore (average $\delta^{34}S$ = +22.8 ± 0.2 ‰) implicate Givetian seawater as the principal source of sulfate given the close agreement with the value of Upper Givetian marine anhydrite ($\delta^{34}S$ = +22.3 ± 0.8 ‰) in Belgium (Nielsen 1985). Barium and strontium were introduced by the reduced hydrothermal fluid and precipitated as sulfate due to mixing with seawater at the margin of the euxinic basin. The isotope ratios of pyrite, sphalerite and galena (total range $\delta^{34}S$ = +11.9 to +24.1 ‰; average of pyrite least affected by recrystallization: +19.8 ‰) suggest the reduction of marine sulfate to hydrogen sulfide in the Devonian sedimentary succession below the deposit (Buschendorf et al. 1963; Nielsen 1985). The tight spread of $\delta^{34}S$ values in the bulk sulfide ore may be explained by the "organic reduction" at >100°C of Devonian anhydrite during the circulation of an initially H_2S-bearing fluid through organic-rich sedimentary rocks prior to fluid ascent and discharge (Ohmoto and Rye 1979; p. 539-544).

Lead isotopes: The lead isotopic composition of galena ($^{206}Pb/^{204}Pb$ = 18.197, $^{207}Pb/^{204}Pb$ = 15.606, $^{208}Pb/^{204}Pb$ = 38.123) suggests that detritus in the Lower to Middle Devonian clastic succession is the source of metals in the Meggen ore body (Wedepohl et al. 1978). The single-stage evolution models of average terrestrial uranogenic lead in Cumming and Richards (1975; Model 3) and Stacey and Kramers (1975) provide ages of 370 Ma and 330 Ma for the Meggen galena, respectively, broadly consistent with the age of the Emsian to Givetian sedimentary succession (408-383 Ma; International Commission on Stratigraphy 2018).

2.24 Slide 24. Meggen deposit: Unfolded ore body

Prior to erosion, the Meggen ore body extended more than 5 km in east-west and about 2.5 km in north-south direction. The isopach map of the unfolded sulfide-barite ore has been compiled from Ehrenberg et al. (1954) and Fuchs (in Clausen 1978). The isopachs define a shallow basin elongated in east-west direction. The highest zinc and lead grades coincide approximately with the central zone of greatest sulfide thickness (4-7 m). Exceptions are local maxima of 8-11 m in the western part of the deposit, which are caused by intercalated beds of sand-siltstone turbidite and black shale. The contact with the Meggen Reef is tectonic.

To the north and south, the sulfide ore pinches out below barite, which thickens in turn to 3-6 m before gradually pinching out beneath the Lagerkalk limestone. The average thickness of the sulfide ore is 3.5-4.0 m, and that of the barite ore 2.5-3.0 m. In the northwest, the barite margin is absent and the sulfide ore thins out in clastic rocks (Krebs 1981).

2.25 Slide 25. Meggen sulfide ore body: Metal zoning

Lateral zoning: The lateral metal zoning in the northwest part of the sulfide ore body has been studied using 17 diamond drill holes (Gasser and Thein 1977; Thein 1985). Zinc, lead, copper, cadmium, arsenic, antimony, nickel and cobalt decrease from the center to the margin, whereas thallium, barium, manganese, and the gangue content increase. The ore also contains 3-8 ppm Ag, 0.02-3.4 ppm Au, and 1.1-8.5 ppm Hg (Ehrenberg et al. 1954; Werner 1988), but the distribution of these metals is not known.

Vertical zoning: Cadmium decreases, zinc shows no trend, and cobalt, nickel, copper, antimony and thallium increase from the base to the top of the sulfide bed (Thein 1985).

Meggen Beds: The metal zoning in the footwall sedimentary rocks is constrained by analyses from the top 20 m of the Meggen Beds, collected in a drill hole fence across the northwest part of the sulfide ore body, and by samples from the top 30 m beneath the Lagerkalk limestone in drill holes to the southwest (Werner 1988). Beneath the ore body, the Meggen Beds are enriched in sulfur, nickel, thallium and barium relative to those in the southwest. The elevated metal contents are related to sulfide-barite nodules. Thallium decreases from an average of 193 ppm beneath the ore body to a background value of 2 ppm in the time-equivalent beds along strike. Typical background values in Devonian siltstones and shales of the Rhenish Massif are: sulfur (350-3400 ppm), nickel (57-163 ppm), thallium (0.3-2 ppm), and barium (333-580 ppm; Werner 1988).

2.26 Slide 26. Meggen: Peripheral barite ore

To the north and south, the sulfide ore body pinches out below barite margins. The barite is dark grey due to trace amounts of disseminated bitumen, and separated into layers by shale partings (Ehrenberg et al. 1954; Buschendorf and Puchelt 1965). In the Meggen Syncline, the maximum thickness of 4-5 m and in the Elspe Syncline about 3 m. The barite ore consists of 94-96 weight percent barium sulfate, 1-2 % strontium sulfate, 4-6 % gangue (quartz, illite, carbonate), and 0.3 % pyrite. The average ore is thus remarkably pure attesting to the sharp spatial separation of sulfide and sulfate. Most of the transition zone, where barite overlies sulfide ore is but a few ten meters wide (Slide 24).

A. Looking southwest at the overturned southeast limb of the Meggen Syncline. The photograph shows black slate of the Meggen Beds in the structural hanging wall, and the barite bed in the center marked by white calcite veins. The smooth curved surface of the Lagerkalk limestone forms the structural footwall. Wolbecke mine, 140 m level, 445 m grid west, 340 m south (Ehrenberg et al. 1954).

B. Dark grey, fine-grained barite ore from the southern margin of the sulfide ore body. At the top is an intercalated seam of fine-grained pyrite (partly oxidized to sulfate). Sicilia shaft 6 level, the US 1 cent coin is 19 mm across.

C. Barite ore from the northern margin, the bedding is defined by layers of barite spheroids, by dark layers of finely granular barite, and by a seam of pyrite (Py). The densely packed, radially textured spheroids are up to 1 mm in diameter. Sicilia shaft, sample S9a collected between Levels 3 and 4 (Buschendorf and Puchelt 1965). In areas of tectonic strain, the spheroids are fractured and partly or totally re-crystallized (Ehrenberg et al. 1954).

At the Rammelsberg deposit near Goslar, Harz, barite spheroids occur in beds intercalated with Eifelian black shale in the stratigraphic hanging wall of the sulfide ore, Schiefermühle quarry (Hannak 1981).

2.27 Slide 27. Meggen: Gel deposition in an euxinic basin

The block diagram (modified from Thein 1985) shows a reconstruction of the sedimentary environment during sulfide-barite deposition at the rifted margin of the Givetian shelf. H_2S-bearing hydrothermal fluid discharged into a third-order pelagic basin protected from turbidite influx by the Attendorn and Meggen reefs (Krebs and Gwosdz 1985). The shallow euxinic basin persisted after the sedimentation of the upper Givetian ore until the lower Frasnian, based on lateral thickness and facies changes in the Frasnian succession below the MT4 tuff and pyrite marker horizon (Dornsiepen 1985).

Fluid conduit: Fluid discharge from faults at the Meggen Reef is inferred, and based on the occurrence of sediment-filled fissures in the pelagic limestone covering the reef. Upper Givetian/lower Frasnian conodonts and rare fragments of pyritic limestone suggest that these fissures are related to faulting during ore deposition (Krebs 1981). Fault-block tilting towards the reef may be indicated by the increased width of the sulfide ore and by the absence of a barite margin in the northwest (Slide 24), consistent with the deposition of sulfides below the O_2/H_2S interface in the deeper parts of the basin and of barite in the shallower parts above (Krebs 1981).

Wall-rock alteration: Bioturbation is absent in the upper Meggen Beds, and wall-rock alteration below the ore body is stratabound (Gwosdz et al. 1974; Krebs and Gwosdz 1985; Renner 1986). Permeable sand-siltstone beds are silicified and decalcified. The siltstone-shale successsion is enriched in illite (66-88 vol. %) and depleted in chlorite relative to other Givetian shales of the Rhenish Massif (27-44 % illite). The footwall argillic alteration and the predominance of illite in the sulfide ore (Gasser and Thein 1977) indicate mildly acidic, low-temperature (150-200°C) hydrothermal conditions (Werner 1988).

Gel deposition: The fluid carried dissolved H_2S and iron, zinc, lead and barium chloride, and pooled as high-density brine in the euxinic basin. The textures in pyrite indicate that the sulfides, silica and clay flocculated as spherical colloidal particles, which preferentially adsorbed thallium (Thein 1985) and remained suspended in brine before settling. They are now preserved as pyrite framboids 20-60 micron in diameter, and as atoll-shaped spheroids composed of concentric pyrite, gangue and sphalerite shells. The radially textured spheroids suggest that marcasite crystals nucleated on suspended silica-clay particles. The shape of these spheroids was largely preserved though most of the marcasite recrystallized to pyrite during diagenesis. The massive sulfide ore type A2 may be the result of early diagenetic liquefaction of the water-saturated gels, perhaps caused by particularly rapid settling or by seismic activity. The upward decrease in cadmium (in sphalerite) and increase in thallium (in pyrite) in the ore suggest that the hydrothermal system cooled with time.

Barium remained in solution in the center of the brine pool and precipitated as sulfate at its margin, where the dense brine mixed with lighter oxygenated seawater. Radially textured barite nucleated on particles forming spheroids suspended in brine before settling. Most of the barite was deposited as mud when seawater influx diluted the brine.

There are distinct similarities in ore texture and element enrichment between Meggen and the metal-bearing brines and sediments pooled in the Atlantis II Deep of the Red Sea (Bäcker and Richter 1973; Thein 1985).

2.28 Slide 28. Meggen district: Shelf-margin paleogeography

Palinspastic map illustrating the paleogeography and facies changes of Upper Givetian sedimentary rocks in the Meggen district (modified from Werner, 1988). The Attendorn Reef and adjacent sandstones are located on the marine shelf, whereas the Meggen orebody (M), the Meggen Reef, and the black shale-turbidite succession of the Meggen Beds are located in the rifted pelagic basin to the southeast. After the Meggen Reef drowned in the lower Givetian, the morphological contrast between the reef and the basin floor persisted. The reef sheltered the brine pool and the accumulating sulfide-sulfate sediments from turbidite influx. Turbidity currents down the shelf slope southwest of the Attendorn Reef are responsible for the sandy composition and increasing thickness (to 265 m) of the Meggen Beds in the clastic fan southwest of the ore body (Krebs 1981).

2.29 Slide 29. Meggen: Regional paleogeography

Top: The cross section through the Middle Devonian shelf of the wider Meggen area, vertically exaggerated, illustrates the paleotopography generated by tilted fault blocks at the margin of the main rift basin (modified from Krebs 1981). Biostromal limestone banks (S = Schwelm facies) and atoll-shaped biohermal reefs (D = Dorp facies), built by stromatoporoidea, corals and crinoids, developed on shelf sandstones of the Honsel and Newberrien Beds in the shallow-water parts of tilted fault blocks. Block tilting is inferred to account for the lateral change in the thickness of the Attendorn Reef from 200-300 m in the southeast to 950 m in the northwest (Krebs 1981). Siltstones and shales were deposited in deeper water between the reefs, and in the main rift basin during formation of the Meggen deposit (M).

Bottom: The palinspastic map below illustrates the changes in lithofacies and marine fauna of the lower Givetian Honsel Group across the paleo-shelf west of Meggen (modified from Langenstrassen 1983). The Givetian strata are up to 1200 m thick but thin to the east and southeast. Sandstones of the inner shelf, proximal to the Old Red Continent, contain red-bed detritus (red line = outer limit). Pure sandstones were deposited as bars and as sheets on the outer shelf together with minor bioturbated siltstones and calcareous shales. Oolitic limestones (green) indicate the turbulent water of the tidal zone, whereas different benthic faunas of brachiopoda (Subrensselandia) and spiriferida (Fimbrispirifer) indicate the deeper water sub-tidal zone (orange and yellow lines). Biostromal carbonate banks (blue), the incipient reefs of the Schwelm facies, formed in sheltered areas of reduced clastic supply. Siltstones and calcareous shales (light brown) are most abundant at the shelf margin, and are characterized by a pelagic fauna of ostracods and conodonts (Langenstrassen 1983).

2.30 Slide 30. Meggen basin: Devonian volcanism

The Meggen deposit is located 10 km northwest of the long-lived K3-K7 felsic volcanic center. The diagram on the left (modified from Rippel 1954) shows the isopachs of the K4 keratophyre horizon. The submarine lavas, crystal tuffs and sills of quartz-feldspar porphyry are up to 300 m thick. The stratigraphic table on the right (modified from Krebs 1981) shows how felsic volcanism correlates in time with submarine hydrothermal activity. The main period of volcanism predates the Meggen deposit, and occurred during the Emsian to lower Eifelian (408 to 390 million years; International Commission on Stratigraphy 2018). The K3 to K7 keratophyres all erupted from an area 25 km long in east-west direction (Rippel 1954). Intercalated shales contain nodules of siderite and pyrite.

Meggen tuffs: The Meggen deposit formed at the Givetian-Frasnian boundary, and is 382.7 ± 1.6 million years old (International Commission on Stratigraphy 2018). Magmatic activity at this time resulted in the deposition of four felsic tuff horizons (Meggen Tuffs MT1 to MT4), which are restricted in extent to the hanging wall of the ore body. They are absent in the Givetian Meggen Beds, and in the Frasnian succession outside the ore body (Dornsiepen 1985).

The light yellow tuffs (3-20 cm thick) occur in black shale separating the ore from the Lagerkalk limestone (MT1), at the hanging wall contact of the Lagerkalk (MT2), and in the Frasnian calcareous black shales above (MT3 and MT4). They are composed of angular quartz and biotite crystals, rare feldspar (3-5 %), accessory apatite and zircon, and a groundmass of illite-sericite, chlorite and calcite. The biotite is partly chloritized. The altered tuffs have high Al_2O_3 (22.1-27.0 wt.%) and K_2O (5.9-7.2 %), moderate TiO_2 (0.29-0.57 %), low P_2O_5 (0.08-0.16 %), and variable zirconium contents (169-1750 ppm). They are interpreted as felsic air-fall tuffs, probably of trachyte or alkali rhyolite composition prior to alteration (Clausen 1978; Krebs 1981; Dornsiepen 1985). The MT4 tuff, located 15 m above the Lagerkalk, is associated with a 0.5-1 m thick bed of black shale marked by pyrite-marcasite nodules and lenses (3300 ppm Zn, 1700 ppm Pb in sulfide).

The spatial restriction of the MT-tuffs to the Meggen ore body, and the proximity to the K3-K7 volcanic center (7 Ma older) support the interpretation of Ehrenberg et al. (1954) of magma emplacement at depth, which caused the circulation of hydrothermal fluid through the thick sedimentary succession below the sulfide-barite deposit.

2.31 *Slide 31. Back-arc basin in the Old Red Continent*

The Middle Devonian paleo-geography of central Europe, modified from the Map Supplement 12 in Ziegler (1990), shows the location of the Meggen (M) and Rammelsberg (R) SEDEX deposits in the sediment-filled rift basin at the southern margin of the Old Red Continent (medium grey = moderate topographic relief, pale grey = low relief). The continent consisted of the Laurentian and Baltic Precambrian cratons, joined by the Caledonian fold belt (520-420 Ma), and of exotic Gondwana-derived continental blocks. The exotic blocks, consolidated at the Gondwana margin during the Cadomian orogenic cycle (650-550 Ma), were accreted during the Silurian (Ziegler 1990). In the Devonian, the assembled blocks formed the "Old Red" Laurussian mega-continent.

During the Middle Devonian, lacustrine and fluviatile sediments (orange) accumulated in several basins on the continent and along the shoreline of the rift basin to the south, grading into deltaic and coastal marine sandstones (yellow). Shallow-water marine mudstones (dark olive-green), carbonates (blue) and anhydrite (pink) were deposited on the outer shelf. The SEDEX sulfide-barite deposits formed at the shelf margin in a rifted deep-water basin characterized by pelagic shales (light grey-green), sand-siltstone turbidites (brown), and submarine volcanic centers (black stars). The rift basin was subdivided by the Mid German High into the northern Rhenohercynian and southern Saxothuringian sub-basins, and formed on a basement of previously accreted Cadomian continental crust. The rift was located in the foreland of the Ligerian-Vosgian Cordillera, a belt of high topographic relief (dark grey) and active plutonism (black crosses).

2.32 *Slide 32. Devonian plate-tectonic setting*

A. The Middle Devonian plate-tectonic setting, modified from Ziegler (1990), shows the position of the Meggen and Rammelsberg SEDEX deposits (red dot) in the back-arc rift basin at the margin of the Laurussian mega-continent. Continental areas above sea level are in yellow, and fault systems are traced in pink. The present-day coasts of northwestern Canada, Greenland, and northern Europe are outlined in red for geographic orientation. Shallow marine basins on the continental shelf are light grey, deep continental basins medium grey, and basins floored by oceanic crust dark grey. The subduction zone northwest of Gondwana (GW) is traced in blue (saw teeth on upper plate).

The rift basin was located in a back-arc position relative to the active fold belt of the Ligerian-Vosgian Cordillera, part of the larger Hercynian orogen (black) suturing Laurussia. The Ligerian orogenic cycle in the Variscan domain of this orogen corresponds to the Acadian cycle in the Appalachian domain. The cycle involved the northward subduction of oceanic crust located between Gondwana and Laurussia and, during the Emsian-Eifelian, the collision of the Gondwana-derived Avalon-Meguma and Aquitaine-Cantabrian terranes with the emerging Appalachian-Ligerian-Vosgian orogenic belt. The Rhenohercynian-Saxothuringian rift basin probably contained ocean-floor segments consumed by local subduction during Upper Devonian compression (Ziegler 1990; Franke 2000).

B. The diagram (modified from Ziegler 1990) shows the plate-tectonic evolution during the Middle Devonian to Lower Carboniferous. The collision of Laurussia and Gondwana led to the creation of the Permo-Triassic supercontinent Pangea.

2.33 Slide 33. Meggen: Key genetic features

Plate-tectonic setting: Continental-margin, sediment-filled, rifted back-arc basin.

Submarine bimodal volcanism: Rift-related basalt and alkali rhyolite lavas and tuffs, district-scale spilitization.

Submarine ore deposits: Hematite ironstone on volcanic ridges composed of basaltic spilites, distal SEDEX sulfide-barite ore in black shale basins containing interbedded felsic tuffs.

Meggen deposit: Formed in a pelagic euxinic basin at the faulted margin of the continental shelf, shielded from turbidite input by the Attendorn and Meggen reefs.

Fe-Zn-Pb sulfides: Vent-distal sedimentation as sulfide gels in a brine pool at 150-200°C, peripheral barite by mixing with seawater.

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