The sedimentary-exhalative Meggen Zn-Pb sulfide and barite deposit, Germany: Geology and plate-tectonic setting

Explanatory Notes

A slide presentation and explanatory notes compiled in April 2005

By

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Introduction

These explanatory notes accompany 31 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 are available free of charge as Adobe pdf-files from the SGA website. They are designed as teaching tools for digital projection and for the study on-screen. This text explains each slide step-by-step. The references quoted are listed below. 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. Meggen is regarded as one of the classic sedimentary sulfide-sulfate deposits. For the exploration geologist, it represents one of the best case histories of this deposit type.

Previous reviews in English

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

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

Explanatory Notes Color Slides

Slide 3. Past production and grade

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 below (from Ehrenberg et al., 1954; Walther, 1986) refer to the crushed ore stripped of 20% (sulfide) and 10% gangue (barite), respectively, by washing and heavy-media 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% sulfur, 32.8% iron, 7.2% zinc, and about 0.5% lead (Ehrenberg et al., 1954; p.138-139). After roasting, most of the 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 washed ore (Ehrenberg et al., 1954), producing approximately 105,000 tons of zinc metal until 1962.

From 1960 onward, the flotation plant was gradually expanded until it became fully operational in 1963. After heavy-media separation, the crushed ore was milled to 80 percent <50 micron permitting successful mineral flotation. From 1963-1992, the plant processed 18.3 million metric tons of sulfide ore at head grades of 8.4% 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 rates were 92% for sphalerite and about 40% for galena (Walther, 1986; Gaul, 1992).

The total sulfide production amounts to 44.7 million metric tons of washed ore at estimated average grades of 7.7% zinc and 0.75% lead. The copper (0.03%) and silver grades (4 g/t) quoted are taken from Ehrenberg et al. (1954, p. 284), and apply mainly to the eastern part of the orebody. The deep sulfide ore in the northwestern part contains only 18-40 ppm copper (Gasser, 1974). The average gold grade is estimated at 0.1 g/t, based on assays of underground drill-hole and channel samples which vary from less than detection (<0.02 g/t) to 3.4 g/t (Ehrenberg et al., 1954). Clausen (1978) reports that only traces of gold (<0.1 g/t) are present.

The total barite mined amounts to 8.98 million metric tons of washed 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 a feedstock for paint pigment.

Slide 4. Cratons and fold belts of Europe.

The Tectonic Map of Europe (modified from Meinhold, 1971) shows the large-scale geologic units and the present-day plate-tectonic setting. The Tertiary Alpine fold belt (red, older metamorphic massifs dark red) formed during the collision of the African and Eurasian continents, leaving the Mediterranean as a remnant ocean basin. Most of Europe is underlain by the Precambrian Fennoscandian-Baltic craton, shown in dark pink where outcropping, in light pink where under thin sedimentary cover, and in yellow where covered by deep sedimentary basins. The Precambrian craton is bounded to the northwest by the Cambrian-Silurian Caledonian fold belt (dark violet), and on all other sides by the Devonian-Carboniferous Variscan fold belt (green). The Alpine orogen overprints part of the older Variscan one. Neogene volcanic fields, like Iceland on the mid-Atlantic ridge, are shown in black.

The satellite image of NOAA-6, in orbit 850 km above surface, shows the geographical units of central Europe. The Rhenish Massif (RM) and the Harz (HZ) are medium-height forested mountains underlain by Variscan slate belt, host to the Meggen and Rammelsberg Sedex deposits. The Black Forest (BF) and the Bohemian Massif (BM) to the south are largely composed of granite-gneiss terranes bounded further south by the high Alps. The Black Forest forms the eastern shoulder of the Rhine valley, a Tertiary graben related to Alpine foreland rifting.

Slide 5. Geologic map of 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, where the Devonian-Carboniferous strata are covered by 2-8km thick Permian to Cenozoic sediments (Ziegler, 1990), and limited by the Tertiary Alpine fold belt and its foreland molasse basins in the south. The Rhenish (RM) and the Harz (HZ) massifs represent the external part of the Variscan orogen, a “slate belt” of Devonian sandstones and shales (dark brown) and Carboniferous graywackes (gray). Most regional folds are upright and strike northeast. The Faille du Midi thrust in Belgium and the Giessen-Harz nappes in Germany indicate large-scale tectonic transport to the northwest (Franke, 2000).

The un-metamorphosed slate belt is separated by a suture zone (white dotted line) of medium-pressure (300-600 MPa) phyllites from the metamorphosed internal part of the orogen, exposed in basement uplifts on both sides of the Rhine graben (RG) and in the Bohemian Massif (BM). Mesozoic platform sediments cover the area between the Black Forrest (BF) and the Bohemian uplift. The Variscan basement consists of eclogite-bearing

para- and ortho-gneisses (pink), enclosing synforms of Late Proterozoic graywackes and Cambrian to Carboniferous clastic strata (greenish gray), and of Carboniferous granite batholiths (red). 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, probably attained during the stacking of crystalline nappes, to low-pressure (200-300 MPa) greenschist facies at 340-300 Ma during post-orogenic extension and the emplacement of granite batholiths. Remnants of eroded nappes indicate large-scale tectonic transport to both the northwest and the southeast (Roetzler et al., 1998; Franke, 2000).

In down-faulted synforms of the Bohemian Massif, folded 560 Ma old graywackes and calc-alkaline volcanic rocks preserve pre-Variscan metamorphic zones of greenschist to amphibolite facies grade (550-540 Ma). They are intruded by Cambrian granites (540-520 Ma), and overlain discordantly by Cambrian red-bed conglomerates (Doerr et al., 2002). These relationships indicate that the continental crust of the Bohemian Massif was consolidated during the Cadomian orogeny (650-550 Ma), a geologic history shared with the London-Brabant Massif in Belgium, the Amorican Massif in France, and the Ossa-Morena Zone in Spain (Ziegler, 1990; Walter, 1995; Doerr et al., 2002).

In the western part of the Rhenish Massif, Devonian strata rest unconformably on Caledonian basement. In the eastern part and in the Harz, isolated enclaves of 600-500 Ma old para-gneiss indicate a Cadomian basement (Walter, 1995; Franke, 2000). Xenocrystic zircons in Permian volcanic rocks suggest that Cadomian continental crust underlies most of the Variscan slate belt in Germany (Breitkreuz and Kennedy, 1999).

Slide 6. Rhenish Massif: Devonian slate belt

The outcrop map shown is part of the Geologic Map of Germany (Walther and Zitzmann, 1973). The main stratigraphic units in the Rhenish Massif (RM) comprise an Early Devonian quartzite-sandstone-shale succession (dark red-brown), a Middle Devonian sequence of sand-banded or calcareous shales (brown-gray), basaltic spilites (green) and limestone reefs (blue), and a Carboniferous flysch-molasse sequence of black shales, graywackes, and sand/siltstones with coal measures (medium gray). The progression in sedimentary facies from sandstone- to shale-dominant indicates a deepening of the Devonian geosynclinal basin with time until the onset of flysch. In total, the Devonian-Carboniferous clastic strata are more than 10km thick. The Carboniferous flysch-molasse sediments are mainly exposed at the northern and eastern margin of the massif but extend far to the north under the German-Polish basin. Most regional folds in the massif are upright, trend about N50°E, and display an axial planar slaty cleavage.

The location of the Middle Devonian Meggen sulfide-barite deposit (M) is shown relative to the Lahn-Dill syncline (LDS), which contains the largest accumulation of

contemporaneous submarine basalts (green). Tertiary trachytes (pink) and alkali olivine basalts (purple) cover parts of the Rhenish Massif, and are related to Alpine rifting.

A. Early Devonian cross-bedded quartzite, a shallow-marine shelf sediment. Quarry at the ring road of the Glaskopf mountain, Taunus range.

B. Middle Devonian sand-banded black shale of the pelagic Wissenbach facies, note the slaty cleavage and the white quartz veins in the sandstone beds, Rammelsberg mine, Goslar, Harz.

Slide 7. Middle Devonian Lahn-Dill Syncline

The Lahn-Dill syncline is characterized by an abundance of Middle Devonian to Early Carboniferous volcanic rocks, but smaller volcanic centers of similar composition and age 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 submarine volcanic succession. Most basaltic pillow lavas and tuffs are strongly altered and composed of a “spilitic” mineral assemblage (chlorite, albite, calcite, quartz; minor actinolite, epidote, prehnite, pumpellyite), interpreted to result from the hydrothermal circulation of seawater and from low-grade metamorphism. The keratophyre suite, mainly lavas, tuffs, and breccias, is characterized by albitized phenocrysts of feldspar (albite-orthoclase perthite after 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 total thickness of the volcanic succession is 500-800 m in the northeastern Lahn syncline, and 150-350 m in the Sauerland east of Meggen. Most volcanic rocks are folded into elliptical anticlines up to 1.5km long and 0.6km wide. These anticlines represent composite volcanoes which formed submarine ridges elevated about 200 m above the adjacent basins. Beds of massive hematite ore were deposited on top of altered basaltic ridges, mainly during the transition from the Middle to Late Devonian (Bottke, 1965). These volcanogenic iron ores are contemporaneous with the sulfide-barite ore at Meggen.

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) basalts, perhaps indicating Middle Devonian oceanic crust southeast of the Lahn area (Wedepohl et al. 1983; Schmincke and Sunkel, 1987).

A. Pillow of basaltic spilite (1.3m long) marked by calcite-filled vesicles at the margin. Quarry at Philippstein, near Braunfels, Lahn area, Hessen.

B. Lapilli tuff of basaltic spilite containing 20 vol. % disseminated calcite (1-2 mm pink aggregates), looking at a cleavage plane in the hand specimen. Foliated tuff

(Schalstein) forming the footwall of hematite iron ore on the 150m level of the Fortuna mine. Oberbiel, west of Wetzlar, Lahn area, Hessen.

C. Coherent lava of quartz keratophyre, marked by 2 vol. % gray quartz and by 5 % white-gray feldspar phenocrysts. The pen is 15 cm long. Goergeshausen quarry, Mensfelder Kopf, Lahn area, Hessen.

Slide 8. Middle Devonian Lahn-Dill iron ore

From 1830 to 1983, more than 40 mines in the Lahn-Dill district produced a total of 97 million metric tons of ore at 35-40 % iron, the largest two being the Koenigszug mine near Oberscheld (8.3 million tons) and the Fortuna mine near Wetzlar (4.7 million tons). Several small mines in the Sauerland east of Meggen produced an additional 3 million tons (Walther, 1986; Walther and Dill, 1995). Some of the proximal iron ores on basaltic ridges are associated with distal rhodonite-rhodochrosite beds and, rarely, with thin (<1m) sulfide beds in tuffaceous black shales. 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 (150m thick), contain several beds of massive pyrite (0.2-3m) and of dark gray barite (1m). The deposit is covered by Tertiary sediments and has not been systematically explored. Individual samples of massive pyrite contain 50-200 g/t silver and 2.5 g/t gold. The barite is intergrown with accessory pyrite, sphalerite, and cinnabar (Werner, 1988).

The cross section (modified from Bottke, 1965) shows the central part of the Koenigsberg iron ore mine near Wetzlar, Lahn. Volcanogenic hematite ironstone overlies basaltic spilite and is intercalated with Givetian-Frasnian (tm2-to1) gray limestones, which are in turn overlain by a condensed ridge-facies of Frasnian-Famennian (to1-to6) red limestones. Early Carboniferous tholeiitic lavas and dikes (diabase) cap the succession. The section illustrates the segmentation of Lahn-Dill anticlines by stacked thrust faults.

The photograph shows siliceous hematite ore on the 150m level of the Fortuna mine. The ore is folded and overlies altered basaltic tuff (yellow sign = 25 cm). The mine is located west of Wetzlar, Lahn, Hessen.

Slide 9. Rhenish Massif: Geologic map, Middle Devonian limestone reefs

The main stratigraphic units in the Rhenish Massif comprise the Early Devonian quartzite-sandstone-shale succession (dark red-brown), the Middle Devonian sequence of sand-banded and calcareous shales (brown-gray), and the Carboniferous flysch-molasse succession of black shales, graywackes, and sand/siltstones with coal measures (medium gray). The location of the Late Givetian Meggen deposit (M) is shown relative to Middle

Devonian limestone reefs (blue), and relative to the contemporaneous basaltic spilites (green) in the Lahn-Dill syncline (LDS).

The long-lived reef complexes (mainly Givetian to Frasnian), up to about 1km thick, indicate the approximate position of the Middle Devonian shelf margin relative to rift-related submarine volcanism in the adjacent pelagic basin. The reefs are composed of a lower biostromal carbonate bank (Schwelm facies), and an upper atoll-shaped bioherm (Dorp facies), built by stromatoporoids, corals and crinoids (Krebs, 1981). Prominent reefs outcrop in the Eifel (ER), near Attendorn (AR), and near Brilon (BR).

Slide 10. Meggen: District geologic map

Generalized geologic map of the Lennestadt 1:25,000 sheet, Nordrhein-Westfalen (modified from Clausen, 1978). The Meggen sulfide-barite ore and the associated limestone marker bed (red) outcrop in the Meggen Syncline (MS), a subsidiary fold of the 30km-long Attendorn-Elspe Syncline (AES), a synclinorium bounded by the Ebbe Anticline (EA) to the northwest and the Siegen Anticline (SA) to the southeast. All folds are upright and vergent to the northwest. The fold axes of the synclines strike N50-60°E and plunge 10-20° NE or SW, reversing in plunge along strike. Their southeastern limbs are overturned, and the axial-planar cleavage strikes N50-62°NE and dips 50-80° SE. Locally, the slaty cleavage is fanned about the axial plane of individual folds, indicating that folding outlasted cleavage formation (Ehrenberg et al., 1954). Stacked thrust faults shorten the outcrop area of the Middle Devonian at the northwestern limb of the Siegen Anticline.

Apart from outcrops of Ordovician/Silurian shales south of Plettenberg, the cores of the Ebbe and Siegen anticlines are composed of Early Devonian (Gedinnian-Emsian) conglomeratic sandstones, quartzites and shales, subdivided by six marker horizons of felsic tuff (keratophyres K1 to K6). The lower Middle Devonian (Eifelian) is represented by a succession of micaceous sandstones, sand-banded shales, and calcareous shales. The sedimentary facies changes gradually from the Rhenish (sand dominant) in the northwest to Wissenbach (shale dominant) in the southeast (Ehrenberg et al., 1954).

The upper Middle Devonian (Givetian) is characterized by pronounced changes in sedimentary facies. Most prominent are the 200-950m thick, massive limestones of the Attendorn Reef (AR). To the west and north, bioclastic limestones of the fore-reef facies grade into calcareous shales and sandstones of the Finnentrop Beds, the total thickness of sandstone increasing to the west. To the east, the Givetian succession is subdivided into the lower Tentaculites black shale (40-60 m thick) and into the upper Meggen Beds, a thin-bedded black shale-siltstone sequence (20-265 m). The Meggen sulfide-barite ore (1-6 m) overlies the Meggen Beds, and is in turn overlain by the Givetian-Frasnian Lagerkalk (1-10 m), a pelagic limestone of district-scale strike extent (Krebs, 1981).

The Late Devonian sedimentary sequence above the Lagerkalk comprises black and green Frasnian shales, marked by thin limestone beds and nodules, red calcareous shales, and Famennian sand-banded shales and sandstones. Early Carboniferous gray to black shales, radiolarian cherts, and graywackes of the Kulm facies define the central Attendorn and Elspe synclines within the broader synclinorium.

Slide 11. Meggen mine: Composite cross-section

The composite NW-SE cross-section shows the Meggen Syncline (MS) at about 400m mine-grid west, and the overturned southeastern limb of the Elspe Syncline (ES) at 1900m west. The Meggen limestone reef (MR) 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 entire mine succession of ore, limestone, and bituminous shale (brown) is thrust over the Meggen Reef (W. Fuchs in Clausen, 1978). Drill holes indicate that the reef forms an overturned anticline segmented by subsidiary thrust faults. Drill hole FB-15 intersected late Givetian shales northwest of the limestone anticline, including a pyrite bed at 1024.15-1024.35 m depth (Krebs, 1981).

Dark gray bituminous silt-banded shales, minor black shales with pyrite nodules, and minor gray sandstones constitute the Givetian Meggen Beds (brown) in the footwall of the sulfide-barite ore. The thickness of the Meggen Beds varies from 30 to 60 m beneath the orebody, and increases to more than 260 m about 4 km to the southwest. The Meggen Beds are separated from the underlying Tentaculites shale by the Odershausen marker bed (5-40 cm), a thin pyrite-bearing limestone (Clausen, 1978).

The Frasnian bituminous shales (brown) in the hanging wall of the Lagerkalk limestone are characterized by a high content of organic matter (1-5%), by thin intercalated limestone beds and nodules, and by three marker beds of keratophyre tuffite (MT2 to MT4) in the lowermost 20m of the succession. Above the orebody, the gray and black shales vary in thickness from 20 to 100 meter. Laterally, they grade into green chloritic shales of lower bitumen content (Ehrenberg et al., 1954; Krebs, 1981).

The Eifelian-Givetian Meggen Reef forms a tabular body more than 250m thick, built mainly by in-situ colonies of stromatoporoids and peripheral bioclastic limestones. Fine-grained bioclastic beds in the Tentaculites shale and the lowermost Meggen Beds are interpreted as detritus from the reef. The upper 30 m of the reef consist of dark gray pelagic limestones (middle Givetian) cut by neptunian dikes. Late Givetian/early Frasnian conodonts and rare fragments of pyrite-rich limestone in these dikes suggest that they are related to faulting during the deposition of the sulfide-barite ore (Krebs in Clausen, 1978).

Slide 12. Meggen: Limestone – shale succession

Limestone, silt-banded black shale, and calcareous shale are the principal rock types of the sedimentary succession in the Meggen mine:

A. Massive Middle Devonian limestone of the Meggen Reef, detritus cemented by calcite sparite, rare single corals (2 cm), and thin micritic beds. Note the sub-horizontal fault lined by white calcite. Sicilia shaft 11 level, close to shaft.

B. Black bituminous shale of the Givetian Meggen Beds from the footwall of the sulfide ore. Nodular pyrite bands define the bedding, cut by the cleavage at a 60-70° angle. The nodules are composed of fine-grained (0.5-1 mm) pyrite (70 %), white-gray barite (soft), and brown sphalerite. Sicilia shaft, no location.

C. Late Devonian red and gray shales (yellow plate = 20 cm). Thin beds and nodules of gray limestone are transposed by the steeply dipping slaty cleavage. Weilburg, Hessen, outcrop at the southern portal of the Lahn river canal and lock. These shales are identical in facies to the Frasnian-Famennian “Cypridina” shales in the mine area.

Slide 13. Meggen mine: Geologic plan Erbstollen level (271m above mean sea level)

Geologic plan of the Sicilia shaft Erbstollen level (modified from Plate 26 in Ehrenberg et al., 1954) showing the sulfide-barite ore in the southwestern part of the Meggen Syncline (MS), separated by the narrow Meggen Anticline (MA) from the overturned limb of the Elspe Syncline (ES). Note the doubly plunging minor folds, the strike-parallel reverse faults (saw-teeth on upper block), and the steeply dipping (60-80°SW) normal faults (black lines) perpendicular in strike to the fold axes.

From the oldest to the youngest, the stratigraphic units are: The Givetian Tentaculites black shale (tmt, dark green), the silt-banded black shales of the Meggen Beds (tmL, light green), the ore bed composed of sulfide (red) and barite (violet), the Lagerkalk limestone (dark blue) marking the Givetian-Frasnian boundary, the Frasnian calcareous black shales of the Buedesheim facies (tot, light yellow), and the green and red calcareous shales of the Cypridina facies (toc, dark yellow).

Slide 14. Meggen mine: Cross sections

Series of four cross sections from 1000m to 700m mine-grid west illustrating the irregular folding of the sulfide ore and Lagerkalk limestone (both red) in the overturned southeastern limb of the Elspe Syncline. The fold axes plunge about 15° northeast. Note the marked change in shape of the main subsidiary anticline along strike. The +500m and +400m grid north lines are shown for reference. The Sicilia shaft 8 (-100m MSL) and 12 levels (-300m MSL) are highlighted in yellow.

Slide 15. Meggen mine: Structural map 12 level (304m below mean sea level)

Structural map of the Sicilia shaft 12 level (from Mueller, 1979), 575m below the Erbstollen level. The sulfide ore (red) defines all structures, separating the silt-banded shales of the Givetian Meggen Beds (white) from the Lagerkalk limestone and Frasnian calcareous shales (light blue). Fold axes (pink lines) strike about N45°E in the southwestern and N55°E in northeastern part of the level, and plunge at shallow angles of 2-13° northeast. The folds are displaced by strike-parallel under- and over-thrusts (green lines), and by normal faults (dark blue lines) oriented perpendicular to the fold axes. The Halberbracht Fault records a normal offset 45m southwest-block-down.

The shales display an axial-planar 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 irregular fold / fault pattern is caused by the nearby Meggen Reef (W. Fuchs in Clausen, 1978). The +600m grid north line and the grid west lines of the cross sections below are highlighted in yellow.

Slide 16. Meggen mine: Cross sections 12 level

Series of northwest-southeast cross sections, looking northeast, illustrating the style of folding and reverse faulting on the Sicilia shaft 12 level (from Mueller, 1979) as defined by the sulfide ore (red). The +600m grid north line, the -304m level, and all mine workings are shown for reference.

The four sections on the left, beginning at 1300m west (bottom) and ending at 1140m west (top), show the northwestern anticline-syncline pair. Note the cleavage-parallel under-thrust in the core of the anticline, and the progressive overturning and faulting of the southeastern limb of the syncline.

The three sections on the right, beginning at 1100m west (bottom) and ending at 900m west (top), show the broad anticlinorium of folds thrust over the northwestern anticline-syncline pair. The southeastern limb of the syncline is progressively dismembered.

Slide 17. Meggen mine: Ore horizon stratigraphy

The lithologic units exposed in the northeastern faces of cross cuts on the Sicilia shaft 12 level were mapped in detail (Mueller, 1979). They represent the sediments in the immediate hanging wall and footwall of the sulfide ore.

A. Cross cut transecting the core of the syncline at 1325m mine-grid west. The Givetian-Frasnian Lagerkalk limestone (light blue) conformably overlies the sulfide ore (red) and is 5m thick. The limestone is light gray, micritic, and subdivided by thin marlstone partings into 0.5m-thick beds. It is overlain by the Frasnian limestone-shale succession of the Buedesheim euxinic facies. The

lowermost part (violet) consists of thin beds (5-20 cm) of dark gray limestone, the black bituminous Lower Kellwasser limestone (heavy black line), and of gray or black shale layers (1-5 cm). Note the two subsidiary anticlines, caused by bedding-parallel slip, which are absent in the thick-bedded Lagerkalk. The upper part (brown) consists predominantly of dark gray marlstones and shales.

B. Southeastern part of the cross-cut at 930m to 1000m grid west, which exposes the Givetian Meggen Beds in the core of a broad anticlinorium (see section in Slide 16). The sulfide ore (red) is underlain by the Upper Shale Unit (black-gray), 3m thick, a bituminous shale marked by pyrite nodules, pyrite bands, and rare silt layers. Below is the Upper Sand Unit (red-brown), 7.5m thick, composed of dark gray sandy siltstones and gray to black shales, both interbedded on the 1-5 cm scale. The basal part of the unit (yellow) consists of gray fine-grained sandstone beds (10-20 cm), which are locally silicified. The sandstones are in faulted contact with the Middle Shale Unit (black-gray).

C. Northwestern part of the cross-cut at 930m to 1000m grid west, showing the Upper Sand (red-brown) and Middle Shale Units (black-gray) at the overturned limb of the anticlinorium, where it is thrust over the anticline-syncline pair to the northwest. The Middle Shale Unit, about 3m thick, is composed of black shale, silt layers, and pyrite nodules. It overlies the Lower Sand Unit (yellow-brown), another thin-bedded (1-5 cm) sequence of dark gray sandy siltstones and shales more than 6m thick. Note the small-scale folding and thrust faulting in the anticline hinge.

According to a district-scale study by Krueger (1973) and Gwosdz et al. (1974), the Givetian Meggen Beds are subdivided into the Upper Shale Unit (2-23m thick), the Upper Sand Unit (4-120m), the Middle Shale Unit (3-22m), the Lower Sand Unit (3-70m), and the Lower Shale Unit (1.5-15 m). Underneath the orebody, the Meggen Beds are 20-30m thick. The shale units are black, bituminous and marked by spaced pyrite bands and nodules. All Shale Units contain thin graded beds of siltstone, and the lower one beds of bioclastic limestone, detritus from the Meggen Reef. Laterally away from the orebody, the Shale Units are gray-green, less bituminous, and contain disseminated rather than nodular or banded pyrite. The two Sand Units are dark gray-green, and composed of numerous graded beds of siltstone and shale, and intercalated fine-grained, cross-bedded or bioturbated sandstones. Southwest of the orebody, the Meggen Beds, in particular the two Sand Units, increase in thickness to more than 250m over a distance of 5 km. To the northeast, they increase gradually to about 50m (Gwosdz et al., 1974).

The sediments below the sulfide orebody contain disseminated pyrite-barite-sphalerite aggregates, which correlate with local zinc contents of up to 7300 ppm (background = 150 ppm). Thin mound-shaped barite lenses occur underneath barite ore. Permeable silt- and

sandstone layers are silicified, and the content of calcite cement is less below the ore than along strike. At least the Upper Shale and Upper Sand Units are also enriched in illite (66-88 vol. %) and depleted in chlorite, resulting in a low iron content relative to other Givetian shales of the Rhenish Massif (27-44 % illite). Strata-bound decalcification, silicification, and argillic alteration represent the footprint of hydrothermal activity in the Meggen Beds (Gwosdz et al., 1974; Renner, 1986; Werner, 1988).

The Lagerkalk limestone in the hanging wall of the ore can be traced over a distance of more than 25km along the southeastern limb of the Elspe Syncline. Conodont and ostracod biostratigraphy indicates that the Lagerkalk above the ore (mostly 2-3m thick) is late Givetian to early Frasnian, whereas the equivalent limestones along strike (up to 10m thick) include middle to late Frasnian beds. The marker horizon is always composed of micritic limestones characterized by pelagic cephalopod fossils (Clausen, 1978).

Slide 18. Meggen mine 8 level (100m below mean sea level): Sulfide ore

The sulfide bed varies in thickness from 1-7m and averages 3.5m in the mined parts of the orebody. The mineral composition by volume is 65-70 % pyrite, 13% sphalerite, 1% marcasite, 0.6 % galena, and 15-20 % gangue (Ehrenberg et al., 1954).

Gasser (1974) published a petrographic reference section mapped in cross cut 14 on the Sicilia shaft 8 level. He subdivides the ore into a thin-bedded lower part (0.5m thick) of distinct sulfide and shale layers (1-2 cm), a massive central part (0.8m) with nodular texture, a graded bed of silicified sandstone (5 cm), and a thinly laminated upper part (1.8m) of sulfide layers (1-3 mm) and shale partings. The graded sandstone bed consists of rounded quartz grains, sericitized alkali feldspar (1-5%), and accessory zircon, tourmaline, apatite, chromite, and rutile. Gasser's subdivision of the sulfide bed is reasonably persistent in the deep northwestern part of the orebody (Gasser and Thein, 1977). In the Meggen Syncline, however, thinly laminated sulfides constitute the lower half and are separated by a layer of black shale (10-20cm) from massive to thick-bedded sulfides in the upper half of the ore (Ehrenberg et al., 1954, p. 134).

The photograph on the left shows an underground exposure of the footwall black slate and of the lowermost part of the sulfide ore, bedded on a 0.5-2cm scale by layers of pyrite, sphalerite-rich pyrite, and black shale. The small-scale folds are probably related to reverse faulting in the Meggen Beds, and caused by slip on the shale layers. Sicilia shaft 8 level, SW-part of sublevel 2, the hammer handle is 30cm long.

The photograph on the right shows the black slate of the Meggen Beds, and the upward transition from thin-bedded to massive sulfide ore. Sicilia shaft 8 level, southwestern part of sublevel 2, the hammer is 32cm long.

Slide 19. Meggen mine: Sulfide bedding

Polished hand specimens illustrating bedding and soft-sediment deformation textures (convolute lamination) in the central and upper parts of the sulfide ore. Convolutions in a bed are formed by the expulsion of water from rapidly deposited sediment, sulfide mud in the case of Meggen. Melnicovite pyrite is a finely crystalline, arsenic- and thallium-bearing pyrite of colloform texture, dark yellow-gray color (often tarnished), and poor polish (Ehrenberg et al., 1954), which oxidizes gradually in air to iron sulfate.

A. Hand specimen from the central massive part. **Top:** 9cm-thick bed with discontinuous lenses and bands (1-5mm) of well-polished colloform pyrite; the darker less polished matrix consists of numerous streaks of gangue, melnicovite pyrite, and shale up to 1mm thick; brown sphalerite (10%) occurs in disseminated aggregates (0.5-1 mm). **Center:** 6cm-thick "convolute bed" composed of contorted and agglomerated laminae of well-polished pyrite (80%), enclosing patches of darker melnicovite pyrite, and cemented by interstitial aggregates of brown sphalerite (7%), rare galena, calcite (reaction 5% HCl), and quartz. **Bottom:** 13cm-thick bed with sparse laminae of colloform pyrite (1-5mm thick) in a darker less polished matrix of melnicovite pyrite and gangue; the melnicovite pyrite and the quartz-carbonate gangue form streaks 0.5-1mm thick alternating with discontinuous black shale partings; the matrix encloses several well polished pyrite nodules (5-15mm long) which display sharp boundaries and no internal texture, about 15% brown sphalerite in evenly disseminated 0.5-3 mm aggregates. Sicilia shaft 8 level, sublevel 3, stope 2/west1.

B. Hand specimen from the laminated upper part of sulfide ore. The tip of the matchstick is 2cm long. Very thin (0.5-3 mm), wavy laminated bedding, some laminae pinching out. The well-polished yellow laminae consist of densely packed pyrite spheroids 20-70 micron in diameter. The darker yellow laminae contain very fine-grained melnicovite pyrite, accessory marcasite, and quartz and carbonate. Sphalerite occurs mainly in diffuse brown layers up to 5 mm thick, forming the matrix of pyrite or marcasite spheroids. Black shale partings are absent. The interstitial aggregates to the right of the matchstick consist of honey-colored sphalerite, white-gray carbonate, and rare gray galena. Fractures are lined with galena and carbonate. Sicilia shaft 12 level, cross cut at 790m grid west, 450m grid north.

C. Pyrite spheroids separated in the treatment plant. The spheroids are composed of bladed, radially oriented pyrite crystals terminating in 3-4 faces. Note the late pyrite cubes replacing part of one spheroid (from Ehrenberg et al., 1954).

Slide 20. Meggen mine: Sulfide ore textures

Polished section photomicrographs of sulfide textures in the two hand specimens shown in Slide 19, plane polarized light reflected in air.

A. Primary gel textures and secondary textures in thinly laminated upper sulfide ore: Spheroids composed of radially oriented, bladed marcasite (anisotropic, tarnished) are set in a matrix of re-crystallized sphalerite (medium gray) and minor quartz-carbonate gangue (dark gray). Some of the spheroids contain a core of framboidal pyrite, others one of gangue minerals. The marcasite is partly replaced by late-stage pyrite (pale yellow, not tarnished). Sicilia shaft 12 level, cross cut at 790mW/450mN.

B. Primary gel textures and secondary textures in massive to thick-bedded middle sulfide ore: Atoll-shaped pyrite spheroids composed of cores of framboidal pyrite (pale yellow, well polished), and thin concentric shells of gangue (dark gray), tarnished melnicovite pyrite, and pyrite. The matrix consists of re-crystallized sphalerite (medium gray), minor quartz-carbonate gangue, pyrite, and accessory interstitial melnicovite pyrite. Some of the matrix pyrite displays fine colloform textures. Sicilia shaft 8 level, sublevel 3.

C. Remnant gel textures and secondary textures in thinly laminated upper sulfide ore: A porphyroblastic aggregate of carbonate (dark gray, in center), displaying perfect rhombohedral crystals faces, is in contact with interstitial galena (blue-gray) and with matrix sphalerite (medium gray). Many pyrite spheroids are rimmed and partly re-crystallized to cube-shaped pyrite (pale yellow). Galena and pyrite cubes are enclosed in carbonate rhombs, indicating particularly late carbonate re-crystallization. Sicilia shaft 12 level, cross cut at 790mW/450mN.

Gangue minerals constitute 15-20 vol. % of the sulfide ore and include bi-pyramidal crystals of quartz, aggregates of fibrous quartz, porphyroblasts of manganoan calcite and ferroan dolomite, and partings of illite-sericite. X-ray analyses of gangue separated by flotation indicate that chlorite is absent, although it is common in shale layers of the Lagerkalk limestone (Gasser and Thein, 1977). However, the occurrence of illite in the ore mirrors the abundance of this mineral in the altered Meggen Beds.

Slide 21. Meggen mine: Barite ore

To the northeast and southwest, the folded sulfide orebody pinches out and is substituted by a barite bed of up to 1.5km strike length (see Erbstollen level plan). The transition zone, where barite overlies and, locally, also underlies the sulfide ore with sharp contact, is generally a few ten meters wide. In the Meggen Syncline, the barite attains a thickness of 4-5m on both sides of the sulfide ore. In the Elspe Syncline the maximum thickness is 2.5 meters. The barite ore is remarkably pure, averaging 95% barite, 2%

strontium sulfate, but only 0.28% pyrite. The average sulfide ore, on the other hand, contains but 0.34% barite attesting to the sharp spatial separation of sulfide and sulfate (Ehrenberg et al., 1954; Clausen, 1978).

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

B. Dark gray, fine-grained sedimentary barite from the southwestern margin. At the left intercalated streaks of fine-grained pyrite (partly oxidized to sulfate), white barite veinlets. Sicilia shaft 6 level (at sea level).

The barite is colored dark gray due to trace amounts of disseminated bitumen, and separated into beds by shale partings. Where primary textures are preserved, the ore is composed of densely packed, radially textured barite spheroids up to 1mm in diameter. In areas of tectonic strain, the spheroids are fractured, progressively re-crystallized, and finally replaced by fine-grained equigranular barite (Ehrenberg et al., 1954).

Slide 22. Meggen ore: Mineralogy and isotopes

The average mineral composition of the sulfide ore (note: gangue = 20 vol. %) has been calculated from the chemical and mineralogical data of Ehrenberg et al. (1954), but using overall base metal contents of 7.7% zinc and 0.75% lead, and an ore density of 4.48 g/cc (Table 25, p. 281). The iron content of sphalerite varies from 1.0 to 1.5 weight percent. The principal copper mineral has not been identified. Optical microscopy indicates traces of chalcopyrite and of tennantite-tetrahedrite (Ehrenberg et al. (1954). Inclusions of boulangerite in galena were identified by electron microprobe analysis (Gasser and Thein, 1977).

The sulfur isotope ratios of the barite ($\delta^{34}S$ = +20.8 to +26.8 ‰) implicate Middle Devonian seawater as the principal source of sulfate, estimated at $\delta^{34}S$ = +23 ‰ from marine anhydrite beds. The isotope ratios of pyrite, sphalerite and galena (($\delta^{34}S$ = +11.9 to +24.1 ‰) indicate that the sulfide sulfur is derived from hydrogen sulfide gas generated by the thermo-chemical reduction of marine sulfate, perhaps in part during leaching of the footwall sediments (Buschendorf et al., 1963; Nielsen, 1985). Lead isotope data suggest that Precambrian detritus in the Early Devonian clastic succession is the main source of metals in the orebody (Wedepohl et al., 1978).

Slide 23. Meggen sulfide orebody: Metal zoning

The lateral metal zoning in the deep northwestern part of the sulfide orebody has been studied using core from 18 drill holes (Gasser, 1974; Gasser and Thein, 1977; Thein, 1985). Sulfur, zinc, lead, copper, arsenic, antimony, nickel and cobalt decrease from the center to the margin, whereas thallium, barium, manganese, and the gangue content increase. The ore contains 1.1 to 8.5 ppm mercury, but the distribution of this metal is not known (Werner, 1988).

The metal zoning in the footwall sediments is constrained by analyses from the top 20m of the Meggen Beds, collected in a drill hole fence across the northwestern part of the sulfide orebody, and by samples from the top 30m beneath the Lagerkalk limestone in drill holes southwest of the mine (Werner, 1988). The Meggen Beds beneath the orebody are significantly enriched in sulfur, nickel, thallium and barium relative to those in the southwest, and relative to other Devonian siltstones and shales. Typical background values in the Rhenish Massif are: sulfur (350-3400 ppm), nickel (57-163 ppm), thallium (0.3-2 ppm), and barium (333-580 ppm).

The elevated barium content is related to barite-sulfide aggregates disseminated in the Upper Shale and Upper Sand Units. Most significant are the enrichment of nickel, the average content being greater than that of the sulfide ore itself, and the enrichment of thallium. Thallium decreases from an average of 193 ppm beneath the orebody to a background value of 2 ppm in the time-equivalent Meggen Beds along strike, and does not define a district-scale geochemical anomaly (Werner, 1988).

Slide 24. Meggen district: Manganese anomaly

In contrast, the manganese content of the Lagerkalk limestone outlines an anomaly extending about 5 kilometers away from the Meggen orebody (Gwosdz and Krebs, 1977). The highest values of more than 2000 ppm occur in limestone above the barite margins, decreasing to 1000-2000 ppm in exposures along the southeastern limb of the Elspe syncline, and to background values of 500 ppm in outcrops to the northwest. On the inset map, the Attendorn Reef is shown in blue and the limestone marker is traced in red.

Slide 25. Meggen mine: Unfolded orebody

The isopach map of the unfolded sulfide orebody is compiled from Ehrenberg et al. (1954) and from W. Fuchs (in Clausen, 1978). The isopachs define a shallow basin elongated in an east-west direction. The highest zinc and lead grades coincide approximately with the central zone of greatest sulfide thickness (4-7m). Exceptions are local maxima of 8-11m in the western part of the deposit, which are caused by more abundant, intercalated sand/siltstone and shale beds. Note that the contact with the Meggen Reef is tectonic. A definitive discharge site for the mildly acidic, reduced, low-

temperature (150-200°C) hydrothermal solutions, which caused pervasive argillic alteration in the footwall sediments, has not been identified. Werner (1988) suggests a vent zone, controlled by syn-sedimentary faults, at the western margin of the basin.

To the north and south, the sulfide ore thins and pinches out in barite, which thickens in turn to 3-6m before gradually pinching out beneath the Lagerkalk limestone. In the northwest, the barite margin is absent and the sulfide ore is in contact with sandstones of the Meggen Beds. The average thickness of the sulfide ore is 3.5-4.0m, and that of the barite ore 2.5-3.0m. Prior to erosion, the combined orebody extended more than 5 km in east-west and about 2.5 km in north-south direction. The iron and base-metal sulfides precipitated as gels under euxinic conditions in a stagnant brine pool. Barium migrated to the margins of the shallow basin, and precipitated at the brine-seawater redox interface by interaction with marine sulfate (Buschendorf et al., 1963; Nielsen, 1985; Werner, 1988).

Slide 26. Meggen district: Paleogeography

Palinspastic map illustrating the facies changes of Late Givetian sediments in the Meggen district (modified from Werner, 1988). The large Attendorn reef complex and adjacent sandy sediments are located on the marine shelf, whereas the Meggen orebody (M), the Meggen reef, and calcareous shales are located in the deep-water basin to the southeast. After growth of the Meggen reef terminated in the Early Givetian, the morphological contrast between the sunken reef and the basin floor persisted (Krebs, 1981). Apparently, the dead reef sheltered the Meggen brine pool and its accumulating sulfide-sulfate sediments from sand-silt influx. The occurrence of neptunian dikes in the reef, and of thin pyrite beds in shales to the northwest, support the interpretation that hydrothermal fluids discharged from faults at the western margin of the brine pool.

Turbidity currents along the eastern Attendorn reef and down the shelf slope are probably responsible for the sandy nature and greater thickness of the Meggen Beds southwest of the orebody (Krebs, 1981). The strike of the Givetian shelf-basin scarp, the main control on the distribution of sand-silt turbidites, was approximately northeast.

Slide 27. Meggen: Shelf-basin paleogeography

The NW-SE section through the Middle Devonian shelf of the wider Meggen area, vertically exaggerated, illustrates the paleo-topography generated by tilted fault blocks at the margin of the main rift basin (modified from Krebs, 1981). Biostromal carbonate banks (S = Schwelm facies) and biohermal limestone reefs (D = Dorp facies) 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, varying from 200-300m in the southeast to 950m 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).

The palinspastic map below illustrates the changes in lithofacies and marine fauna of the Early Givetian Honsel Group across the paleo-shelf west of Meggen (modified from Langenstrassen, 1983). The Early Givetian strata are up to 1200m thick but thin to the east and southeast. Sandstones of the inner shelf, proximal to the Old Red Continent, contain red-bed detritus (red band = 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 brachiopods (Subrensselandia) and spirifers (Fimbrispirifer) indicate the deeper water the sub-tidal zone (orange and yellow bands). 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).

Slide 28. Meggen basin: Devonian volcanism

The Meggen deposit is located 10 km northwest of a long-lived felsic volcanic center. The diagram on the left (modified from Werner, 1988) shows the isopachs of the K4 keratophyre horizon as mapped by Rippel (1954). The submarine lavas, crystal tuffs and sills of quartz-feldspar porphyry are up to 300m 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 or, in terms of absolute radiometric age, from about 407 to 395 million years (International Commission on Stratigraphy, 2004). Mapping by Rippel (1954) has shown that the K3 to K7 keratophyres, the K4 being the most voluminous, all erupted from an area 25km long in east-west direction. Shales intercalated with keratophyres contain nodules of siderite and pyrite.

The Meggen deposit, straddling the Givetian-Frasnian boundary, is 385±3 million years old (International Commission on Stratigraphy, 2004). At this time, the buried source pluton of the inactive K3-K7 volcanic center may have been the locus of a decaying thermal anomaly (Krebs, 1981). The deposit and associated sub-economic beds of exhalative pyrite correlate in time with four tuffite horizons (Meggen Tuffs MT1 to MT4).

The light brown-gray MT-horizons (2-10 mm thick) occur in black shale separating the orebody from the Lagerkalk limestone (MT1), at the hanging wall contact of the Lagerkalk (MT2), and in the Frasnian calcareous 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 sericite, illite, and calcite. The biotite is chloritized and partly

replaced by sericite. The tuffites are characterized by high contents of aluminum oxide (25.1 %), potassium oxide (6.6 %), and zirconium (590 ppm), and are interpreted to contain air-fall tuff of alkali rhyolite composition. The youngest tuffite (MT4), located 15m above the Lagerkalk, is associated with a 0.5-1m thick bed of calcareous black shale, marked by lenses of pyrite and marcasite and by an enrichment in zinc (3300 ppm) and lead (1700 ppm in sulfide). The source of the air-fall tuffs has not been identified (Clausen, 1978; Krebs, 1981; Dornsiepen, 1985).

Slide 29. Central Europe: Paleogeography

Middle Devonian paleo-geography of central Europe, modified from the Map Supplement 12 of Ziegler (1990), showing the locations 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 gray = moderate topographic relief, light gray = low relief). The continent comprised the Laurentian-Greenland and Fennoscandian-Baltic Precambrian cratons, joined by the Caledonian fold belt (520-420 Ma), and exotic Gondwana-derived continental blocks. These exotic blocks, consolidated during the Cadomian orogeny (650-550 Ma), were accreted in the Silurian (Ziegler, 1990). In the Devonian plate-tectonic setting, these combined Old Red continental blocks represent the 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 geosynclinal basin to the south, grading into deltaic and coastal marine sandstones (yellow). Shallow-water marine mudstones (dark olive-green) and carbonates (blue) were deposited on the outer shelf. The Sedex sulfide-barite deposits formed along the shelf margin in a rifted deep-water basin, characterized by pelagic shales (light gray-green), sand-silt turbidites (brown), and submarine volcanic centers (black stars). The rift basin is subdivided by the Mid German High into the northern Rhenish and the southern Saxothuringian sub-basins, and formed on a basement of previously accreted Cadomian continental blocks. The rift was located in the foreland of the Ligerian-Vosgian Cordillera, a fold belt of high topographic relief (dark gray) and active plutonism (black crosses).

Slide 30. Devonian plate-tectonic setting

The map on the left shows the Middle Devonian plate-tectonic setting, modified from Ziegler (1990), and the position of the Meggen/Rammelsberg Sedex deposits in the Rhenish-Saxothuringian rift basin at the margin of the Laurussian mega-continent. Continental areas elevated above sea level are in yellow, and continent-scale 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 gray, deep continental basins medium gray, and basins floored by oceanic crust dark gray.

In the Middle Devonian, the Rhenish-Saxothuringian basin is located in a back-arc position relative to the active fold belt of the Ligerian-Vosgian Cordillera, part of the larger Hercynian orogen 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 Appalachian-Ligerian-Vosgian subduction system (Ziegler, 1990). The Rhenish-Saxothuringian back-arc basin probably included ocean-floor segments, consumed by local subduction to the south during Late Devonian compression (Franke, 2000).

The diagram on the right (modified from Ziegler, 1990) shows the interpreted plate-tectonic reconstruction of continents during the Devonian and Early Carboniferous. The final collision of Laurussia and Gondwana led to the creation of the Permo-Triassic super-continent Pangea.

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