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REVIEW ARTICLE

Radiolarian cherts and associated siliceous rocks of the Rhenish Massif and Harz Mountains, lower Carboniferous (Mississippian), Germany

Hans-Jürgen Gursky[1]

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Abstract
Siliceous sedimentary rocks are major constituents of the rock succession in the Central European part of the Kulm Basin (Mississippian) and crop out in the eastern Rhenish Massif and the western Harz Mountains. These rocks occur in five lithostratigraphical units: Oberrödinghausen Formation, subdivided into Kahlenberg Subformation ("Untere Alaunschiefer") and Hardt Subformation ("Schwarze Kulm-Kieselschiefer/-Lydite"), Laisa Formation ("Helle Kulm-Kieselschiefer") and coeval Hillershausen Formation ("Kulm-Kieselkalke"), as well as Bromberg Formation ("Kieselige Übergangssschichten"); upper Hastarian to Asbian. Biostratigraphically, the formations can be dated by means of radiolarians and, in the upper part of the Kulm succession, also by ammonoids. Various siliciclastic, calcareous and, locally, mafic volcanic and pyroclastic rocks are associated with these strata. Four palaeogeographical facies zones have been identified. Radiolarian chert, spiculitic chert, homogenous chert, and silicified tuff are the main siliceous rock types. These mostly form current-laminated grey, black, greenish or reddish beds rhythmically alternating with layers of siliceous mudstone and are, in places, variably intercalated with grey and black mudstones and siltstones, phosphorites, metabentonites, turbiditic limestones, greywackes and quartz arenites. The depositional area of the Kulm Basin was situated at the northwestern margin of the elongate, relatively narrow tropical Palaeotethys Ocean, a shallow-bathyal sea strait between Gondwana and Laurussia that was successively closed during the Variscan Orogeny. Westbound nutrient-rich currents favoured high fertility of siliceous plankton (radiolarians). The latter gave rise to the formation of relatively pure biosiliceous oozes and muds under temporarily anoxic conditions at the seafloor, when, contemporaneously, terrigenous detrital input and sedimentation rates became low (approx. 2 mm/1000 a) due to relatively high sea level and dry climate. Biosiliceous sedimentation terminated, when, due to the Gondwana–Laurussia collision, terrigenous detrital input multiplied, the basin narrowed and oceanic circulation was restricted resulting in lowering of radiolarian productivity.

Keywords Radiolarian chert · Stratigraphy · Sedimentology · Petrography · Facies · Palaeogeography · Mississippian · Harz Mountains

Introduction

The Kulm Basin forms part of the Rhenohercynian Zone of the Variscan Orogenic Belt. It is one of the classical marine basins in Central Europe. Main characteristics are its well-defined and widely correlatable rock successions, good biostratigraphic control and minor orogenetic deformation. Thus, intensive stratigraphic and facies studies have been carried out since the beginning of the twentieth century. The siliceous rocks of the Kulm Basin, however, which represent more than one half of Mississippian time, have been neglected for decades. This is mainly due to their seemingly petrographical monotony and scarcity of macroscopical features and macrofossils.

Nevertheless, progress in radiolarian biostratigraphy and deep-sea-drilling-based better understanding of fundamental sedimentary and diagenetic processes of marine siliceous sediments have been strong tools for precise age dating and deciphering nature and origin of the siliceous rock units in the Kulm Basin (e.g. Dehmer et al. 1989; Braun and Gursky 1991;

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✉ Hans-Jürgen Gursky
gursky@geologie.tu-clausthal.de

1 Institut für Geologie und Paläontologie, Technische Universität Clausthal, Leibnizstr. 10, 38678 Clausthal-Zellerfeld, Germany

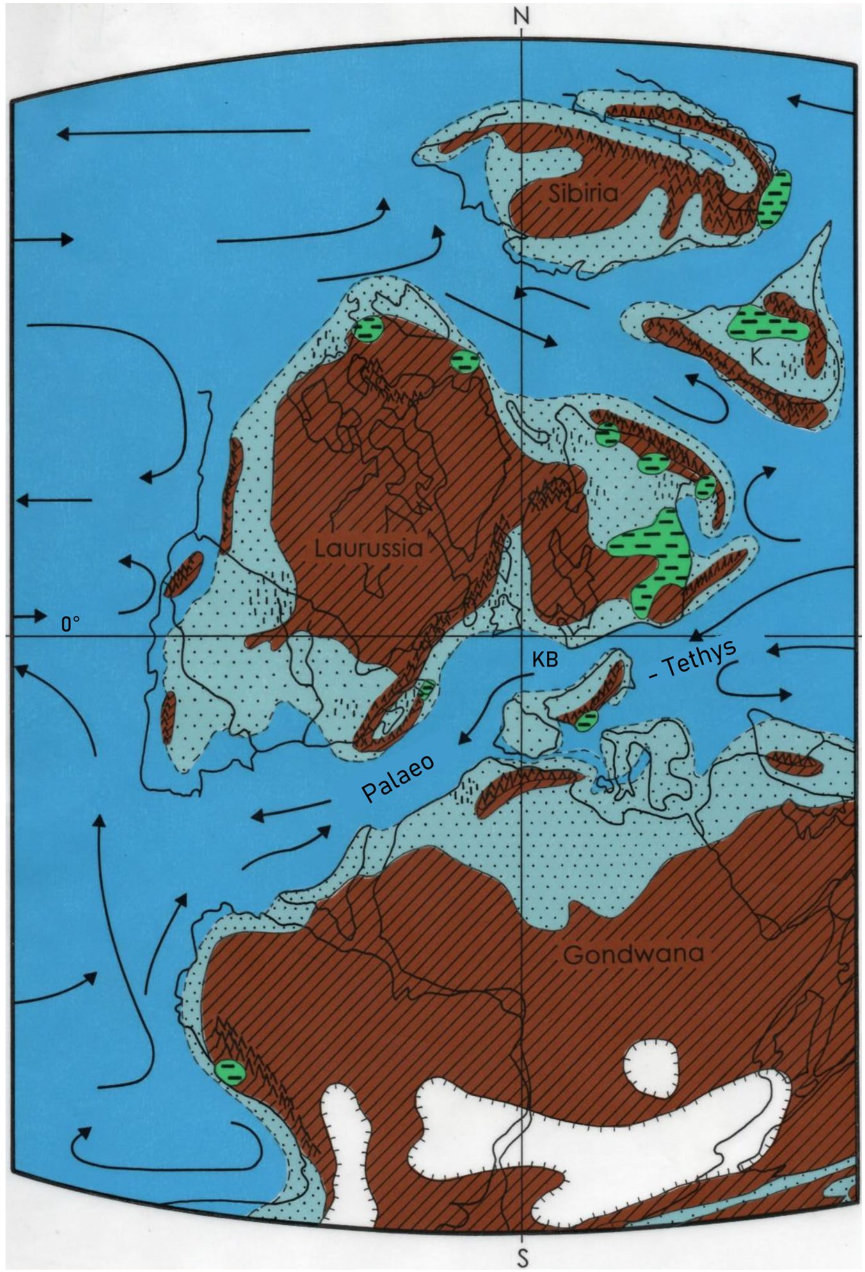

Fig. 1 Palaeocontinental configuration in the Viséan. KB: Kulm Basin, K: Khasachsthania, brown: land areas, light blue: shelf seas, dark blue: open oceans, green: coal basins, white: ice shields. Compiled and modified mostly from Parrish (1982), Scotese and McKerrow (1990), Witzke (1990), and Gursky (2006)

Braun and Schmidt-Effing 1993; Gursky 1996, 1997; Zellmer 1997). In the present paper, the state-of-the-art concerning stratigraphy, palaeogeography, sedimentology, microscopical petrography and palaeoceanographical evolution of the cherts of the Central European Kulm Basin are summarised.

Palaeogeography

Mississippian palaeogeography was dominated by the major Gondwana and Laurussia continents, in the southern and northern hemispheres, respectively (e.g. Scotese and McKerrow 1990; Torsvik and Cocks 2004; Franke et al. 2017, 2019; Fig. 1). They were separated by a wide marine realm that was subdivided into individual oceans by microcontinental terranes. The southern margin of Laurussia bordered the relatively small and narrowing Rhenohercynian Ocean (e.g. W. Franke et al. 2019), a tropical seaway connected with the Palaeotethys. Siliceous oozes were mostly deposited in this basin off the southern Laurussian coast as well as in the northeastern and western Palaeopacific Ocean (also called Panthalassic Ocean; Hein and Parrish 1987). Apart from the Central European Kulm Basin, Carboniferous siliceous rocks are also present e.g. in the Pyrénées

(Randon and Caridroit 2008), southern Spain (O'Dogherty et al. 2000) and the southern USA (e.g. Lowe 1975). Calcareous pelagic oozes were subordinate in Palaeozoic times and began to dominate during the Mesozoic only when calcareous planktic organisms broadly evolved.

The Kulm Basin was a relatively deep marginal sea of the Rhenohercynian Ocean in the subsiding outer passive margin of southeastern Laurussia. To the South, the Kulm Basin was bordered by an intra-oceanic magmatic arc, tied to a Variscan subduction zone, on top of a micro-continental terrane, the precursor of the Mid-German Crystalline Zone (Fig. 2). Open seaways existed southwestward to the southwestern Rhenohercynian Ocean via southern England, Ireland and Portugal, and eastward to the western Palaeotethys via Eastern Europe.

In northern Germany, onset of Kulm magnafacies deposition was triggered by a sea-level rise, high-stand and transgression in mid-Tournaisian time (cf. e.g. Herbig 2016). The Kulm Basin extended into a large embayment that included most of northern Central Europe and was connected to southwestern England (Paproth 1989). The Kulm Basin was bordered in the West, North and East by the narrow slope of a carbonate platform (the Carboniferous Limestone, "Kohlenkalk"; Franke 1990), a broad shallow shelf belt that included local evaporite formation and intra-shelf basins with Kulm-type successions. From its edge calciturbidites were temporarily shed into the adjacent basin (cf. Franke et al. 1975; Korn 2008). This shelf area was limited landward by the complicated coastline of SE Laurussian continental lowlands.

The Kulm Basin achieved its maximum palaeogeographical extension in late mid-Viséan time and became successively narrower in the Late Viséan. The latter was the result of the formation of large fluvial delta complexes (Leeder 1987) and extended paralic coal formation along the northern margin, as possible effects of a climatic change from (semi-) arid to moderately humid conditions. And from the South, the northward advancing Variscan Orogeny caused the progressive filling of the basin mostly by deposition of turbiditic lithic clastics (greywackes). By early Pennsylvanian time, the Kulm Basin had finally shallowed into a paralic delta and swamp landscape.

The Kulm Basin was divided into subbasins with submarine rises including local islands. Relics of eroded Devonian fringing and atoll reefs, founded at the Laurussian shelf edge or on submarine volcanic structures, acted as local highs or islands until Viséan time. They controlled the facies pattern of the siliceous and associated sediments. Subaerial volcanic eruptions, e.g. in the eastern Harz area (Elbingerode Complex) are responsible for part of the tuffs interbedded with the biosiliceous sequences (Gursky 1992; Zellmer 1997).

During the Mississippian, northern Central Europe was situated south of the tropical rainforest belt crossing Laurussia and at the northern margin of the high-pressure climatic belt of the southern subtropical zone (Parrish 1982; Bless et al. 1987; Witzke 1990; Gursky 1996). Palynologic (Zwan et al. 1985) and palaeopedologic investigations (Wright 1990; Peeters et al. 1992) suggest that, in southern Laurussia, climate changed from moderately humid in the Early Tournaisian to hot, semi-arid to arid in the Early Viséan and back to moderately humid in the Late Viséan.

Sea level rose from a low-stand in late Upper Devonian time to a relative high-stand in late Tournaisian time (Ross and Ross 1987; Herbig 2016) and remained high until the end of the Mississippian with a possible maximum in late Asbian time (Herbig 1998, 2016). In the early Pennsylvanian, however, sea level dropped dramatically to a deep low-stand caused by the onset of the Permocarboniferous glaciation.

A strong westbound equatorial surface current was probably present in the western Palaeopacific Ocean, driven by tropical trade winds. This nutrient-rich current may also have passed through the Rhenohercynian Ocean from east to west in an attenuated manner, whilst cold bottom currents from polar regions with resulting regional upwelling were probably absent due to the palaeocontinental configuration (Parrish 1982).

In combination, these conditions clearly favoured planktic life (radiolarians) and, thus, biosiliceous sedimentation in the Kulm Basin. Semi-arid to arid climate in southeastern Laurussia resulted in reduced continental runoff and very low clastic sedimentation rates in surrounding marine areas. In addition, the wide shelf areas intercepted most of the detritus. These factors lead to starved terrigenous input into the Kulm Basin, so that purer planktic oozes accumulated. The Rhenohercynian Ocean had narrowed, was in an "intercontinental" position and had a WSW–ENE orientation near the equator. These factors were not favourable for upwelling conditions, unlike in the modern equatorial Pacific Ocean. However, high planktic fertility can be assumed for the neighbouring equatorial Palaeopacific Ocean. Trade wind-driven currents transported nutrient-rich surface waters from the western Palaeopacific Ocean westward into the Rhenohercynian Ocean. Radiolarian plankton flourished and radiolarian oozes were deposited here.

Litho- and biostratigraphy

Mississippian siliceous rocks (the classical "Kulm-Kieselschiefer" and equivalents of the German literature) crop out in the Rhenish Massif and Harz Mountains (Fig. 3) which are part of the external fold-and-thrust belt of the Variscan Orogen. The radiolarian cherts and associated siliceous and non-siliceous sedimentary rocks were

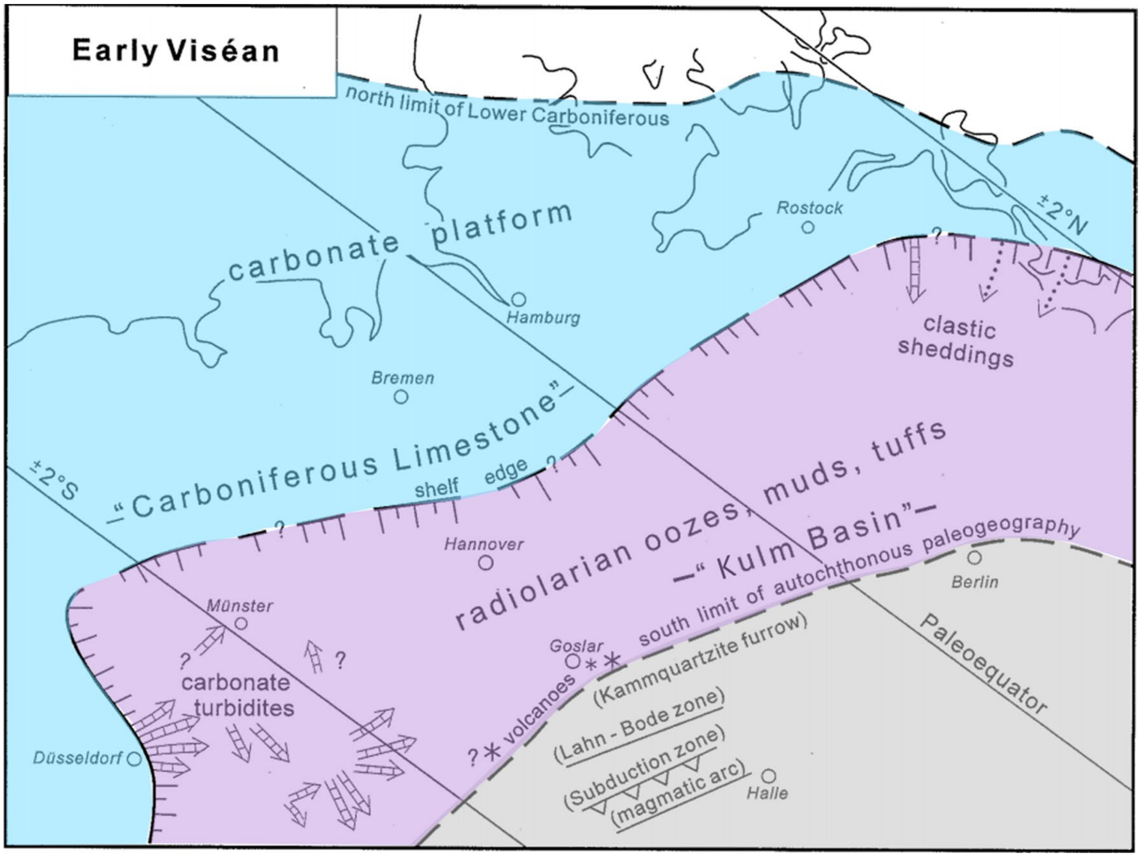

Fig. 2 Palaeogeography of northern Central Europe in the Early Viséan, modified and extended from Franke (1990) and Gursky (2006)

deposited from the Late Tournaisian (Ivorian) to the early Late Viséan (Asbian; Fig. 4). Traditionally, these basinal successions have been biostratigraphically subdivided and dated mostly by ammonoids, conodonts and foraminifers (Stoppel and Amler 2006). But macrofossils and conodonts are scarce in the siliceous units and foraminifers nearly exclusively occur in local calcareous interlayers. Thus, biostratigraphy was imprecise here for a long time. However, Braun (1990) and Braun and Schmidt-Effing (1993; see also Braun 2006; Braun in Amler and Gereke 2002) presented for the first time a radiolarian biozonation for the Mississippian in Central Europe, based on novel laboratory procedures applied to siliceous and non-siliceous rocks. Henceforth, also the siliceous units are continuously datable by fossils.

In most areas, the siliceous sequences are underlain by upper Devonian to lower Tournaisian basinal mudstones with intercalated turbiditic sandstones supplied from southeastern Laurussia or nodular limestones ("Hangenberg Shale/Limestone" and equivalents; e.g. Herbig 2016). The first siliceous beds occur in the upper part of the overlying Kahlenberg Subformation (Korn 2010, "Liegende Alaunschiefer"; middle Tournaisian) of the Oberrödinghausen Formation (Korn 2010). This black alum shale unit is traditionally defined as the first lithostratigraphic unit of the Central European Kulm. It is up to 45 m thick (Rottenberg section, Fig. 5), lithologically monotonous and poorly stratified. The rocks are rich in organic carbon (up to more than 3%) and fine-grained pyrite, but poor in fauna. However, early-diagenetic phosphorite concretions are locally abundant and rich in well-preserved radiolarians (Braun and Schmidt-Effing 1993). This suggests that the entire formation was originally rich in biogenic silica which was mostly dissolved during diagenesis and then recycled. It was mainly deposited during the *Albaillella paradoxa* Zone of the radiolarian biozonation (late Hastarian and early Ivorian).

Upsection, the Kahlenberg Member grades into the Hardt Subformation (Korn 2010, "Schwarze Kieselschiefer", "Kulm-Lydite") of the Oberrödinghausen Formation by an increase in distinct chert beds. It is up to 20 m thick and consists of a uniform rhythmic alternation of cm to dm-thick

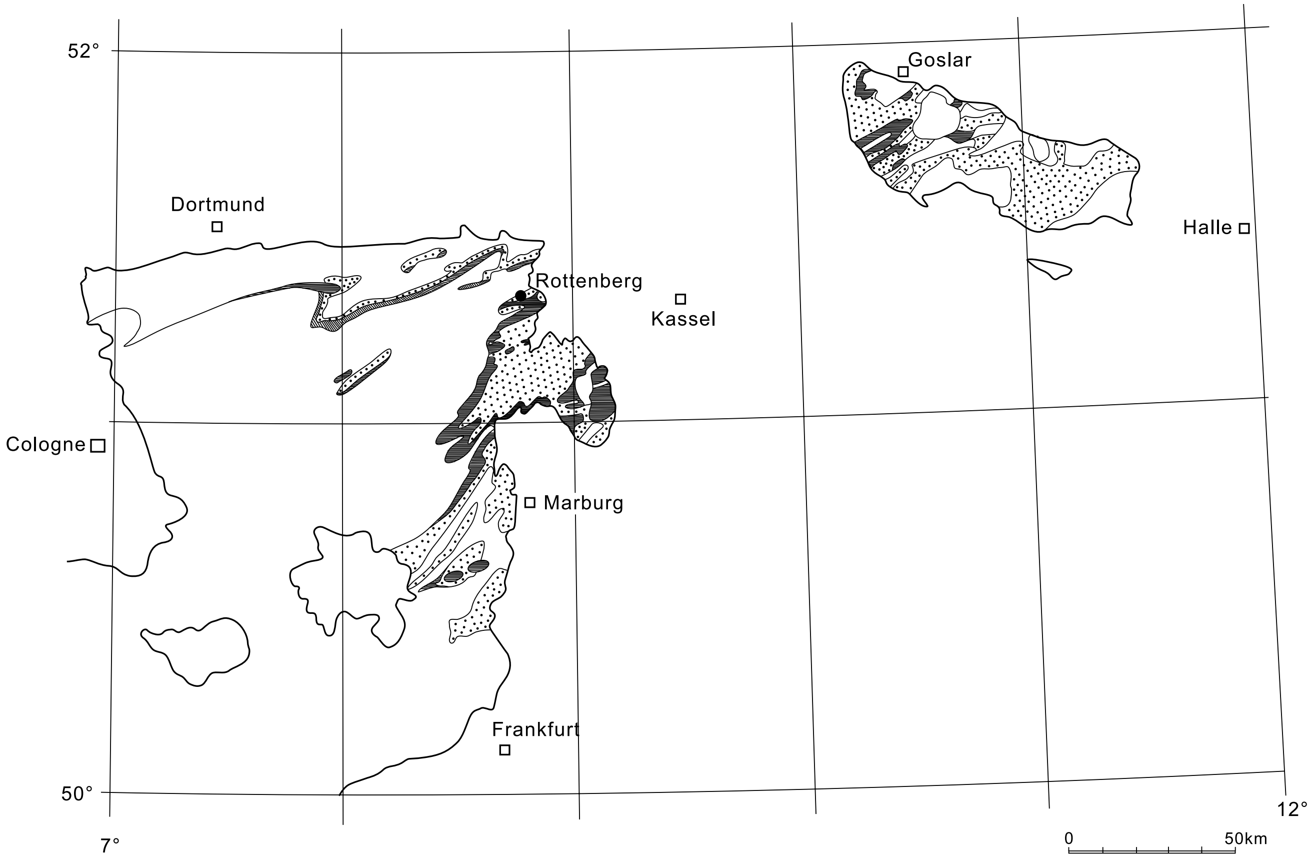

Fig. 3 Occurrence of Early Carboniferous rocks in the eastern Rhenish Massif and Harz Mountains. Areas with siliceous-rock bearing sequences are hatched. Modified from Gursky (1997)

black radiolarian chert beds and mm-thin black siliceous mudstones. Minor intercalations of altered tuffs (metabentonites), calciturbidite beds and phosphorite nodules are locally present. The sediments of this formation were deposited during the *Albaillella deflandrei*, *Albaillella indensis* and early *Eostylodictya rota* zones (Braun and Schmidt-Effing 1993; late Ivorian to early Arundian).

The content of organic carbon decreases up-section, and the Oberrödinghausen Formation passes into the Laisa Formation (Korn 2010, "Helle Kieselschiefer"). It is up to 25 m thick and composed of alternating cm to dm-thick grey, greenish and reddish chert beds and thin siliceous mudstones. The cherts are radiolarites, spiculitic rocks, siliceous tuffs or, rarely, homogeneous. Thin light-coloured altered tuff interbeds are frequent. In the northeastern Rhenish Massif, this formation grades laterally westward into the Hillershausen Formation (Korn 2010, "Kulm-Kieselkalk") by intercalation of variably silicified limestone turbidites (Fig. 6) which may be dominant. The Hillershausen Formation is generally up to 30 m thick. It was deposited during the late *Eostylodictya rota*, *Albailella cartalla* and *Latentifistula concentrica* zones (Braun and Schmidt-Effing 1993; late Arundian and Holkerian).

The uppermost siliceous unit is the overlying Bromberg Formation (Korn 2010; "Kieselige Übergangsschichten", Nicolaus 1963; Lautenthal Formation in the Harz Mountains, Gursky et al. 2021). This unit is up to 15 m thick and generally a thin-bedded alternation of grey to black mudstones, siltstones, cherts, limestones and altered tuffs. A triple bed of goniatite limestone ("crenistria Limestone") forms a conspicuous index horizon. The uppermost part of the formation is dominated by mudstone and variably rich in macro-fauna, mostly flattened *Posidonia*-type bivalves and goniatites ("Posidonien-Schiefer"; e.g. Brauckmann 1970; Dieken Formation, Korn 2010). The sediments of this formation were deposited mostly in the *Albaillella rockensis* Zone (Braun and Schmidt-Effing 1993; Asbian).

The chert-bearing formations are widely overlain by the flysch facies of the Kulm Basin. The monotonous pelitic Glindfeld Subformation of the Lelbach Formation (Korn 2010, "Kulm-Tonschiefer") and equivalent Schulenberg Formation (in the Harz Mountains; Jantosch 2015; Gursky et al. 2021) are variably several tens of metres thick and

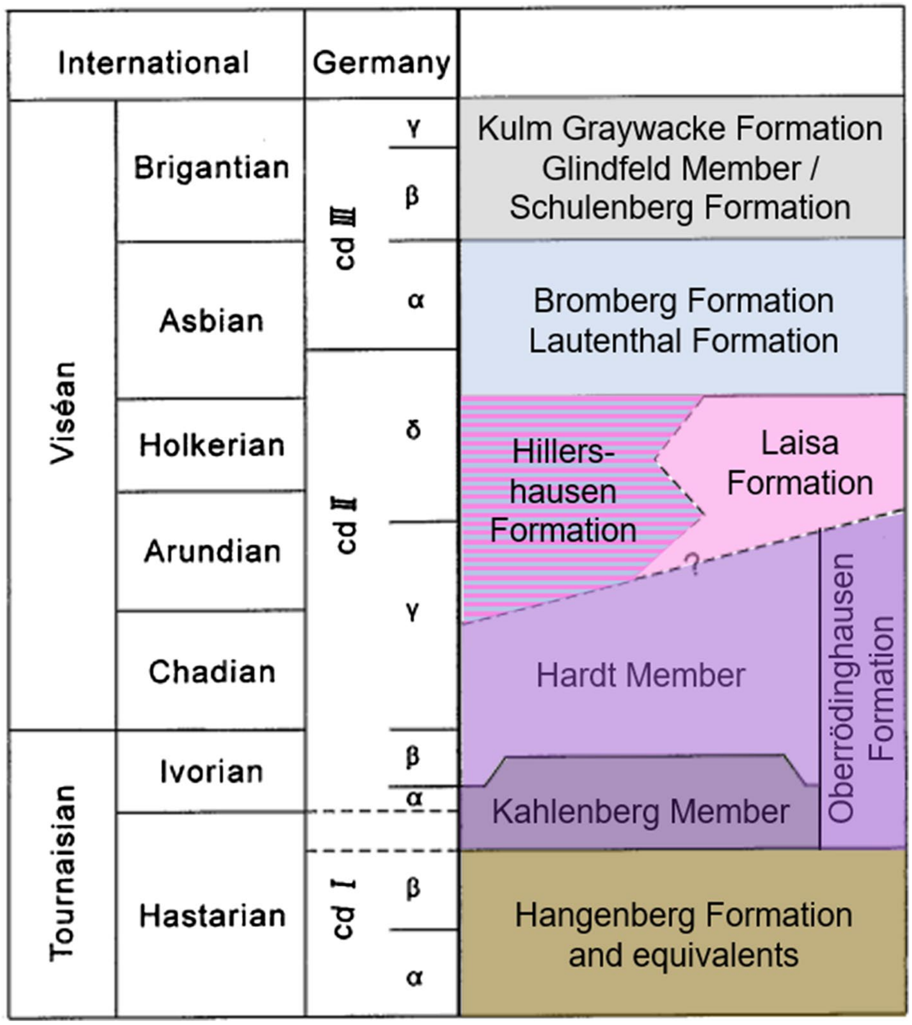

Fig. 4 Chrono- and lithostratigraphy of the Central European Kulm sequence in the eastern Rhenish Massif and Harz Mountains

the overlying diachronous Dainrode Formation (Korn 2010; "Kulm-Grauwacken") is several hundred metres thick. In age, these formations range up to the latest Viséan. At the northern rim of the Rhenish Massif, the flysch facies and time-equivalent local series are followed by up to 3000 m of molasse sediments including the coal measures of the Ruhr area (mostly Pennsylvanian in age).

The siliceous formations of the Central European Kulm show a number of regional facies variations due to palaeogeographical factors. The thicknesses of the formations are variable: Kahlenberg Subformation 0–45 m, Hardt Subformation 0–20 m, Laisa Formation 0–25 m, Hillershausen Formation 0–> 150 m, Bromberg and Steigertal formations 0–20 m. The proportion of individual formations in the chert-bearing succession is also variable (Gursky 1996). The amount of limestone turbidites is variable and depends on distances from bioclast-shedding shelf areas and intrabasinal shoals. In the northwesternmost part of the eastern Rhenish Massif, the Kulm grades into the slope facies of the Carboniferous Limestone platform (proximal calciturbidites). Further east, the uppermost part of the Bromberg Formation and the lower part of the Glindfeld Subformation are replaced by the thick-bedded calciturbidites of the Herdringen Formation (Korn 2010, "Kulm-Plattenkalk"). Along the eastern rim of the Rhenish Massif, the Laisa Formation grades laterally into the Hillershausen Formation by increasing intercalations of limestone turbidites (Witten 1979; Herbig et al. 2019; "Kulm-Kieselkalk").

In Ivorian and Chadian times, parts of the Kulm Basin were affected by submarine and, locally, subaerial volcanism. Tholeiitic basalt flows (now altered to meta-basalt called "Diabas" in Germany) are dominant, alkalibasaltic magma is subordinate, doleritic sills and dykes also occur (Nesbor 2006, 2007). The thickness of these volcanic units ("Deckdiabas") reaches 500 m in the southeastern Rhenish Massif (Lippert et al. 1970), but is generally much less. Due to the formation of such volcanic structures and to other intrabasinal rises, the Oberrödinghausen Formation is

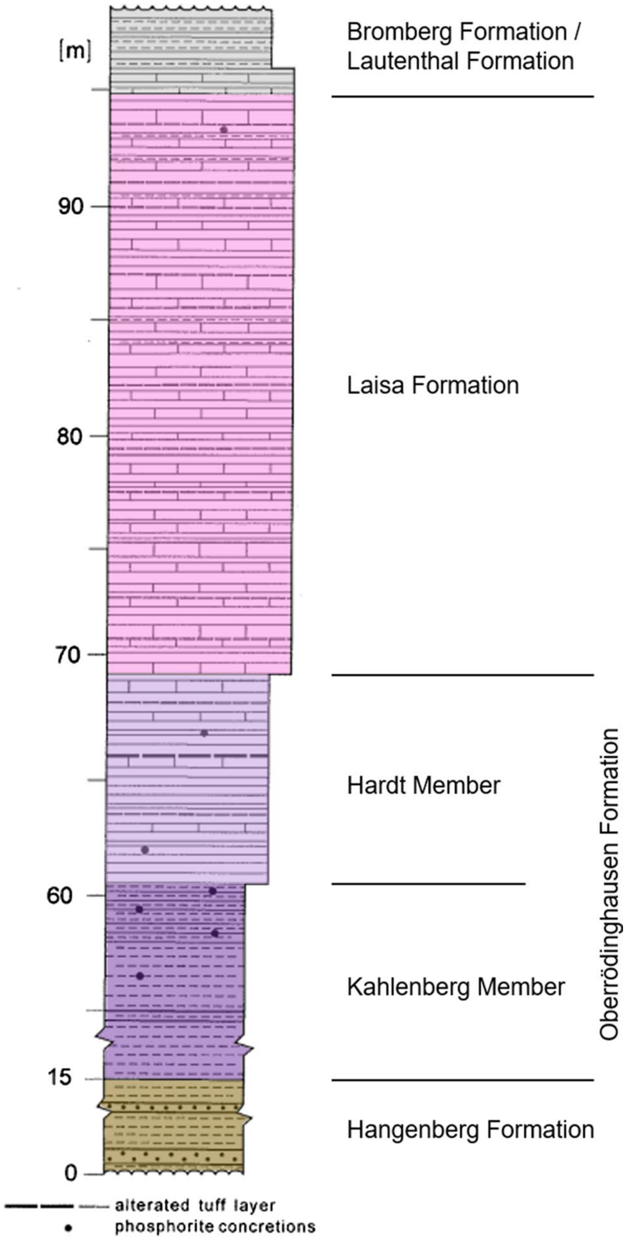

Fig. 5 Lithostratigraphic sketch of the Hastarian to early Asbian Kulm sequence in the representative Rottenberg section (abandoned quarry and adjacent road cut between Adorf and Flechtdorf, eastern Rhenish Massif). Explanation of the rock sequence in the text. Details in Gursky (2007)

locally absent or its thickness is markedly reduced (Fig. 7). The amount of altered, partly silicified tuff layers is regionally variable, too. It increases towards the east and southeast and reaches maxima in some sections of the northwestern Harz Mountains (Gursky 1992, 2007; Zellmer 1997). These tuffs were originally trachytic to quartz-trachytic (Gursky 1997) and/or dacitic to rhyodacitic and they derived predominantly from island-arc volcanism outside of the Rhenoherynian Basin (Nesbor 2006, 2007).

Gursky (1992, 1996; Fig. 2) defined four major facies zones for the middle Lower Carboniferous succession of the Kulm Basin. The *Bergian Zone* includes rocks of the transition from the Carboniferous Limestone shelf into the Central European Kulm Basin. The individual sections are composed of a variable proportion of proximal limestone turbidites and pelagic rocks; siliceous rocks are subordinate. In the *Westphalian Zone*, the most complete siliceous succession is developed. Cherts range in age from Ivorian to Asbian. In places, siliceous rocks and black shales of late Brigantian age are present (Korn 1989; "Eisenberg Formation", Korn 2006, 2010). The "Deckdiabas" is absent. The Hillershausen Formation is well developed and the Bromberg Formation is lithologically variable. In the *Dill-Innerste Zone*, the "Deckdiabas" is present and the Oberrödinghausen Formation may be missing or replaced by volcanic rocks (Fig. 6). The Laisa Formation is mostly free of calciturbidites and locally variegated. The Bromberg Formation and Steigertal Formation, respectively, are present but in places poorly developed. The "classical" Kulm succession is not developed in parts of the southeasternmost Rhenish Massif and the central Harz Mountains, the *Lahn-Bode Zone* (Fig. 2). In its *Hörre-Gommern Subzone*, in particular, and in adjacent regions, Upper Devonian to Lower Carboniferous fine-grained clastic and siliceous rocks are associated with greywackes, limestone turbidites and "exotic" turbiditic quartz arenites, the latter deposited in a separate elongate trench ("Kammquartzite Formation"; Jäger and Gursky 2000; Jäger 2002).

Sedimentology, petrography and radiolarian fauna

Siliceous rocks of the Kulm Basin include: radiolarian cherts, spiculitic cherts, pelitic cherts, homogeneous cherts and silicified tuffs. These rock types are variably associated with shales, greywackes, altered tuffs (metabentonites), carbonates, phosphorite concretions and non-bedded quartz-hematite rocks. Various lithologic alternations occur as laminae, beds or groups of beds (Gursky 1997). The most conspicuous macroscopic feature in outcrops is the rhythmic bedding made up of hard, splintery cherts and thin, weathered interlayers poorer in SiO_2. This basic rhythmicity may vary: it interferes in most sections with other rhythms caused by calciturbidite or tuff beds that may be regionally dominant or result in heterolithic successions (e.g. Bromberg and Steigertal formations). In general, the cherts of the Kulm Basin are monotonous with respect to their macroscopic sedimentology. Important features are characterised as follows.

Bedding planes are mostly sharp and even, but transitions may be present, especially at contacts with tuffs and limestone turbidites that may grade upward into cherts.

Fig. 6 Detail of the Hillershausen Formation in the Rottenberg quarry. The sequence includes alternating beds of grey radiolarian chert and siliceous mudstone, greenish silicified and altered tuff, and light grey calciturbidite

Weathering accentuates lithologic differences. Sand-sized basal parts of tuff layers may be masked within chert beds by diagenetic silicification. Ichnofauna is rare and concentrated on bedding planes, e.g. *Spirodesmos* (Huckriede 1952; Horn 1989).

Lamination is the most important, nearly omnipresent sedimentary structure of the Kulm cherts and laminae are their fundamental sedimentary units. Homogeneous ("structureless", "massive", "single-layered") bedding is subordinate. Lamination is variable and includes three dominating types:

Type 1 is a continuous parallel lamination made up of pale, radiolarian-rich laminae and darker laminae rich in fine-grained detritus and/or organic carbon particles. Thickness of laminae ranges from 1 to > 10 mm, sub-lamination is frequent. The boundaries of the laminae are well-defined or transitional and often accentuated by microstylolites. Braun (in Braun and Gursky 1991) points to the presence of beds with "triple layering" sensu Iijima et al. (1985) characterised by a silica-rich centre with many well-preserved radiolarians.

Type 2 mostly occurs in the grey to greenish chert beds of the Laisa and Hillershausen formations. It is a discontinuous parallel lamination of pale and dark, sharp, < 1–3 mm thick laminae organised in a microlenticular or microflaser style and caused by minimal compositional variations.

Type 3 is a pale-dark, often variegated parallel lamination and typical in the Laisa Formation, especially in biosiliceous and tuffaceous microalternations. Laminae are well defined and 1–> 10 mm thick; sub-lamination is typical. Secondary cloudy colourations and discolourations may be present. Load casts and dewatering structures with microconvolutions, disrupted laminae and formation of ball structures are frequent. Schwarz (1989) suggested "volcanoseismic" interpretation for such features and Zimmerle (1986) pointed to tuff layers with angularly unconformable bases.

Weak and irregular pinch-and-swell structures are frequent diagenetic phenomena in the Kulm cherts and result in local slightly wavy to mounded bedding surfaces. In contrast to many other chert occurrences, however, pinch-and-swell intensity is low. Like local silica concretions, it originates from early-diagenetic lateral silica migration, differential compaction and possible subsequent pressure solution. Tectonic and syndiagenetic microfolding due to extreme anisotropy between chert beds and interlayers is typical in some

Fig. 7 Central part of the representative Kulm section in the road cut west of Lerbach (federal road B 241, western Harz Mountains). Left side: altered basalt ("Deckdiabas"); around the hammer: overlying strongly reduced Hardt Subformation; right side: lowermost part of following Laisa Formation. Details in Gursky (1992) and Zellmer (1997)

outcrops, like in many other chert occurrences worldwide. Based on a systematic regional study, Hausmann (1983) concluded that most microfolds are syndiagenetic and originated on smooth submarine slopes of intrabasinal highs.

Microscopic petrography and diagenetic development of the most important chert types are described as follows:

Radiolarian cherts are made up of < 60% radiolarian tests, rarely more (Fig. 8). The cherts are composed of quartz/chalcedony (radiolarians, sponge spicules, bioclasts, silica cement) and accessory siliciclastic and authigenic minerals (quartz silt, feldspar, phyllosilicates), volcaniclastic fragments (quartz, feldspar, mica, altered glass shards), organic carbon, metal oxides and sulphides (especially hematite and pyrite), heavy minerals and crystals of calcite, dolomite and apatite.

Mainly Braun (1990) and Braun and Schmidt-Effing (1993) have discovered, extracted and described in detail 20 radiolarian genera including 79 species in the Mississippian of Germany. They show a wide range of skeleton forms which are in general only well discernible after careful extraction of the entire tests from their host rocks, under the optical and scanning electron microscope. Braun (1990) identified seven groups: Albaillellidae, Ceratoikiscidae, Entactiniidae, Latentifistulidae, Pylentonemidae, Archocyrtiidae and Palaeosceniidae. They include robust spheroidal forms with coarse spines, conical forms with stirrup-shaped appendages, delicate needle lattices, triple-beamed stellar to triangular forms, and others. In thin sections of cherts however, radiolarians show mostly typical circular cross sections up to 300 µm in diameter, internal skeletal elements, pore structures, spines and spine fragments up to 200 µm long and 60 µm thick (details in Gursky 1992, 1996, 1997). Although delicate and complex forms are hardly recognisable in thin sections, it is obvious and plausible that mostly robust, roundish forms and many of their spine fragments survived ooze deposition and subsequent siliceous diagenesis and therefore dominate strongly in thin sections.

Degree and type of radiolarian preservation are variable and depend on diagenetic and metamorphic grain growth and selective dissolution. Preservation quality ranges from excellent to poor and extreme grain growth may result in complete obliteration of the radiolarian tests and the formation of microquartzitic textures ("cryptoradiolarite"). Diagenetic mineralogy and crystal size of the replaced tests and

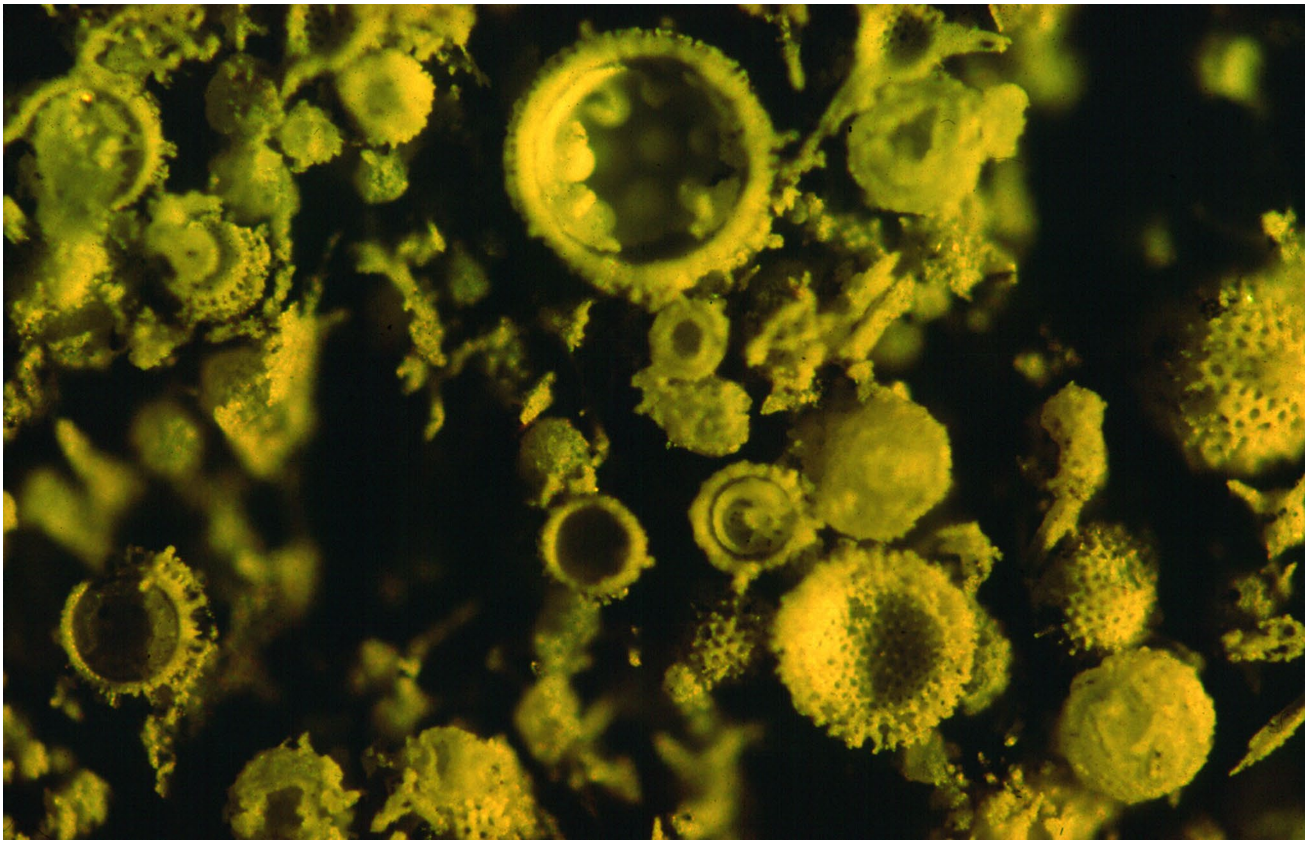

Fig. 8 Photomicrograph of radiolarian chert (etched sample surface, reflected light, photo width approx. 1.3 mm). Note details of well-preserved radiolarians and opal-CT lepispheres inside the large radiolarian. From Gursky (1992)

their infillings define the type of radiolarian preservation: The tests consist of quartz/chalcedony (< 5–30 µm) with subordinate pyrite, hematite, chlorite, calcite, dolomite and carbon. The infillings are made up of cryptocrystalline to microcrystalline quartz-pigment mixtures, quartz aggregates and mosaics, spherulitic chalcedony, chlorite, pyrite, hematite, calcite, carbon and clay minerals. Some radiolarian infillings contain early diagenetic cristobalite-tridymite lepispheres ("opal-CT") replaced by late diagenetic microquartz (Fig. 8). Pressure solution resulted in microstylolitic bands subparallel to bedding, has accentuated the bedding surfaces and is largely responsible for the typical macroscopic "ribbon-chert" fabric in outcrops.

However, the present mineralogy of the radiolarian cherts, their texture and many of the sedimentary structures were caused by diagenesis. Microfauna and siliciclastic components indicate the existence of an original radiolarian ooze with fine-grained terrigenous admixtures. During early diagenesis, the ooze was compacted and retained robust radiolarian tests that had "survived" dissolution during pelagic settling and at the sediment/water interface. Phosphorite nodules grew during early diagenesis, in horizons deposited during anoxic phases. The original biogenic silica of the radiolarians ("opal-A") was partly dissolved and transformed to opal-CT. Opal-CT silica cement precipitated from pore waters, which resulted in lithification as "porcellanite" (opal-CT rock). During late diagenesis, metastable opal-CT transformed to quartz/chalcedony and mature quartz cherts were formed. Pressure solution and weak regional metamorphism followed.

Spiculitic cherts make up only a few per cent of the Kulm cherts and occur in the Laisa and Hillershausen formations. Mostly they form individual laminae within beds of radiolarian chert. Such laminae may represent the tails of calciturbiditic currents (Herbig and Mamet 1994). Several microlithotypes are present with dominating fine-grained, carbonate-free radiolarian-bearing spiculite. Diagenetic alteration of spiculitic and radiolarian cherts was similar.

Homogeneous cherts are pale-coloured and very fine-grained with less than 1% of microscopically identifiable non-siliceous components, mostly phyllosilicates. Compositionally, they grade into siliceous mudstone/pelitic chert. Typical microlithotypes include homogenised radiolarite with few relictic radiolarian "ghosts", strongly silicified mudstones, siltstones and fine-grained tuffs as well as extremely fine-grained cherts of unknown origin.

Tuff layers are regionally abundant in the Central European Kulm Basin, mostly in the Laisa and Bromberg formations of the southeastern Rhenish Massif and western Harz Mountains. They crop out as soft, highly altered and weathered metabentonite beds reported by many authors (e.g. Hoss 1957; Dehmer et al. 1989; Zellmer 1997; Herbig et al. 2019) and as massive chert beds (Gursky 1992, 1996, 1997). Many chert beds reveal their volcaniclastic origin only in thin section: They are silicified vitric tuffs, silicified crystal tuffs (Fig. 8) and silicified tuffites and consist of silicified volcanic glass shards, fragments of alkali feldspar, minor plagioclase, quartz (partly with resorption embayments; Fig. 9), biotite and heavy minerals. The groundmass is a cryptocrystalline to microcrystalline quartz cement. Parallel lamination and graded bedding are typical. The tuffs are interpreted as fine-grained fallout tephra resulting from subaerial eruptions with dacitic to rhyodacitic (Nesbor 2006) and/or trachytic to quartz-trachytic composition.

Most tuff beds were strongly altered during submarine diagenesis and later subaerial weathering resulting in the conspicuous light-coloured, recessively weathering metabentonite layers of the modern outcrops. Many others, however, were affected by late-diagenetic silicification due to silica supplied from adjacent biosiliceous beds. Many silicate fragments were replaced by silica (especially glass shards; Gursky 1996) and massively cemented by silica. This process transformed many tuff layers to massive quartz chert. Some bioclastic carbonate detritus in the limestone turbidites was likewise cemented and partly replaced by silica (formation of "siliceous limestones"; cf. Witten 1979). These observations and the fact that diagenesis of tephra releases only insignificant quantities of silica (e.g. Rad 1979) give evidence that nearly all of the silica stored in the Kulm cherts is biogenic in origin. This disproves the opinion of earlier authors (e.g. Schwan 1952; Dehmer et al. 1989; Zellmer 1997) that the silica of the Kulm cherts is mostly volcanic in origin.

Palaeoenvironment, palaeoecology and basin evolution

The abrupt onset of anoxic sedimentation in mid-Tournaisian time (base of Kahlenberg Subformation) was contemporaneous with a marked sea level rise (Ross and Ross 1987).

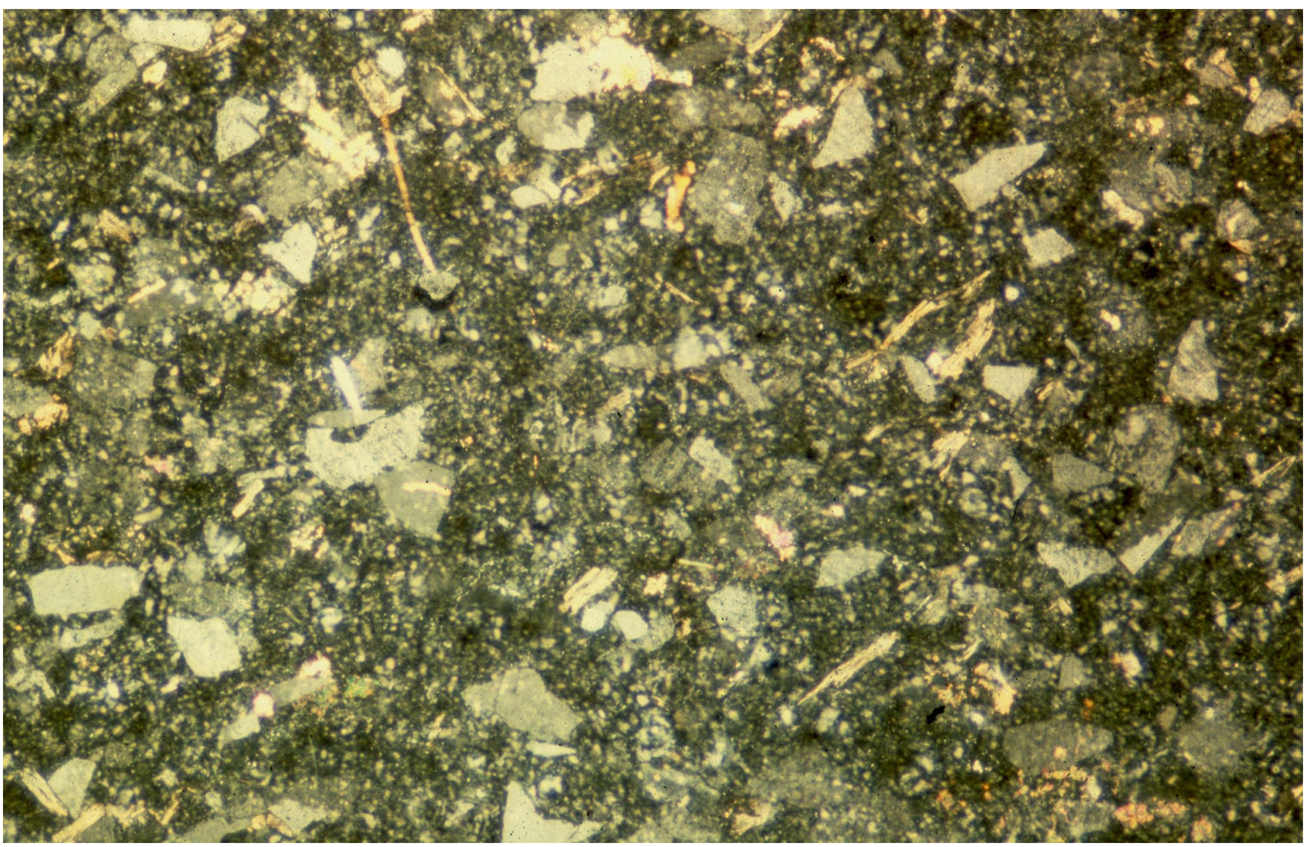

Fig. 9 Photomicrograph of silicified crystal tuff (thin section, crossed polarizers, photo width approx. 2 mm). Crystal fragments are mostly quartz, feldspar and biotite; cement is submicroscopic quartz. Note resorption embayment in quartz fragment left of the centre. From Gursky (1992)

The latter also resulted in a transgression onto the Laurussian limestone shelf and adjacent coastal lowlands and may be responsible for local calciturbidites in the southeastern Rhenish Massif ("high-stand shedding"; Rüchenbach Limestone, Herbig and Bender 1992). Herbig (2016) developed a model of stratigraphic sequences for the Central European Kulm Basin. He emphasised the transgressional character of this black-shale unit and, consequently, interpreted it as part of a transgressive systems tract (no. 2 of 11 third-order sequences in the Tournaisian and Viséan). On a basinal scale, sea level rise and transgression caused enhanced production of organic carbon due to wide and highly productive shelf areas, reworking of nutrient-rich lowland soils and reduced mixing of ocean waters and intrabasinal circulation. In consequence, this favoured oxygen consumption in bottom waters and triggered deposition of monotonous black muds with phosphorite concretions. Well-preserved radiolarians included in these concretions give evidence that biosiliceous sedimentation was contemporaneously stimulated.

Radiolarians are exclusively marine zooplankton and mostly live in warm ocean water near the surface, but also occur at greater depths (De Wever et al. 2001). Braun (1990) stated that most Mississippian radiolarians are found in deep-water sediments, including the Kulm Basin, where they may have accumulated from all water depths, so that individual groups cannot directly be attributed to a specific water depth. He added however, that local co-occurrences with depth-specific macro-fauna suggest that e.g. the Albaillellaria were deep-water forms, whereas the Entactiniidae lived in shallow water. Nevertheless, the radiolarian faunas do not provide unequivocal constraints for estimating basin depths. These have always been under discussion for the Central European Kulm Basin. Gursky (1997) suggested a pelagic realm with generally shallow bathyal depths (apart from intrabasinal highs and islands), whereas Brauckmann (1970), Randon and Caridroit (2008) and others have also envisaged deeper shelf conditions of less than 300 m, at least locally.

In the region of southeastern Laurussia and adjacent seas including the Kulm Basin, after deposition of the anoxic muds, the tropical climate changed from semi-humid to semi-arid and arid in Ivorian to Holkerian times (Zwan et al. 1985; Wright 1990). Clastic input from the smooth Laurussian hinterlands to the Palaeotethys was successively reduced and river deltas temporarily retrograded (Leeder 1987). Additionally, the wide shelves acted as efficient sinks for terrigenous debris and the Kulm Basin starved (cf. Herbig 2016). Terrigenous "dilution" of basinal sediments diminished and, consequently, high equatorial radiolarian bioproduction resulted in deposition of relatively pure radiolarian oozes under still anoxic seafloor conditions. The sedimentary succession (Hardt Subformation) is characterised by an extremely low sedimentation rate of approximately 2 mm/1000 a indicating starved basin conditions (Gursky 1992; Kahlenberg Subformation: 8 mm/1000 a, Jackson 1985). According to Herbig (2016), the deposition of the black siliceous oozes corresponds to the third-order sequences 3 and 4 that represent mostly high-stand-systems tract conditions, including a temporary low-stand situation during the early sequence 4 (approximately mid Ivorian).

At this time, high carbonate production in the Carboniferous Limestone shelf and some intrabasinal highs resulted in the deposition of relatively proximal calciturbidites in slope areas inter-fingering with the pelagic Kulm Facies (Franke et al. 1975). Thus, calciturbidites are locally intercalated in the succession of the Hardt Subformation at the basin margins and around intrabasinal highs (e.g. on top of Devonian reef remains) where carbonate production temporarily revived in shoals. Herbig (2016) explained the temporal increase in carbonate production with three distinct high-stand intervals during his third-order sequences 3, 4 and 5, interrupted by two low-stand to transgressive systems tracts.

In the southeastern Rhenish Massif and in the western Harz Mountains, the "Deckdiabas" volcanism regionally modified thickness and facies of the Oberrödinghausen Formation and included the formation of Lahn-Dill-type Fe mineralizations and local Mn mineralizations. The Hardt Subformation grades into the Laisa or Hillershausen formations across an interval of alternating black and grey beds that represents approximately 0.5–2 Ma. This is combined with a remarkable facies change in the siliceous succession due to the contemporaneous volcanism: Tuff layers are increasingly intercalated and well identifiable especially in the southeastern Rhenish Massif and the Harz Mountains (Dill-Innerste Zone). Particularly, the Elbingerode Complex, a diabase-reef structure in the middle Harz Mountains, was a volcanic island with subaerial eruptions in early to middle Viséan time. It was probably responsible for some of the tuff layers in the Kulm Basin. In the Elbingerode area, the Oberrödinghausen Formation is generally absent and the Laisa Formation is replaced by relatively coarse-grained tephra (part of the local "Büchenberg Formation").

Mostly low-concentrated calciturbidites intercalated with biosiliceous and fine-grained clastic sediments make up the Hillershausen Formation. In the Arundian and Holkerian, this formation was deposited around partly unknown intrabasinal highs, first in the northern and northeastern Rhenish Massif, later in its southeastern parts. In some areas, relatively thick-bedded limestone successions even become dominant ("Becke-Oese Formation", "Hellefeld Formation", Korn 2006). In the Harz Mountains, however, siliceous–calcareous alternations are absent at this time. Crinoid "meadows" indicate temporal recolonization of intrabasinal shoals (e.g. on top of the former Attendorn-Elspe atoll complex), partly accompanied by ooid production. Sea level was high enough for turbidite-favouring carbonate production in shallow marine areas. Even channelized debris-flows (e.g. "Schlagwasser Brekzie" in the Warstein region) and seismogenic fissures are locally present indicating some tectonic activity. Efficient carbonate production in shallow water is also indicated by constant calciturbidite deposition in the northwestern Rhenish Massif (upper "Velberter Kalk"; Amler and Herbig 2006; Franke et al. 1975). Herbig (2016) postulated four successive low-stand–transgressive–high-stand systems tracts making up his third-order sequences 5 to 8 during the Arundian and Holkerian.

Nevertheless, already during the following early Asbian the breakdown of open-marine sedimentation in the Kulm Basin is heralded: Black shale intervals within the uppermost metres of the Hillershausen Formation represent temporal anoxic conditions in bottom waters and then, up-section, siliceous and calcareous beds are continuously replaced by grey and black shale beds. In this Bromberg Formation, sedimentation rate rises up to approximately 8 mm/1000 a (Jackson 1985) due to increased fine-grained clastic input. The sea level dropped and the climate became more humid. This resulted in temporal reduction of carbonate production on the intrabasinal highs and lack of calciturbidites. However, this formation contains some calcareous beds. The most conspicuous and peculiar one of these is the almost basin-wide developed "crenistria Limestone" yielding mass-occurrences of well-preserved conchs of *Goniatites crenistria* (Ammonoidea; cf. Mestermann 1998). Herbig (1998) postulated that this limestone represents a major mid-Asbian transgressional pulse and later (2016) interpreted it as indicating a maximum flooding interval near the beginning of a high-stand systems tract that followed after a low-stand and transgressive tract. These three tracts make up his third-order sequence 9 which embraces the entire Bromberg Formation.

Other indicators of changing environmental conditions at a large scale were the increase of sedimentary input from terrestrial weathering, more detritus supply to prograding delta complexes by Laurussian rivers (Leeder 1987), and the narrowing adjacent shelves. As a result, fine-grained clastic supply to the Kulm Basin increased. Pelitic sedimentation was even more stimulated, however, by the progressive narrowing of the basin due to the accelerated convergence between Laurussia and Gondwana. The Variscan Orogen developed northwards from south of the Kulm Basin and its emergent southern parts were continuously eroded resulting in the onset of the flysch stage in the basin. Additionally, the end of biosiliceous sedimentation was probably related to reduced oceanic circulation caused by the interruption of westbound nutrient-rich currents within the Rhenohercynian Ocean and resulting in the breakdown of radiolarian production. The remnant parts of the narrowed Kulm Basin became an elongate gulf with anoxic events.

The flysch sequence of the Kulm starts with the monotonous Dieken and Schulenberg formations ("Kulm-Tonschiefer"; early Brigantian). Upsection, the shales grade into thick greywacke successions (e.g. Dainrode Formation, "Kulm-Grauwacken"; late Brigantian) with a sedimentation rate of 100 mm/1000 a (Jackson 1985) equivalent to a continental denudation of 180 m/Ma (Schrader 2000). At the northern rim of the Rhenish Massif and in the Ruhr Area, the flysch grades into the thick coal-bearing molasse succession caused by orogenetic closing of the basin and drastic worldwide sea level drop due to the onset of the Permocarboniferous glaciation.

Conclusion

Biosiliceous sedimentary rocks form a conspicuous and significant—however volumetrically minor—part of many marine successions throughout the Phanerozoic. This is also true in the case of the Lower Carboniferous deep-water basins of Central Europe ("Kulm Facies"), where radiolarian cherts are cropping out widely in the Rhenish Massif and Harz Mountains.

The Kulm Basin was situated in the narrow tropical Rhenohercynian Ocean that stretched between the major Gondwana and Laurussia continents and connected the Palaeotethys with the Palaeopacific Ocean. Here, palaeooceanographic conditions favoured plankton production, mostly represented by radiolarians, whilst other sedimentary input was temporarily scarce. Radiolarian-rich oozes could form consequently.

The siliceous Kulm succession addressed here is generally some 60–80 m thick. It starts with the Kahlenberg Subformation of the Oberrödinghausen Formation, a black alum shale unit that includes siliceous layers. It is overlain by the Hardt Subformation which consists of black well-bedded radiolarian cherts. Upsection, these grade into the Laisa Formation, mostly made up of grey and greenish radiolarian cherts intercalated with altered tuff layers. In the Rhenish Massif, calciturbidites are increasingly intercalated, so that the resulting alternation is called Hillershausen Formation here. Siliceous sedimentation fades out in the overlying Bromberg Formation (Lautenthal Fm. in the Harz Mts.), an alternation of variegated thin siliceous, calcareous, shaly and tuffitic beds. The Kulm succession is dated by conodonts, ammonoids and—in the dominating purer siliceous parts—by radiolarians of the *Albaillella paradoxa* to *A. rockensis* zones (Hastarian to Asbian). The formation names were given by Korn (2003a, b) and are formally defined in Litholex (2020).

Petrographically, the siliceous rocks are mostly made up of radiolarians with variable admixtures of sponge spicules, phyllosilicates and laminae of rhyodacitic or trachytic fragments. Phosphorite nodules are locally present in the black parts. Bedding is monotonous and generally even:

cm to dm thick siliceous beds are rhythmically intercalated with mm thin shaly layers and, up-section, metabentonitic tuffs and dm-bedded fine-grained calciturbidites. Mineral composition, textures and most sedimentary structures are diagenetic. Silica is microquartz/chalcedony as final products of the diagenesis that started from original biosiliceous ooze (Opal-A) and passed through a metastable Opal-CT phase.

Siliceous sedimentation started in the black-shale phase of the Early Carboniferous, probably caused by a sea-level rise in Tournaisian time. The associated transgression onto adjacent shelf areas and increasingly dry climate resulted in reduced sedimentary input into the basin, which became starved, so that in early Viséan time relatively pure radiolarian oozes could be deposited, at very low accumulation rates. In the Asbian (late Viséan) these pelagic conditions slackened and finally vanished, when the seaway narrowed and sedimentary input from the shelf areas increased, so that gradually radiolarian oozes could no longer form.

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