The Rhenish Massif: More than 150 years of research in a Variscan mountain chain

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Introduction

The Rhenish Massif is a classical fold-and-thrust belt and is interpreted to be part of the Avalonia Terrane, which separated from Gondwana in the Early Ordovician (e.g. Romer and Hahne 2010; Linnemann et al. 2014). The later collision with Baltica and Laurentia led to the closure of the Iapetus Ocean and Laurussia (“Old Red Continent”, ORC) was formed (Kroner et al. 2007; Nance et al. 2010). The Rhenish Massif, as one of the structural units of the Variscan orogen, was subdivided by Kossmat (1927) into the Moldanubian, Saxothuringian, and Rhenohercynian zones as well as the Subvariscian. Kossmat’s (1927) model was later modified by Brinkmann (1948), who added the Mid-German Crystalline Zone, which is interpreted as a structural high between the Rhenohercynian and Saxothuringian zones.

The Rhenish Massif represents a classical region of Palaeozoic successions, particularly Devonian and Carboniferous rocks, which have a wide distribution (Fig. 1). Palaeozoic sedimentary rocks are well known for their rich faunas, which were described from various facies settings (Fig. 2). Facies analysis and detailed knowledge of fossils are crucial to get a better understanding on complex interactions of palaeoecology and facies settings. This finally led to the intention to publish this special issue, which has a clear focus on palaeontology, facies analysis, biostratigraphy, and biogeography.

Facies analysis and rich faunas from the Rhenish Massif provided the background to interpret various facies settings and fossils were used to define international biostratigraphic units and regional stages. The Wetteldorf section (Fig. 3) at the southern limb of the Prüm Syncline, Eifel region, is the Global Stratotype Section and Point (GSSP) of the Lower-Middle Devonian Boundary (Emsian-Eifelian Boundary). The base of the Eifelian stage is defined by the first occurrence of the conodont Polygnathus costatus partitus. Based on the well-established biostratigraphic record, the section was restudied in a cyclostratigraphic framework, which points to the imprint of the 18-kyr precession cycle (De Vleeschouwer et al. 2018). However, there is further potential to define biostratigraphic units and boundaries as is suggested in this issue.

Lower Devonian rocks exhibit thick siliciclastic successions, which have been traditionally assigned to two facies settings, the “Rhenish” and the “Hercynian” facies (Erben 1962). As this “two facies” concept oversimplifies diverse neritic environments, new subdivisions have been proposed, based on benthic assemblages (see Jansen 2016, cum lit). Biostratigraphic correlation of neritic facies and more hemipelagic settings is a challenge and requires more future research.

During the Mid- and early Late Devonian, the palaeogeographic position of the Rhenish Massif favoured the development of coral-stromatoporoid reefs and carbonate platforms, which are widely distributed. On a global scale, the Eifelian to Frasnian represents the time of maximum reef growth in Phanerozoic Earth history. Caused by lateral and vertical changes in palaeoecology, reef palaeotopography, synsedimentary tectonics, and/or active volcanism, the reef development varied greatly at a local scale. Whereas in the northern part of the Rhenish Massif, east of the river Rhine, laterally extensive and hundreds of metres thick reef complexes became established on the inner shelf (e.g. Hagen-Balve Reef) or at its margin (e.g. Attendorf and Brilon reefs), in the Lahn-Dill area to the south, most reefs are associated with volcanic buildups within the outer shelf basin. West of the river Rhine platform carbonates with bioherms and mud-mounds prevail (e.g. Krebs 1974; Becker et al. 2016a, b; Königshof et al. 2010; Stichling et al., this issue). A number of
outcrops provide a three-dimensional view in fossil reefs, particularly in the Lahn Syncline (Fig. 4). Extinction of reefs within the Rhenish Massif did follow the global picture, which means they were drowned in the course of the global Taghanic Event (see Aboussalam 2003) or of Frasnian transgressions, mostly well before the global end-Frasnian Kellwasser Crisis. Thus, drowning and final extinction in different reef settings did not happen isochronically.

The mid-Palaeozoic was a time of rapid, fundamental change in Earth’s climate system resulting in significant sea-level fluctuations and catastrophic changes in ocean chemistry producing global oceanic anoxia. Ecosystems were severely impacted by a series of mass extinctions and ecological perturbations. Anoxic sediments are well known within the Rhenish Massif and are still a research focus. Global extinction and radiation events may reflect the accumulation of synchronous regional trends, affecting at the same time different endemic taxa and biota, or biotic changes in dominant cosmopolitan populations. In most cases, this aspect has not yet been sufficiently studied. Furthermore, records of biomarkers for anaerobic photosynthetic bacteria, which prove that anoxic conditions reached the photic zone of ocean surface regions (e.g. Joachimski et al. 2001; Hartkopf-Fröder et al. 2007), will become more important in order to better understand long- and short-term crises and events.

Much progress has been made over the last centuries in terms of biostratigraphy, facies development, and, more recently, by the application of analytical methods, such as isotope analysis, geochemistry, geophysics, and provenance analysis (e.g. Eckelmann et al. 2014; Mende et al. 2019; Van der Boon et al. 2022) in order to get a better understanding of complex facies settings, palaeogeography, tectonic framework, and age-determinations of non-fossiliferous units within the Rhenish Massif.

Nevertheless, there is still need for further research in the Rhenish Massif, which will provide new insights into diverse facies settings at the southern margin of Laurussia.

**Contributions to the special issue**

The special issue on “The Rhenish Massif: More than 150 years of research in a Variscan mountain chain” includes ten contributions
Fig. 2 Representatives of important fossil groups from the Rhenish Massif. 

a *Aulatornoceras posterior* Becker, 1993, Bergisch Gladbach, Knoppenbissen Formation, lower Famennian, UD II-C/D, lateral view, photo R. Thomas Becker, Münster. 
b *Serpulospira serpula* (de Koninck in d’Archiac and de Verneuil, 1842), Bergisch Gladbach, Büchel Formation, lower middle Givetian, collection Ruhr Museum Essen, re-illustration of Hartkopf-Fröder and Weber (2016, pl. 1, fig. 4). 
c *Dianops* aff. *griffithides griffithides* (Richter and Richter, 1919), Wuppertal Uellendahl, Famennian, UD V, dorsal view, photo Stephan Helling, Bonn. 
d–e *Scaphignathus velifer velifer* Helms, 1959, Beringhauser Tunnel, Bed 2, regional *Palmatolepis gracilis sigmoidalis* Subzone of the *Pseudopolygnathus granulosus* Zone, Famennian, UD III-C, (d) lateral view, (e) oral view. 
f Almost complete coccosteomorph arthrodire, Lohplatz Quarry, Strunde Valley, Oberer Plattenkalk Formation, upper Givetian to lower Frasnian, collection Ruhr Museum Essen, re-illustration of Hartkopf-Fröder and Weber (2016, pl. 7, fig. 4). 
g *Euryspirifer assimilis latissimus* Mittmeyer, 2008, internal mould of ventral valve, Wernborn, Spitznack Formation, lower Emsian, photo Ulrich Jansen, Frankfurt a.M.
covering taxonomic research on a new Early Devonian zosterophyllopsid plant, two new trilobite species, bryozoans, molluscs, and conodonts (including new taxa), the rise and extinction of reefs and high-resolution conodont biostratigraphy. Besides these publications some more additional contributions are planned to be published as a supplement in a forthcoming issue of Palaeobiodiversity and Palaeoenvironments in 2023.

Early and Mid-Devonian plant remains from the Rhenish Massif are world-famous among palaeobotanists and frequently figured in modern textbooks (e.g. Taylor et al. 2009). During the last years, numerous large plant specimens up to 2 m in length, including almost complete trees, have been excavated by Peter Giesen in two quarries near Lindlar (Fig. 5). Plant remains (Fig. 6, from the Schiffarth Quarry,
Fig. 5  Active quarry of the BGS Vitar, Lindlar, which yielded well preserved and large plant remains
Lindlar) and the invertebrate fauna provide a snapshot of a Mid-Devonian (Eifelian, approx. 390 Ma) coastal ecosystem. The host sediment is a fine-grained sandstone with thin intercalated mudstones and claystones. Sedimentary structures such as large channels, hummocky and swaley cross stratification, and erosive bases of sandstone beds suggest high energy flooding events (Giesen and Berry 2013). The exceptional preservation of trees with roots and crowns indicates that these specimens have been deposited not far away from their original habitat. Based on these recent discoveries and a new whole-plant reconstruction of the pseudo-sporochlaneous Calamophyton primaevum by Giesen and Berry (2013), a reconstruction of the Mid-Devonian Lindlar forest, one the world’s oldest known forests, has been presented by Peter Giesen and Mikko H. Kriek (Fig. 7, for details see Giesen 2020).

Gossmann et al. (2022, this issue) provide a new contribution to the famous Devonian macroflora of the Rhenish Massif. From the Siegenian (Pragian and early Emsian), a new zosterophyllopsid species is erected, of which vegetative and fertile remains are described. Surprisingly, this very distinct plant has been found in numerous localities. Obviously, it was a widespread component in the Siegenian macroflora and occasionally formed monotypic stands. The new species is distinct from other Zosterophyllopsida in having compact strobili of up to seven rows of helically inserted sporangia (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-021-00509-9).

Dating back to the pioneer publications by Goldfuss (1826), Steininger (1849), and Sandberger and Sandberger (1856) on the palaeontology of the Rhenish Massif, Devonian fenestrate bryozoans have been described. Ernst (2022, this issue) provides a detailed analysis of seven phylloporine and fenestellid species from the Eifelian and Givetian of the Eifel and Sauerland area. Four species are described in open nomenclature. As is true of many fossil groups, a re-study of previously described taxa is urgently needed but hindered by loss of types or material that cannot be used to produce thin sections (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00544-0).

Another taxonomic study is presented by Nagel-Myers (2022, this issue) with her contribution on the bivalve genus Ontaria. More than a dozen of species have been previously assigned to this genus but based on an extensive literature review and material from numerous Devonian basins all over the world, only three valid species are accepted. Ontaria is the first cardiolid reported from the Devonian and occurs in Mid- and Late Devonian pelagic environments, probably living semi-infaunal in or on muddy sediment. The appearance of the genus is in the late Eifelian and its last occurrence is in the late Famennian (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-021-00491-2).

Several publications in this special issue deal with reefs in the Rhenish Massif. Reef limestones are of high quality and, thus, of economic interest. They have been exploited for centuries and are well exposed in huge quarries. Cores from exploration boreholes offer additional insights into the succession facilitating investigation of reef development and subsequent extinction.
Fig. 7 Reconstruction of the Mid-Devonian Lindlar forest. Scientific draft by Peter Giesen, realisation and copyright Mikko Kriek/LVR-Landesmuseum Bonn (with courtesy of P. Giesen and M. Kriek)
Ribbert and Piecha (2022, this issue) investigated siliciclastic and volcanic input into middle Frasnian sandstones and reef limestones of the Velbert Anticline Reef Complex. Admixture of volcanic detritus to a neritic carbonate platform usually characterised by reefal sediments is quite unusual in the Rhenish Massif. The source of the quartz grains was a rhyolitic volcanic rock, which was eroded in an area nearby, probably the successor of the Givetian Krefeld High. Later, near the Frasnian/Famennian Boundary, the semi-consolidated rocks were uplifted due to tectonic movements and eroded again resulting in complex sedimentation phases (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00524-4).

Löw et al. (2022, this issue) describe in detail the initial phase of the Hönne Valley Reef, which is part of the extensive Hagen-Balve Reef Complex, a classic area for the study of Givetian coral-stromatoporoid reefs in the Rhenish Massif. A section located near Binolen in the Hönne Valley was logged bed-by-bed. Seven microfacies types and six microfossil biofacies types are distinguished resulting in the definition of seven depophas. They enable a detailed reconstruction of periods of deepening, regression, biostrome growth, and the establishment of a lagoon. The study clearly emphasises that microfaunal data are significant proxies in the interpretation of reefal environments (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00540-4).

From the Binolen section (see Löw et al. 2022, this issue), i.e. from the initial phase of the Hagen-Balve Reef Complex in the Hönne Valley, Athüppe and Becker (2022, this issue) report a new genus and species of a discosorid nautiloid. In addition, two other taxa are discussed. A single specimen, probably also a new species, is provisionally assigned to the archiacoceratid Cyrtoceratites. A summary of previous records of Mid-Devonian nautiloids from reefal facies of the Rhenish Massif demonstrates that they are still insufficiently studied, although they are quite diverse and can contribute to ecosystem analyses (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00541-3).

The Hagen-Balve Reef Complex in the Hönne Valley is also subject of a third contribution by Stichling et al. (2022, this issue) which, however, focuses on the drowning and extinction of one of the largest reefs in the Rhenish Massif and the overlying succession including pelagic limestones and sediments of the Lower and Upper Kellwasser Event intervals. The initial drowning was caused by sea-level rise and subsidence while local tectonic movements seem to have been negligible. Subsequent rapid deepening correlates with the global Middlesex Event at the lower/middle Frasnian boundary and resulted in the final extinction of the reef. Based on numerous conodont samples a detailed biostratigraphical framework is provided. The semichatovae Event Interval is developed as cyclic anoxic black shales (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00539-x).

Helling and Becker (2022, this issue) introduce two new species of Gondwanaspis, a cosmopolitan trilobite genus ranging from the early Frasnian until the base of the Upper Kellwasser Event. The material comes from the Velbert Anticline Reef and the final phase of the Hönnne Valley Reef, i.e. from late Givetian–early Frasnian reefal limestones. Gondwanaspis is a rather rare constituent of the trilobite fauna of the Rhenish Massif and the new records probably represent the first evidence of the genus in the latest Mid-Devonian (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00525-3).

One Global Boundary Stratotype Section and Point, the GSFP for the base of the Eifelian Stage, has been defined in the Rhenish Massif near Schönecken-Wetteldorf (Fig. 3). Two contributions to this special issue deal with sections, which have the potential to be taken into account to define the position of the middle/upper Frasnian substage boundary and to redefine the base of the Carboniferous.

Saupe and Becker (2022, this issue) present a detailed bed-by-bed documentation of the famous Martenberg section, where the classical Frasnian goniatite and conodont zonation has been developed. It is recommended to place the upper Frasnian substage boundary at the base of Frasnian Subzone 11b, which coincides with the global eustatic semichatovae Event. The restudy of the conodont fauna from Martenberg shows that at present the section offers the best record for a conodont zonation at the middle/upper Frasnian transition. The conodont biostratigraphy is complemented by microfaucies analyses and a taxonomic review of key conodonts, including the description of a new taxa (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00537-z).

Hartenfels et al. (2022, this issue) present the currently best and most complete Devonian/Carboniferous Boundary succession of the Rhenish Massif and, therefore, propose the Borkewehr section as a candidate for the new base of the Carboniferous. The multiprox study includes conodont and ammonoid biostratigraphy, the description of some rare corals, microfaunas analyses, sequence stratigraphy, inorganic geochemistry, and cyclostratigraphy. It is suggested to use the First Appearance Datum (FAD) of Protognathodus kockeli s. str. as a potential biostratigraphic tool for a new DCB definition. Taxonomy of key conodont taxa is extensively discussed and a new conodont species is proposed (Palaeobiodiversity and Palaeoenvironments, 102(3) https://doi.org/10.1007/s12549-022-00531-5).

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