GEOLOGICA BELGICA (2016) 19/1-2: 81-110

Mississippian (Early Carboniferous) sequence stratigraphy of the Rhenish Kulm Basin, Germany

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ABSTRACT. The Rhenish Kulm Basin is a deeper-water foreland basin developing in front of the Variscan Orogen in Germany. Three major facies interfinger and might overwhelm the adjacent one in time. These are (1) internal siliciclastic flysch facies, (2) central starved basin facies, and (3) calciturbidite facies. Calciturbidites are derived from the Northwest European shallow-water carbonate platform or not preserved intrabasinal sources. Besides, a deep intrabasinal swell facies is characterized by condensed successions. Diagnostic rock types within each facies enable the recognition of systems tracts of third-order depositional sequences. The interpretation of faunal developments and bioevents support these attributions. Hence, for the first time a sequence stratigraphic subdivision of the Rhenish Kulm Basin into 13 sequences is achieved, ranging from the latest Devonian to the early Namurian. The lower nine sequences are correlated with the Dinantian sequences earlier established on the Belgium shallow-water platform. Two Brigantian sequences 10 and 11 are identified and, despite the prograding Variscan Orogen, the two lower Namurian (Pendleian, Arnsbergian) sequences 12 and 13. The results demonstrate the successful application of sequence stratigraphy in a deeper-water basin, show that sea-level changes overrule the general, more gradual tectonic development of the basin, and prove the Palaeotethyan, if not global isochroneity of Mississippian sequences.

KEYWORDS: Sea-level changes, starved basin, calciturbidite, flysch, lithostratigraphy, faunal changes, epiboles, biostratigraphic correlation

1. Introduction

The relation between sea-level variations and sedimentary sequences that are bound by erosional unconformities was already elucidated by Sloss et al. (1949) and Sloss (1963) concerning the cratonic sequences of the conterminous U.S. (see also Sloss, 1988). However, only introduction of sequence stratigraphy on a seismic scale (Vail et al., 1977) caused a revolution of stratigraphic studies (Van Wagoner et al., 1987, 1989; Vail et al., 1991). It was a major step to understand the lateral genetic relationships of rock units in platform-slope-basin transects as well as their vertical genetic superposition, both based on the unifying aspect of relative sea-level changes. In the meantime, a plethora of studies is available from all kinds of sedimentary lithotypes throughout geological times, ranging from the sequence stratigraphic interpretation of single sections to seismic scale basins. However, most studies are devoted to shallow-marine platform settings. Sequence stratigraphic approaches to continental and basinal settings are underrepresented, and for the latter are almost completely confined to siliciclastic turbidite fan systems. Case studies and principles for deeper marine settings were reviewed by Catuneanu (2006) and Catuneanu et al. (2009, 2011), but miss an example of a complex deeper water foreland basin with differentiated lithosomes, as seen in the European and Northwest African Kulm basins.

Herein, the sequence stratigraphic development of the Mississippian (Early Carboniferous) deeper-water succession of the Rhenish Kulm Basin (RKB) is elucidated and correlated with the carbonate platform sequences of Northwest Europe. The approach contributes to a refined correlation of both megafacies. Biostratigraphic correlations started already in the 19th and earlier 20th century (Sedgwick & Murchison, 1842; Paul, 1937, 1939; Paproth, 1969), but remained limited due to different biofacies with zonal schemes based on ammonoids, conodonts and radiolarians in the RKB (e.g. Amler et al., 2002; Stoppel & Amler, 2006a, b; Korn, 2010), and brachiopods, corals and calcareous smaller foraminifers in the platform facies (e.g. Paproth et al., 1983; Conil et al., 1990; for the current scheme see Poty et al., 2006). Calcareous smaller foraminifers, reworked from shallow water sediment and abundant in the calciturbitic formations of the RKB are a most promising tool (Conil & Paproth, 1968, 1983), but their correlation potential is hampered by hydraulic sorting (Herbig & Mamet, 1994), the unknown extent of diachronic reworking, almost complete absence of calcareous Tournaisian rocks, and missing modern biostratigraphic and taxonomic studies of foraminifers in the Viséan formations of the RKB (Herbig, 2006a).

2. Previous sequence stratigraphy studies of the Mississippian Northwest European carbonate platform and the Rhenish Kulm Basin

Sequence stratigraphy studies of the Mississippian (Early Carboniferous) platform succession of Belgium and adjacent regions in northern France (Avesnois, Boulonnais) were initiated by Hance et al. (2001). Firmly rooted in biostratigraphy, they were rapidly expanded to correlate British sequences, especially based on sections in southern Wales (Hance et al., 2002), and to the Krakow area of southern Poland (Poty et al., 2007). Correlation with southern China might lead to a global sequence stratigraphic model for the Mississippian (Poty et al., 2011a, see also Poty & Hance, 2008). This was underlined by the proposal that Belgian substages might serve for the chronostratigraphic subdivision of the Tournaisian and Viséan stages (Poty et al., 2014).

For the latest Devonian (‘Strunian’) and the Devonian-Carboniferous transition, already Hance et al. (1993) recognized an identical sequence stratigraphic development in southern China and Belgium. This study followed on a first approach to that time slice in Belgium by Van Steenwinkel (1990, 1993a). Still earlier, Ramsbottom (1973, 1979) recognized sea-level changes on the Northwest European Mississippian carbonate platform as a powerful tool for correlation, followed by Ross & Ross (1985, 1987a, b, 1988), who demonstrated synchroneity of Late Palaeozoic sea-level changes on the major carbonate platforms in North America, Northwest Europe and Russia.

Recognition of the Mississippian sequence stratigraphy in the Belgian Namur-Dinant Basin and correlation with platform deposits in Great Britain later also enabled to decipher the sedimentary history in the complex block faults of the Visé-Maastricht area at the eastern tip of the London-Brabant Massif (Poty & Delculée, 2011). That study is an impressive example of the interplay between sea-level induced flooding and emergence and the contemporaneous block faulting and demonstrates the applicability of sequence stratigraphic methods in tectonically active regions. Further, Bábek et al. (2010, 2013) and Kalvoda et al. (2011) showed the powerful application of outcrop gamma-ray spectrometry and magnetic susceptibility in combination with carbonate facies stacking patterns and high resolution biostratigraphy to trace the sequences close to the Tournaisian-Viséan boundary. In their studies they could correlate ramp to intraplatform basin sections around the Wales-Brabant Massif in the British Isles and Belgium, as well as at western margin of the RKB in the Velbert anticline.

http://dx.doi.org/10.20341/gb.2016.010

In the RKB, a first detailed interpretation of sequence stratigraphy, including correlation with the platform development from the Belgian Dinant Synclinorium, was devoted to the Devonian-Carboniferous transition, respectively to the time interval from the late Famennian *Wocklumeria* Limestone to the 'mid-Tournaisian' Lower Alum Shale (Van Steenwinkel, 1993b). Simultaneously, but without notation of sequence stratigraphic terms, eustatic cycles of this interval were deduced from the sedimentary development by Bless et al. (1993).

Already Herbig & Bender (1992) interpreted the facies development of a 'mid-Tournaisian' calciturbiditic formation from the Hörre Belt, eastern RKB, as transgressive systems tract/highstand systems tract and the 'Lower Alum Shale' as time equivalent starved basin facies. Based on that, Bender et al. (1993) and Herbig (1993, 2007, 2011) stressed the importance of sea-level variations for the facies development of Late Devonian (Famennian) and Early Carboniferous lithostratigraphic units in the RKB and introduced sequence stratigraphic terms for some units. Due to unresolved biostratigraphic problems and the unknown importance of synsedimentary tectonics, sequence stratigraphic approaches were limited to single time slices. They were centred at the 'mid-Tournaisian' Lower Alum Shale Event (Herbig & Bender, 1992; Siegmund et al., 2002), the Tournaisian-Viséan boundary (Velbert anticline; Bábek et al., 2010), the late Asbian-early Brigantian (Herbig, 1994; Mestermann, 1998; Piecha et al., 2004), and the mid-Brigantian *Actinopteria* Shale Event in the sense of Nyhuis et al. (2015). The importance of sequence stratigraphy in deeper-water basins similar to the RKB was demonstrated by the recognition of the same late Asbian-early Brigantian sequence stratigraphic system tracts in the deeper-water Kulm environment of the Bardo Mountains (Sudetes; Herbig, 1998) and the South Portuguese Zone (Mestermann, 1998; Herbig et al., 1999). Later, Herbig (2011) proposed a first correlation of sequences from the RKB with the Northwest European shallow water carbonate platform. The sequence stratigraphic interpretation of a completely cored latest Famennian ('Strunian') to late Viséan succession in the Velbert Anticline, western margin of the RKB (Herbig et al., 2013, 2014b), provided further links for the correlation of both megafacies.

3. Facies setting

The Mississippian succession of the RKB displays the typical deeper-water Kulm facies of the asymmetrical Variscan foreland basins in Europe and Northwest Africa. In spite of the generally assumed monotony, facies development is considerably differentiated in space and time (Fig. 1).

In space, lithology was controlled by the distance to the two major sediment sources, i.e. the southeastern orogenetic siliciclastic source (Mid-German Crystalline Rise) and the external Northwest European carbonate platform. In

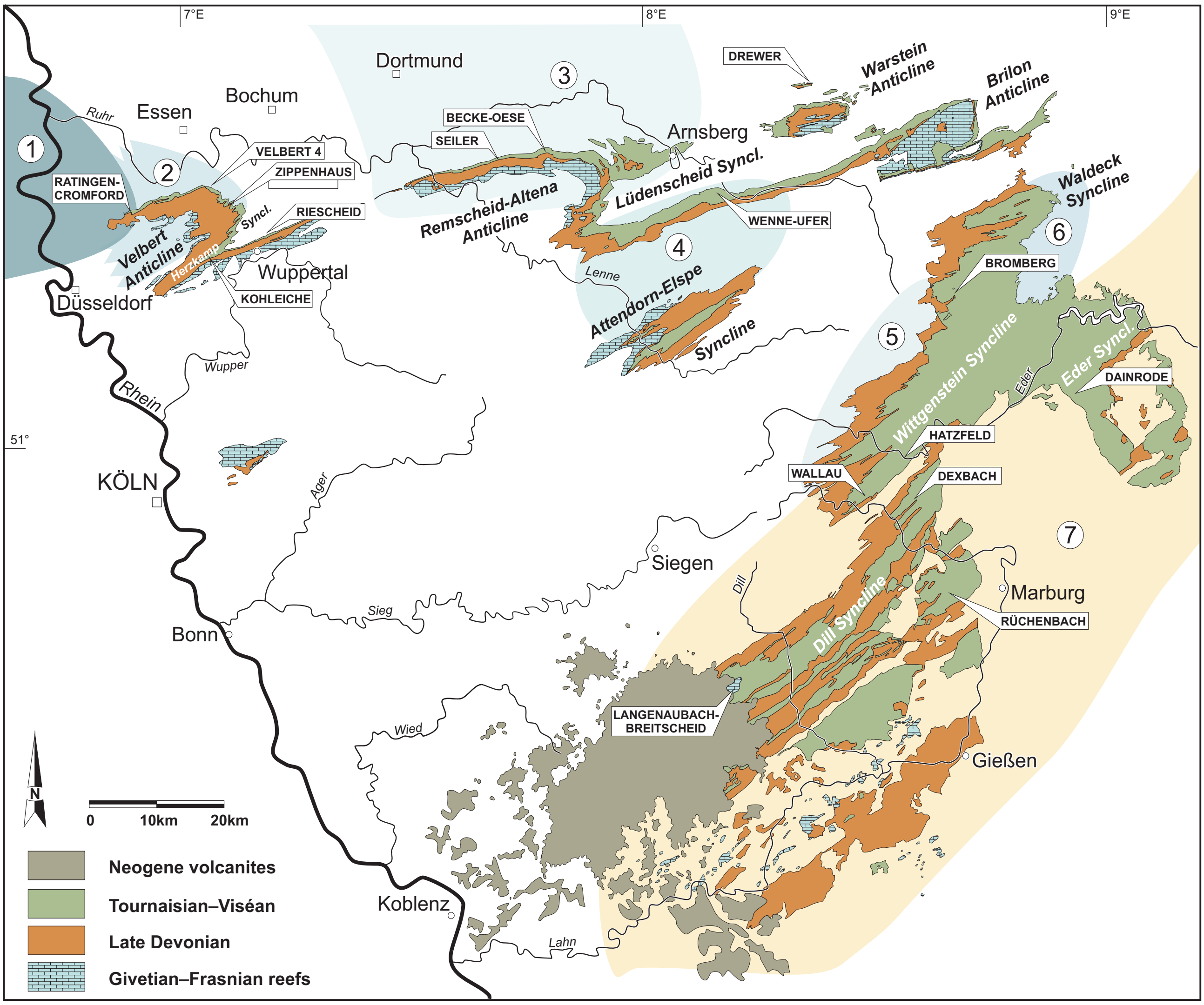

Figure 1. Geological overview of the Rhenish Mountains showing major tectonic structures, described key sections, and major facies realms. 1: Shallow-water carbonate platform of the Ratingen Sedimentation Area (Aretz et al. 2006); 2-3: Calciturbidite facies fed by external platform sources (2: Velbert Calciturbidite System; 3: Herdringen Calciturbidite System). 4-6: Starved basin facies including calciturbidite systems fed during different stratigraphic intervals from intrabasinal sources (4: Hellefeld Calciturbidite System; 5: Hesseberg and Wittgenstein calciturbidite systems, not differentiated; 6: Rhena Calciturbidite System). 7: Flysch facies. Based on Herbig (1998), Herbig et al. (2006), and Korn (2008, 2010).

consequence, three major facies are discerned (Herbig, 1998): (1) an *internal siliciclastic flysch facies* with predominance of siliciclastic sediments shed from the extrabasinal orogenetic source, (2) a central *starved basin facies* with thinner successions of predominantly basinal rocks, such as shales, siliceous shales and bedded cherts, and (3) an external *calciturbidite facies* fed by gravitative resedimented shallow-water carbonate particles derived from the Northwest European platform (Velbert and Herdringen calciturbidite systems; Korn, 2008). This generalized facies distribution is complicated by smaller, not preserved intrabasinal shallow-water carbonate platforms, which shed in part coarse-grained calciturbidites into the adjacent basinal realms (allodapic limestones; Meischner, 1964). One of these platforms probably developed on top of a drowned Givetian-Frasnian reef in the central part of the basin within the later Attendorn-Elspe Synclinorium; derived resediments are widespread in the area of the Lüdenscheid Syncline (Hellefeld Calciturbidite System; Gauglitz, 1967; Helmkampf, 1969; Korn, 2008). Further platforms with differentiated shedding patterns are known from the northeastern part of the basin. These are the Hesseberg and Rhena calciturbidite systems from the Waldeck Syncline and another calciturbidite system from the Wittgenstein Syncline (Meischner, 1962; Eder et al., 1983; Franke, 1991; Korn, 2008).

Finally, intrabasinal deep-water swells capped by micritic, partly nodular limestone of the ‘Erdbach type’ are known. Such limestones occur in the type region in the southern Dill Syncline (‘Erdbach Limestone’), the Brilon, Warstein, and Belecke anticlines in the northeastern RKB, and the Herzkamp Syncline in western RKB (‘equivalents of the Erdbach Limestone’ of authors, see e.g. Krebs 1968b). They developed on top of drowned Givetian-Frasnian reefs or on embryonic tectonic structures of the advancing Variscan Orogen. Thus, Franke et al. (1975) assumed a forebulge position for the nodular limestones of the Herzkamp Syncline.

In time, lithology was controlled by eustatic sea-level variations and the advancing Variscan orogen front, which besides the general progradation of the flysch facies caused embryonic Variscan faulting and folding within the proximal parts of the basin (Ricken et al., 2000; Schrader, 2000). Facies shifts in space and time resulted in lateral and vertical mixing of the rocks typifying one of the major facies, or its complete substitution.

4. Fundamentals of sequence stratigraphy in the Rhenish Kulm Basin

In sequence stratigraphy, the distinction of depositional sequences and the constituting systems tracts is based on the recognition of sea-level variations. They are easily traced in platform settings. In seismic profiles, they can be observed across the slope in platform-basin transects due to the development of erosional unconformities, that bound single sequences. Basinwards, unconformities and recognizable sequences fade out and at best a hardground surface might separate them, if not obliterated by pelagic rain. Therefore, in deeper water basins the main question is how to recognize sea-level changes acting far above in the water column. Although single sequences tend to be masked on wide basin plains, fundamental deeper water lithofacies types enable to classify systems tracts (Fig. 2). It has to be stressed that most but not all lithofacies are related to a palaeobathymetrically differentiated basin topography as elucidated for the RKB above, and rely on gravitative reworked sediment types. Although formed at internal highs and at the margins of the basin, especially turbidites might prograde widely across the basin.

Lowstand systems tracts (LST) are characterized by erosional unconformities at the basin margins and on highly elevated intrabasinal highs. At their slopes coarse-grained gravitative resediments develop, e.g. conglomerates and debris-flow sediments. Resediments deriving from the external carbonate platform and from intrabasinal highs – whether restricted to deeper water or projecting into shallow water – are exclusively composed of intrabasinal sedimentary clasts. According to the scale of sea-level drop and the resulting depth of erosion, the age of components might be notably older than the host sediment. However, often they are almost penecontemporary in age, proving erosion of sediment from the immediate preceding highstand. Calciturbidites are rare.

Also at the slopes of low intrabasinal deeper water swells resedimentation is proved. There, slope failure and formation of resediments are apparently related to lowered hydrostratic pressure. Resediments from the internal flysch facies are characterized by thick successions of coarse-grained, in part conglomeratic greywackes without notable fine-grained interbeds. Especially important are conglomerates and debris-flow sediment bearing crystalline extrabasinal components from the rising Variscan hinterland, i.e. the Mid-German Crystalline Rise. In some sequences, LSTs were not recognized, probably due to sediment starvation. In these cases, the base of the sequences was associated with the base of the transgressive systems tract.

Transgressive systems tracts (TST) are often characterized by black shales that spread throughout the basin and homogenize facies differences. In spite of the manifold genesis of black shales (Wignall, 1994), this relation was amply demonstrated in sequence stratigraphic studies. In the RKB, the successions are

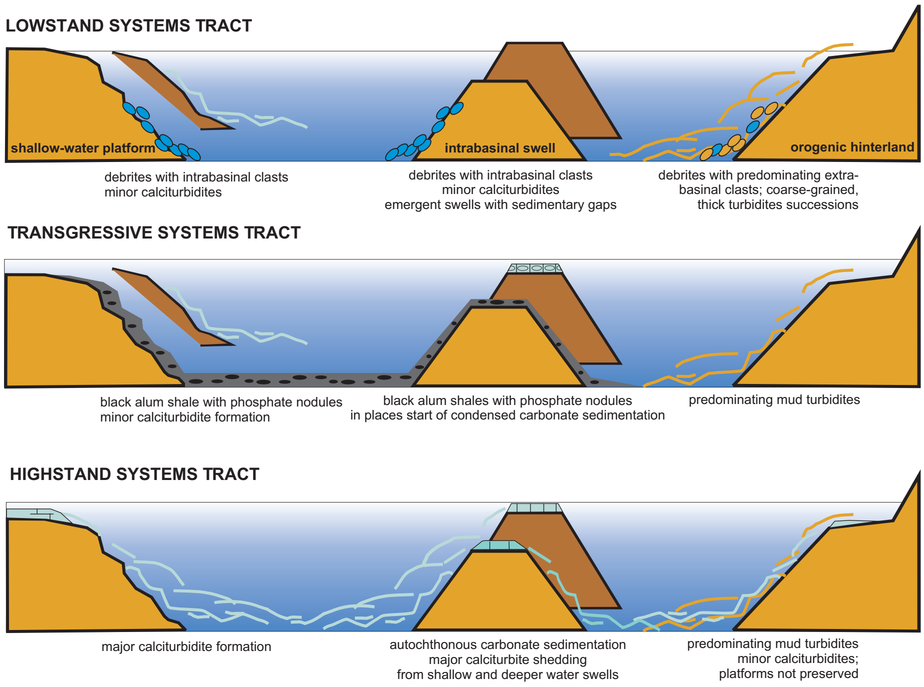

Figure 2. Major sequence stratigraphic building blocks from the deeper-water Rhenish Kulm Basin.

mostly developed as phosphate nodule-bearing alum shales and siliceous shales. At the base of the successions basal lag sediments containing reworked phosphate nodules and detrital quartz might occur. The transgressive nature of Devonian and Mississippian black shales of the Rhenish Mountains was already discussed by Krebs (1969) and, concerning the 'Lower Alum Shale', by Siegmund et al. (2002).

Highstand systems tracts (HST) within deeper water basins record high water depth, as progradation of the coastline due to minimized accommodation space does not apply. Opposed to shallow water platforms absolute water depth is the ruling factor. Outside the internal flysch facies and adjacent to shallow-water sources, HSTs show well-developed, relatively thick calciturbidite successions. They are composed of thick, narrow-spaced calciturbidite beds with shallow-water bioclasts, as calcareous algae, calcareous smaller foraminifers, and brachiopods. They also include non-skeletal shallow-water allochems such as ooids and cortoids. These successions are the typical consequence of highstand shedding from flooded, highly productive shallow-water platforms (Mullins, 1983; Mullins et al., 1983; Droxler & Schlager, 1985; Eberli, 1991; Schlager et al., 1994). The calciturbidites might be coarse-grained, but also

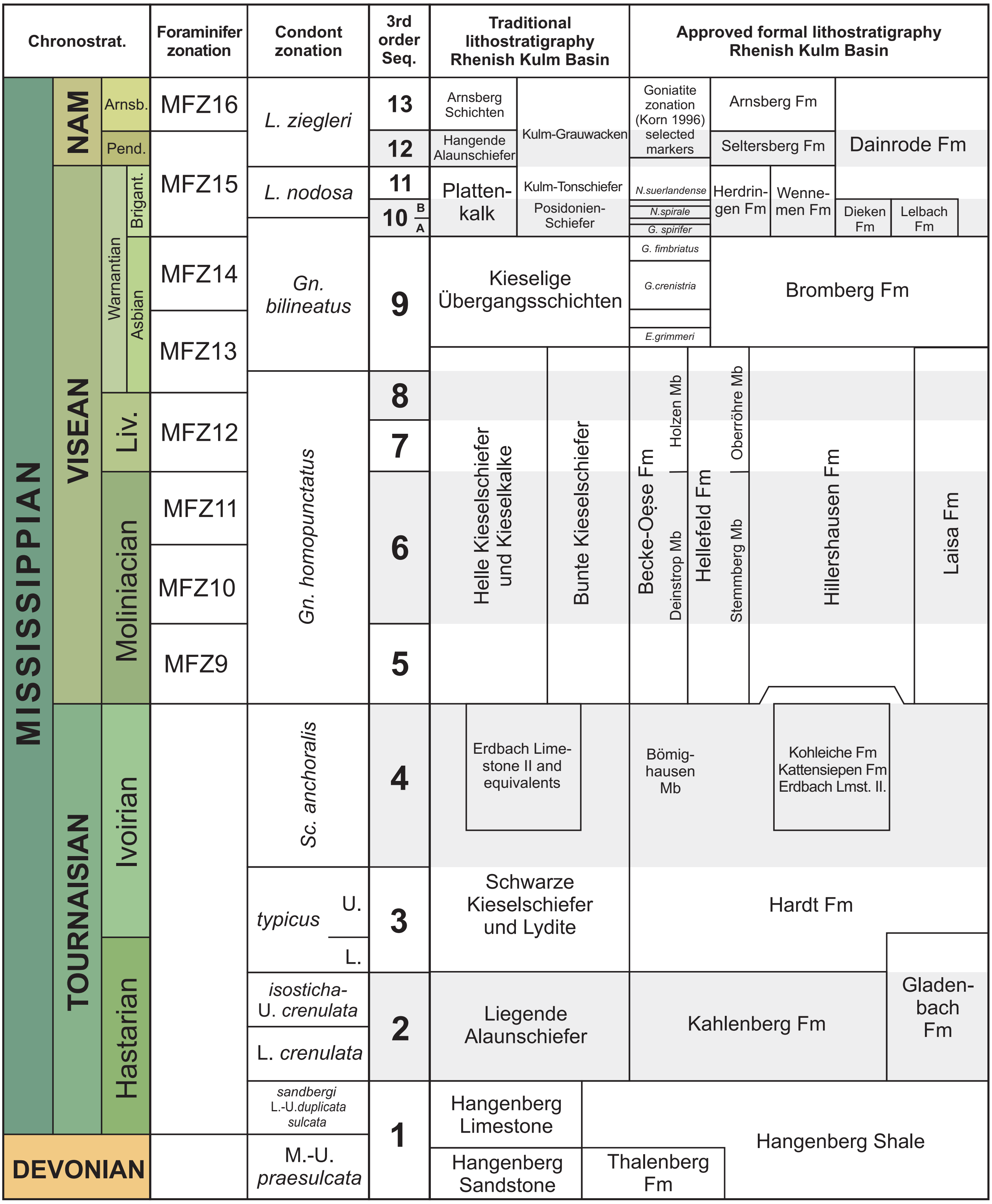

Figure 3. Correlative tableau of chronostratigraphy, biostratigraphy, 3rd order sequences and lithostratigraphic units of the Mississippian Rhenish Kulm Basin. Lithostratigraphic units approved by the German Subcommission on Carboniferous Stratigraphy and described in the online data base 'Litholex' (litholex.bgr.de).

more than metre-thick, completely fine-grained and apparently ungraded beds are observed. They result from presorting of components at platform margins; missing grading results from multiple amalgamation within the bed.

Calciturbidites also derive from deeper water swells. Such intrabasinal deep-water turbidites (Scholle, 1971; see also Stow et al., 1984) are very fine-grained; shallow-water components are completely missing. Peloids and undeterminable microbioclasts, often just pure carbonate silt, predominate. Bioclasts are thin-shelled ostracodes and radiolarians; in part even radiolarian turbidites might develop. Scholle (1971) related the origin of intrabasinal turbidites to destabilisation of slope deposits by tectonic origin or upstirring of deeper water muds by platform edge turbidites and successive replacement of the coarser grained material. Alternatively, Herbig & Bender (1992) proposed a relation to sea-level. During HST carbonate overproduction on the platform also generates surplus periplatform muds, that travel with surface currents or along internal water mass boundaries far into the basin. Fallout on deep swells might cause overload and subsequent destabilisation and slope failure. Such fine-grained turbidites, irrespective of their origin from distal shallow-water sources or from deeper-water swells, are known as 'Flinz Limestone' in the Devonian and Carboniferous of the Rhenohercynian Basin (Buchholz et al., 1991).

The top of deep intrabasinal swells, or drowned intrabasinal carbonate platforms will harbour condensed successions of micritic, in part nodular deeper water limestones with heterotrophic biota during the HST.

Within the flysch facies, the HSTs are characterized by diminished coarse-grained terrigenous input. In consequence, shaly successions predominate; thin-bedded greywackes are rare or might miss completely.

On the basin plains of the starved basin facies, sedimentation of black shales and alum shales might continue during late TST and HST. Sedimentation might also grade into siliceous rocks due to minimized sediment input and installation of a biogenic dominated pelagic sedimentary regime. However, it has to be stressed that in the RKB the diminished sediment input during TST in connection with tectonic subsidence of the basin might cause further deepening and installation of a siliceous regime across a sequence boundary and in spite of a globally lowered sea-level (see sequence 3, see 5.3).

Maximum flooding surfaces (mfs) are difficult to recognize in many cases. Therefore, Wiese & Wilmsen (1999) introduced the term maximum flooding zone (mfz) for the relatively thin lithostratigraphic unit representing the most distal conditions. Nyhuis et al. (2015) used the term 'maximum flooding interval' (mfi) to avoid confusion with biostratigraphic 'zones'. In the Mississippian of the RKB only a single maximum flooding interval was recognized hitherto, composed of an unique autochthonous deep-water microbe-cephalopod limestone (sequence 9: *crenistria* Limestone Horizon, see 5.5.1). Moreover, Nyhuis et al. (2015) identified a true mfs characterized by the record of otherwise not preserved delicate shells (sequence 11: maximum completeness epibole within the *Actinopteria* Shale in the sense of Nyhuis et al., 2015).

Sequence boundaries (SB) are placed at the basal unconformities of the sequences. In the RKB, they are rarely expressed by erosional unconformities, but more often as sharp-cut boundaries between different facies. It is assumed that in most cases the sequence boundaries coincide with the end of the base-level fall (e.g. Van Wagoner et al., 1989; see also discussion in Catuneanu, 2006; Catuneanu et al., 2009).

5. Mississippian sequences of the Rhenish Kulm Basin

In the following chapters the Mississippian sequences of the RKB are described and correlated with the time-equivalent platform sequences (Fig. 3). Key sections and key facies realms were used to construct a sequence stratigraphic framework. Elsewhere, systems tracts might be masked within undifferentiated deeper water successions. Therefore, the approach resembles in part the assembly of sequence stratigraphy from 'spot outcrops' by Van Steenwinkel (1990).

The position of the sections and their tectonic setting is indicated in Figure 1. The lithostratigraphic terminology (Fig. 3) follows the refined and formalized subdivision of the Mississippian succession of Korn (2003a, 2006a, 2010), if not further mentioned. Some units, e.g. the Tournaisian formations from the submarine swells in the Herzkamp Syncline and the Warstein and Belecke anticlines, were recently revised by a task group of the German Subcommission on Carboniferous Stratigraphy with the aim to define generally accepted mappable lithostratigraphic units, to avoid oversplitting, and to the reflect best the sedimentary history of the basin fill. A more detailed publication is in preparation, but ratified valid names as well as invalid and traditional names were published in the online database Litholex (litholex.bgr.de) by D. Korn. For better comparison with older literature also the traditional informal names are indicated in Figure 3.

5.1. Sequence 1 – Latest Devonian–lower Hastarian

In Belgium, Hance et al. (2001) and later authors (e.g. Poty et al., 2014; see also discussion in Denayer et al., 2015) placed the base of sequence 1 at the base of the transgressive mixed siliciclastic-carbonate succession of the Etroeungt Fm, or at the base of its lateral equivalents in eastern Belgium (Comblain-au-Pont Fm, Dolhain Fm). Sequence 1 was not recognized in southwestern England (Hance et al., 2002), but correlated with the stratigraphic succession in the Krakow Upland, southern Poland (Poty et al., 2007).

Earlier, Van Steenwinkel (1990, 1993a) interpreted the Etroeungt Fm and its lateral equivalents as an HST. The next sequence should comprise the Hastière Fm (LST), followed by the TST of the Pont d'Arcole Fm. This interpretation was strengthened by comparison with the RKB, where the strata deposited during the Hangenberg Sandstone Event indicate a major sea-level drop (Van Steenwinkel, 1993b; Bless et al., 1993). Hence, Van Steenwinkel (1993b) postulated a sequence boundary below the Hangenberg Sandstone and regarded it and the overlying early Hastarian Hangenberg Limestone, i.e. the pelagic equivalent of the Hastière Fm, as LST. The following 'Lower Alum Shale' (= sequence 2, see 5.2) was regarded as TST.

Concerning Belgium, Kumpan et al. (2014) proposed a model similar to Van Steenwinkel (1990, 1993a, b), but like Bábek et al. (2016) used a different sequence stratigraphic model. They placed the sequence boundary not at the end of base-level fall (i.e. at the basal unconformity of the sequence), but at the maximum regression surface (see Catuneanu, 2006; Catuneanu et al., 2009). Based on biostratigraphy, stacking patterns and supported by petrophysical and geochemical proxies, they showed an unconformity at the base of the Hastière Fm and the correlative base of the Avesnelles Fm in the Avesnois sedimentation area (southern Belgium, northern France). The unconformity was attributed to the basal surface of the forced regression, which is equivalent to the base of the Hangenberg Sandstone Event. Beds of the basal Hastière Fm above were addressed as the falling stage systems tract (FSST), with the sequence boundary at the top. Above, most of the lower and the middle Hastière member were interpreted as LST, the upper Hastière Member as TST.

In fact, the base of the Hastière Fm is thought to follow above a hiatus (Bless et al. 1993; Mamet & Préat, 2003; Kumpan et al., 2014). A biostratigraphic gap does not exist (Prestianni et al., 2016, this volume), but the distinctive thick basal bed contains reworked fauna (e.g. Conil et al., 1986; Casier et al., 2004). Recently, Mottequin & Poty (2014) gave a short overview of beds related to the Hangenberg Events in the Namur-Dinant Basin and also stated a strong sea-level fall causing deposition of the Hangenberg Sandstone. However, Denayer et al. (2015) again rejected the model of an associated sequence boundary based on stacking patterns, similar facies across the D-C boundary, and homogenous composition of the middle member of the Hastière Fm, as originally stated by Hance et al. (2001).

The thorough and extensive reviews of Kaiser et al. (2015) and Becker et al. (2016) once more elucidated the global recognizable perturbations of the 'Sixth Phanerozoic Mass Extinction' during the Hangenberg crisis and concomitant sea-level changes at the 'end-Devonian sequence boundary' (Kaiser et al., 2015). Hence, it appears to be warrantable to place the base of sequence 1 at the base of the Hangenberg Sandstone.

5.1.1. General development: the northern rim of the Rhenish Kulm Basin

The base of sequence 1 is placed at the base of the Hangenberg Sandstone, which is attributed to the LST (see references in the preceding paragraph, and for further arguments based on petrophysical and geochemical methods in Kumpan et al., 2015). Kaiser et al. (2015) estimated a sea-level fall in the scale of more than 100 m. Hence, locally incised valley fills such as the Seiler conglomerate at the northwestern margin of the RKB developed (Koch et al., 1970; Paproth, 1986; Van Steenwinkel, 1993b). Becker et al. (2016, based on data of Koch et al., 1970) stressed the fact that the canyon was filled during three successive late to latest Famennian episodes, the last one occurring above presumed equivalents of the Hangenberg Black Shale. This implies that the Seiler palaeovalley was a persistent, repeatedly reactivated structure.

Outside the source of sand-grained siliciclastics, the greenish Hangenberg Shales represent the LST. However, that unit might be bipartite. Hangenberg Shale occurring below the Hangenberg Sandstone represents the HST above the Hangenberg Black Shale, or the initial regression (Kaiser et al.; 2015, Becker et al., 2016, and references therein). Sections on intrabasinal swells, as in Drewer (Fig. 1), do not record the package (Fig. 4; Fig. 5A, C). They stress the important erosion at the base of sequence 1. Hangenberg Shale occurring above the Hangenberg Sandstone records the rising sea-level. In most sections along the northern margin of the RKB pelagic carbonate sedimentation started rapidly. It is represented by the thin veneer of the Stockum Limestone and the overlying nodular Hangenberg Limestone. Both represent the undifferentiated TST/HST of sequence 1 (Becker et al., 2016, fig. 2). Along the northern margin of the RKB, a few metres thick, shale dominated unit is developed on top of the Hangenberg Limestone (Korn & Weyer, 2003, see also Becker et al., 2016). It is attributed to the FSST below the sequence boundary that separates the sharply overlying black alum shales of the Kahlenberg Fm (sequence 2; Fig. 4; Fig. 5B, D).

The interpretation of an undifferentiated TST/HST represented by the major part of the Hangenberg Limestone (including the thin veneer of the Stockum Limestone below) is supported by the biofacies of agglutinating foraminifers (Herbig, 2006b). The oligo-generic *Hyperammina* biofacies indicates deposition in still deeper water than within the HST of the Wocklum Limestone before the Hangenberg Event, which is characterized by the generically more diverse Saccaminid biofacies. The interpretation of part of the Hangenberg Limestone as HST is consistent with the fact that within a basin the HST records high water depth. This is also demonstrated by dwarfed, blind trilobites from the upper Hangenberg Limestone (Hahn et al., 2004).

Facies analogies between the Hangenberg Limestone and the Wocklum Limestone support the interpretation of the latter as HST and a thin topmost FSST below sequence 1 (Fig. 5C, D), and, in consequence, the correct placement of the base of sequence 1. The HST/FSST character of the Wocklum Limestone can be deduced e.g. from descriptions of Korn (1995), Becker (1996), Korn & Weyer (2003), and Becker et al., (2016) that noted increased faunal content and condensation close to its top. Moreover, the interpretation is compatible with the first influx of siliciclastics seen by the Drewer Sandstone in the uppermost Wocklum Limestone in the Drewer section (Clausen et al., 1989; Korn et al., 1994), and by increased Zr/Al values at the top of the Wocklum Limestone in other sections (Kumpan et al., 2015).

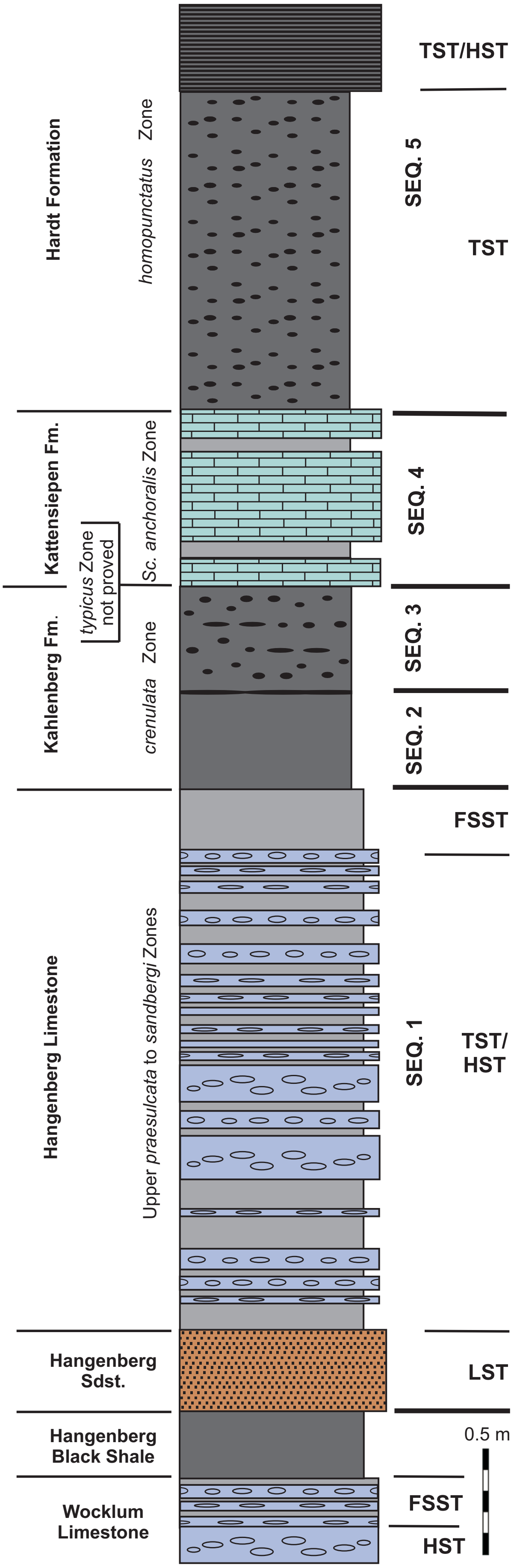

Figure 4. Late Famennian to earliest Viséan (early Moliniacian) sequences 1-5 from the Drewer quarry. Deep intrabasinal swell of the Belecke Anticline, northeastern Rhenish Kulm Basin. Section WA at the northwestern quarry from Korn et al. (1994), modified.

Figure 5. Late Famennian to earliest Viséan (early Moliniacian) sequences from the Drewer quarry, section at the northwestern quarry entrance (compare Fig. 4). Belecke Anticline. Condensed facies of a deep intrabasinal swell. A: General view. Wocklum Limestone (WLst), Hangenberg Black Shale (HBS), and overlying sequences 1-5. Sequence 1: Hangenberg Sandstone (HSdst) and Hangenberg Limestone (HLst). Sequences 2-3: Kahlenberg Fm. Sequence 4: Kattensiepen Fm. Sequence 5, basal part: black shale at the base of the upper Hardt Fm. Hammer at HSdst for scale. B: General view, as in Fig. A. Hammer for scale at Sequence 4. C: Top of Wocklum Limestone showing transition from HST into FSST. D: Top of Hangenberg Limestone showing transition from HST into FSST. Note identical development as at the top of the Wocklum Limestone (Fig. C). E: Erosive boundary with signs of reworking at the base of Sequence 4. Below: upper Kahlenberg Fm; above: Kattensiepen Fm. Diameter of coin 22 mm. F: Sharp boundary between light calcareous shale in the uppermost bed of Sequence 1 (FSST of the Hangenberg Limestone) and fissile black alum shale at the base of sequence 2 (TST of the Kahlenberg Fm). G: Sequences 2 and 3 within the Kahlenberg Fm. Note phosphatic crust at the top of sequence 2 (red arrow) and lithological difference between the fissile black alum shale of sequence 2 and the brownish, thick laminated, siliceous shale of sequence 3; lamination at the top of sequence 3 resembles hummocky cross stratification. H: Detail of Fig. G (rectangle). Top of sequence 2 with phosphatic crust indicating omission. Crust and further phosphatic clasts reworked above in sequence 3.

5.1.2. Eastern Rhenish Kulm Basin

In the eastern part of the RKB, sequence 1 completely consists of siliciclastic rocks. The base has to be sought on top of red shales which are the basinal equivalents of the Wocklum Limestone. The lower part of the succession, i.e. the equivalent of the Hangenberg Sandstone, is most probably the Thalenberg Fm (Pirwitz, 1986). Widespread in the eastern RKB, it contains uppermost Famennian sandstones (Piecha, 2004) and locally debris-flow sediment filled channels incised into the underlying strata, as seen in the type region of the Formation southwest of Biedenkopf (Pirwitz, 1986; Amler et al., 1994). The overlying Hangenberg Shale is mostly the equivalent of the Hangenberg Limestone. Diminished siliciclastic influx and some carbonate content in certain sections indicate the attribution to the undifferentiated TST/HST. In the Dexbach section, few dolostone beds close to the top of the Hangenberg Shale and associated ferruginous, conodont-rich lag sediments indicate the HST (Herbig et al., 2006). The first interpretations of the section by Bender et al. (1993) and Amler et al. (1994) are in parts still erroneous.

A 'Hangenberg Breccia' consisting predominantly of Frasnian reef limestone and further Upper Devonian limestone clasts is known in the neighbourhood of the Langenaubach-Breitscheid reef, southwestern Dill Syncline (most detailed description in Lippert, 1970; but see also Krebs, 1966; Bender in Amler et al., 2002). Like the local debris-flow sediments of the Thalenberg Fm, it can be compared with the Seiler channel from the northwestern RKB (see 5.1.1).

5.1.3. General evaluation

In summary, sequence 1 is interpreted to start with the Hangenberg Sandstone above a sequence boundary type 1 (SB1). Opposed to Van Steenwinkel (1993b) and Siegmund et al. (2002), the Hangenberg Limestone (and the thin veneer of the Stockum Limestone below) is regarded as the undifferentiated TST/HST. The recognition of a sequence boundary at the base of the overlying Kahlenberg Fm contradicts the earlier model of a continuing transgression that attributed the latter as TST succeeding the LST of the Hangenberg Limestone (e.g. Van Steenwinkel, 1993b; Siegmund et al., 2002; see also Bless et al., 1993) (Fig. 4).

5.2. Sequence 2 – late Hastarian

Sequence 2 is well developed throughout Belgium and correlated with strata from the Krakow carbonate platform, southern Poland (Hance et al., 2001; Poty et al., 2007). Its base coincides with the base of the upper member of the Hastière Fm which is thought to lie above a not recognizable hiatus. Previously interpreted to represent the TST of sequence 2, it is now attributed to the LST, overlain by the TST of the Pont d'Arcole Fm (Poty et al., 2014). The latter Formation is still recognized in the Velbert Anticline at the western margin of the RKB. Basinwards, it is substituted by the Kahlenberg Formation, i.e. the classical 'Lower Alum Shale' (Amler & Herbig, 2006).

The 'Lower Alum Shale Event' or 'mid-Tournaisian Event' is a globally recognized transgression in the later Hastarian (see e.g. Siegmund et al. 2002), i.e. at the base of the traditional "Middle Tournaisian". According to the thorough review in Krebs (1968a; see also Krebs, 1969) the transgression is the most important sea-level rise within the RKB during the Mississippian, being a "palaeogeographic turning point" in the development of the European Variscan Kulm basins. It is of historical interest that already Schindewolf (1927) stated the transgressive nature of the 'Lower Alum Shale'. A LST was not recognized at the base of sequence 2 in the RKB.

5.2.1. General development: the starved basin facies

The TST starts at the base of the Lower *Siphonodella crenulata* Zone with the black alum shales of the Kahlenberg Fm (formerly Kahlenberg Member (Mb) of the Oberrödinghausen Fm; Korn, 2003a), i.e. the classical 'Liegende Alaunschiefer'. The transgression caused a remarkable facies homogenization in the RKB and the spread of shale dominated lithostratigraphic units also onto the Northwest European carbonate platform.

In the starved basin facies, the sequence boundary is marked by an abrupt colour change from grey to black shales at the base of the Kahlenberg Fm (and at the base of discarded lateral lithological units, see Fig. 2). Therefore, already Korn (2010) stressed the existence of a major sequence boundary and still earlier placed the base of the Drewer Group at this boundary (Korn, 2003a). Also Herbig et al. (2006) inferred a sequence boundary from the basinal Dexbach section, northern Dill Syncline (see also 5.1.2). Other authors (e.g. Voges, 1960) mentioned a gradual transition from underlying greenish shales within few decimetres. Siegmund et al. (2002) stated a generally conformably developed basal contact. From a section on the deep intrabasinal swell of the Herzkamp Syncline (Kohleiche/B 224n), they described a gradual transition from the underlying Hangenberg Shale, expressed by decreasing carbonate content, increasing C_{org} content, and a corresponding change in colour from grey to black within a 0.5 m thick interval. In contrary, a gradual transition cannot be deduced from the very detailed description of the same section by Thomas & Zimmerle (1992), who mentioned sparse phosphorite nodules and badly preserved plant remains from the lower part of the Kahlenberg Fm. Their observations unequivocally indicate the beginning TST, but in certain basinal sections the sequence boundary seems to be masked.

In fact, the general transgressive nature of the Kahlenberg Fm is well demonstrated by the phosphorite nodules, which are especially common in the lower part of the formation (e.g. Voges, 1960; Bender et al., 1997). In spite of the complex and diversified settings of phosphate-bearing sediments and phosphorites, the formation of pristine phosphate nodules is well known to occur during early transgressive intervals. It is related to sediment starvation, rising of the oxygen minimum zone and increased influx of phosphorus, either by upwelling or by the flooding of the terrestrial hinterland (e.g. Föllmi et al., 1994; Glenn et al., 1994; Trappe, 1998, and references therein). Also associated plant remains derive from the flooding of the vegetated hinterland and transport of the debris towards the open sea.

5.2.2. Western basin margin – Velbert Anticline

In the Velbert Anticline, west of the Herzkamp Syncline mentioned above, a sharp contact exists between oolitic limestone (Laupen Mb of Hastière Fm) and overlying dark grey shale (Pont d'Arcole Fm) in the core Velbert 4 (Herbig et al., 2013, 2014b). Absence of any interbedded strata of the lithotypes is the unequivocal expression of a hiatus and of a SB1.

5.2.3. Deep intrabasinal swells and adjacent slopes

Also on deep intrabasinal swells the contact between the nodular Hangenberg Limestone and the overlying black shales of the Kahlenberg Fm is sharp and, thus, indicates a SB1. This is very well illustrated in the classical section of the Drewer quarry (Fig. 4; Fig. 5B, D, F), which is situated at the sunken northeastern margin of the earlier Devonian Warstein reef platform (Clausen et al., 1989; Korn et al., 1994; Herbig et al., 2006). There, Korn (2003a, 2010) included the Kahlenberg Fm as Belecke Mb within the Eichenberg Fm. Both units are discarded.

Rarely, the black shales are interbedded or mostly substituted by pelagic calciturbidites. Two well-elucidated examples include the Gladenbach Fm (Hörre Belt, eastern Rhenish Mountains, Herbig & Bender, 1992), and the Kahlenberg Fm at Riescheid (northeastern Herzkamp Syncline, Amler & Herbig, 2006; Aretz et al., 2006; Hartenfels et al., 2016).

The Gladenbach Fm mostly consists of metre-sized fining-upward calciturbidite-black shale cycles. In its lower part exclusively basinal components are reworked from the lower slope or from a deep intrabasinal swell, indicating the TST. Upper slope and platform edge components are admixed in the upper third of the formation which is from the *Si. isosticha*-Upper *Si. crenulata* and *Gnathodus typicus* zones (Voges, 1960; Herbig & Bender, 1992). The facies succession demonstrates the waning of the transgression and transition into the HST, which in general

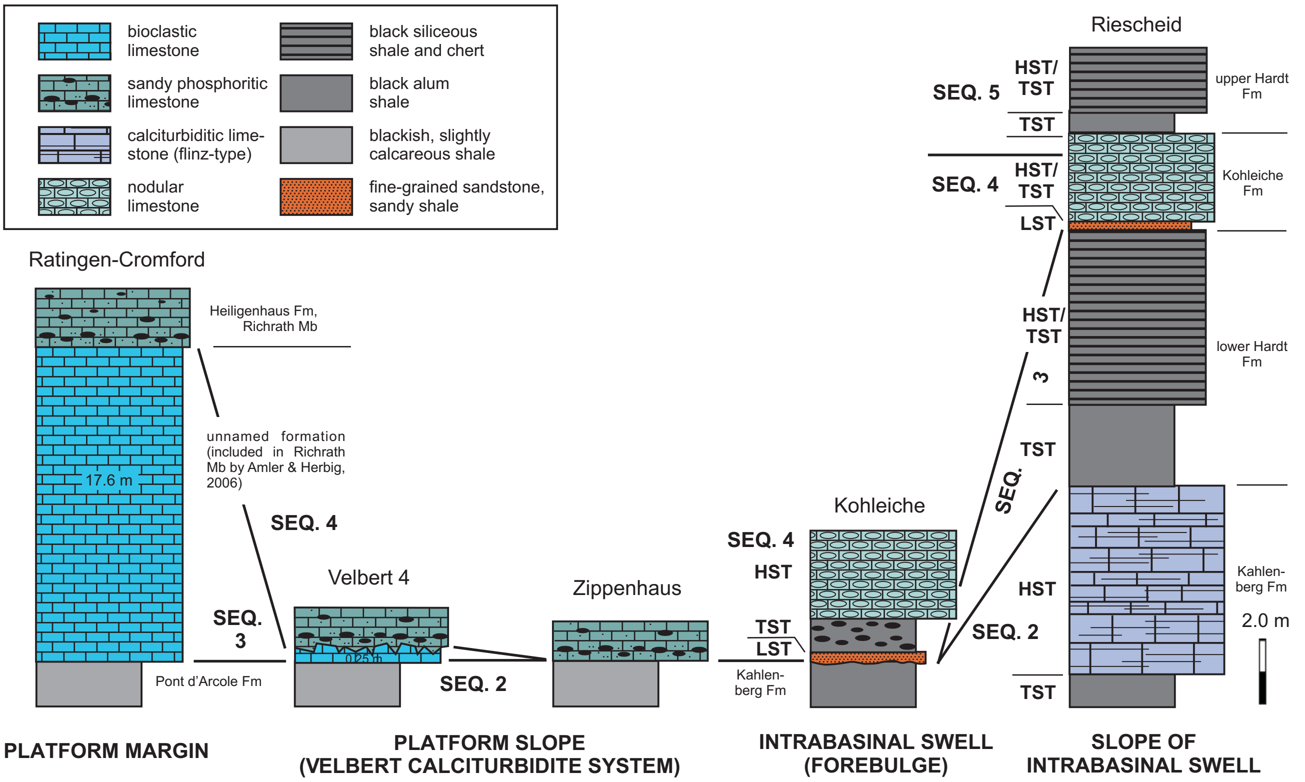

Figure 6. The Hastarian and Ivorian sequences 2-4 at the western margin of the Rhenish Kulm Basin (Velbert Anticline and Herzkamp Syncline). Sections except for Riescheid idealized and not to scale. Log of Riescheid based on Zimmerle et al. (1980).

records reworking of platform components due to continuously diminishing accommodation space.

In the Riescheid section, on top of a thin black shale unit (TST) some metres of finely laminated intrabasinal calciturbidites of the Flinz type follow (Fig. 6; Fig. 7A, C). As in the upper Gladenbach Fm, they contain a conodont faunula of the *Si. isosticha*-Upper *crenulata* Zone (Hartenfels et al., 2016). According to the biostratigraphic data and the lithostratigraphic position within the succession, the calciturbidites are related to highstand shedding deriving from an intrabasinal swell and, hence, are attributed to the HST.

5.2.4. Emergent intrabasinal swells

A hiatus at the base of the Kahlenberg Fm proving a SB1 was locally described from the top of high-rising intrabasinal swells which persisted on the top of drowned Middle Devonian reefs. From the Balve reef area (Remscheid-Altena Anticline), Schäfer (1975) noted the transgressive nature of the 'Lower Alum Shale' describing the curious Wettmarsen section. Above a hiatus on top of Famennian nodular limestone, an about one metre thick calcareous sandstone yielding early Carboniferous conodonts was recorded, overlain by a single about 0.3 m thick calciturbidite bed with conodonts of the former indifferentiated *Si. crenulata* Zone (= Lower *Si. crenulata* + *Si. isosticha*-Upper *Si. crenulata* Zone + Lower and Upper *Gn. typicus* zones). The calciturbidite is a fine-grained laminated radiolarian-peloid packstone with few calcispheres, foraminifers, ostracodes and crinoids strongly resembling time-equivalent calciturbidites from Riescheid and the Gladenbach formations (see 5.2.3.). Therefore, the sandstone-calciturbidite unit is considered to be a relictic, not further differentiated sequence 2. On top of the calciturbidite another sandstone bed and overlying black bedded cherts follow (Hardt Fm). This sandstone bed appears to represent the LST of sequence 3, followed by the siliceous deposits of the TST/HST.

From further drowned Middle Devonian reefs, limestones with conodonts of the *Si.crenulata* Zone in its old sense had been recorded directly overlying the reef limestone.Walliser & Mitarbeiter (1958) described black crinoid limestone including reworked late Devonian conodont ghost fauna transgressing onto the Frasnian Langenaubach-Breitscheid reef. Bender & Stoppel (2006) mentioned the intercalation of this limestone and black alum shale. Similar crinoid limestones bearing clasts of shale, Devonian reef limestone and phosphorite nodules below black bedded cherts were described from the Scharfenberg Anticline in the Brilon reef area. First thought, to be from the '*Si. crenulata* Zone', they proved later to be from the latest Tournaisian *Scaliognathus anchoralis* Zone (Bär, 1968). However, Bär (1968) also identified a black, fine-grained breccious, pyrite and phosphorite bearing limestone from a crevasse fill within the Brilon reef at Messinghausen, which in fact derived from the '*Si. crenulata* Zone'. Hence, an at least localized 'mid-Tournaisian' transgression has to be assumed.

5.2.5. Biotic response

The TST of sequence 2 coincides with a major bioevent. An important turnover was postulated concerning the ammonoid fauna (Becker, 1993a; 1993b). Data from Morocco now suggest a less severe extinction mostly on species level (e.g. Korn et al., 2007), but, in general, an extensive spread of ammonoid genera (Becker, 1993a; Korn et al., 2002). In the RKB, drowning led to the extinction of benthic and nectonic macrofaunal elements, like trilobites and ammonoids, which before flourished especially on deep swells characterized by the deposition of the Hangenberg Limestone. Besides conodonts, preserved as imprints on bedding planes of shales, and very rare thin-shelled pseudoplanctic eupteriomorphid bivalves (M. Amler, pers. comm.), only radiolarians flourished. The outburst of radiolarians is most probably linked to the increased input of nutrients from different sources. Siegmund et al. (2002) suggested upwelling through new gateways in consequence of the rising sea-level, or eutrophication of the former platform and concomitant break-down of the shallow-water carbonate factory. However, most probably eutrophication was linked to the inundation of emergent platform realms at the transition between sequences 1 and 2. This explains also the relatively common permineralized plant relicts preserved within phosphorite nodules (Rowe, 1992a; Paproth in Van Steenwinkel, 1993b; Braun, 1994). In fact, time- and facies-

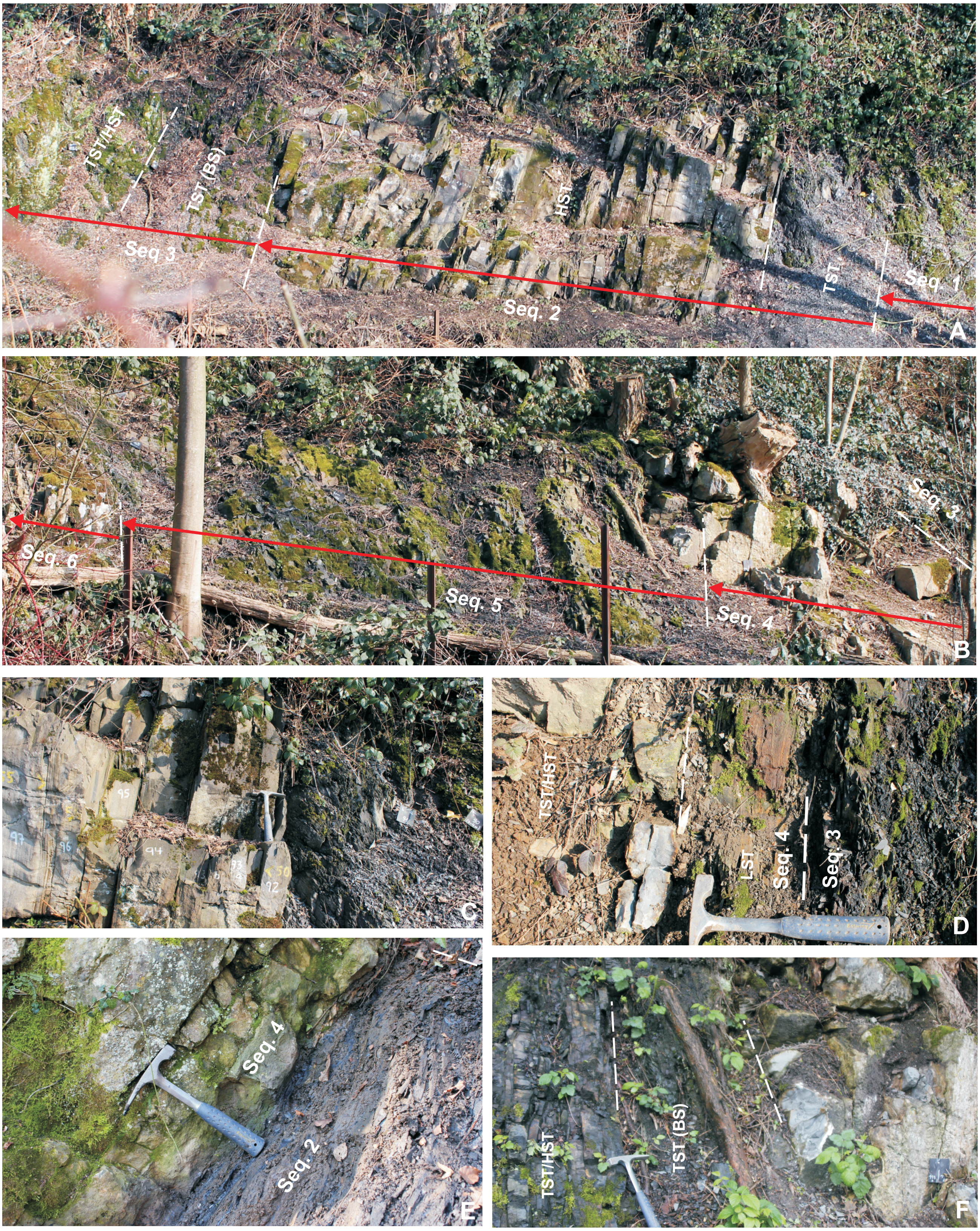

Figure 7. Tournaisian and early Viséan sequences at the western margin of the Rhenish Kulm Basin: deep intrabasinal swell of Herzkamp Syncline (Fig. A-D, F), Velbert Anticline (Fig. E). A: Riescheid section, general view of sequences 2-3. Sequence 2: Kahlenberg Fm; basal black shale (TST) and, flinz-type calciturbidites above (HST). TST of sequence 2 underlain by dark grey shale with thin calciturbidite beds and occasional limestone nodules (equivalent of Hangenberg beds, sequence 1). Sequence 3: lower Hardt Fm; basal black shale (BS) of the TST, overlain by black siliceous shale and bedded chert (indifferentiated later TST and HST). B: Riescheid section, general view of sequences 4-6. Sequence 4: Kohleiche Fm (nodular limestone, TST/HST). According to biostratigraphic data boundary to sequence 5 in the upper part of the limestone. Sequence 5: upper limestone beds of Kohleiche Fm, and black shale and bedded chert of upper Hardt Fm. Sequence 6: light grey siliceous calciturbidites of Hillershausen Fm. C: Riescheid section, sequence 2. Boundary between the fissile black alum shale of the TST and the laminated, very fine-grained, flinz-type calciturbidites of the HST. D: Riescheid section, boundary between sequences 3 and 4. Laminated black shale (HST) in the topmost sequence 3. Sequence 4: LST consisting of fine-grained sandy shale (Richrath beds), above undifferentiated TST/HST (nodular limestone, Kohleiche Fm). E: Zippenhaus section. Sequence 2 (Pont d'Arcole Fm) overlain by sequence 4 (Richrath Mb of Heiligenhaus Fm). Sequence 3 not preserved. F: Riescheid section, lowermost sequence 5. The amalgamated, not visible basal boundary is according to biostratigraphic data within the upper limestone beds of the Kohleiche Fm. TST: black shale (BS) at base of upper Hardt Fm, undifferentiated later TST/HST: black bedded chert and siliceous shale of upper Hardt Fm.

Figure 8. Erosive contact between sparsely packed bioclastic wackestone of sequence 3 and phosphate and detrital quartz bearing bioclastic wackestone of sequence 4 (Richrath Mb). Core Velbert 4, Velbert Anticline. Scan of thin-section, depth 81 m.

equivalent strata from the Thuringian Forest (Saxothuringian Zone) are among the most important plant localities of the European Mississippian ('flora from the Rußschiefer of Saalfeld', see review in Kerp et al., 2006).

5.2.6. General evaluation

Earlier sequence stratigraphic interpretations of the Kahlenberg Fm deviate from the interpretation presented herein. Van Steenwinkel (1993b) interpreted the Formation as TST of a third-order sequence developing conformably above the LST ("distal lowstand prograding wedge") of the underlying Hangenberg Fm. Siegmund et al. (2002) mostly followed Van Steenwinkel (1993b) and attributed the later TST and maximum flooding to the Kahlenberg Fm. However, the sharp basal contacts, especially the unconformable contact observed on top of the Laupen Mb of the Hastière Fm in the Velbert Anticline unequivocally point to a sedimentary break at the base of the sequence. Already Ross & Ross (1987a, 1988) noted an extensive sea-level fall and a corresponding sequence boundary somewhat below the base of the 'Tn2' followed by a major transgression (Chouteau transgression). This correlates with the base of sequence 2 in Belgium, thus with the base of the upper member of the Hastière Fm., which accordingly to Poty et al. (2014) represents the LST.

In the RKB, a LST was not recognized. Reasons for that remain unclear. Within the basin, sediment starvation might be responsible, caused by minimized sediment influx due to widespread emergence and low sea-levels of adjacent platform areas. Such a setting might be deduced from the epigenetic dolomitization of the Binsfeldhammer Mb, a local facies of the Hastière Fm in the Aachen region close to the eastern tip of the Wales-Brabant Massif (Amler & Herbig, 2006), prior to the formation of the mud-dominated TST of sequence 2. Unequivocally, the Kahlenberg Fm and its less deep equivalent, the Pont d'Arcole Fm, represent the TST of the globally recognized 'Lower Alum Shale transgression'.

Besides the few examples of calciturbiditic highstand shedding the HST of sequence 2 is not proved and is masked by continuing black shale deposition in very deep starved basin environments. The extraordinary high amplitude of the transgression is seen by isolated relicts of limestones from the '*Si. crenulata* Zone' on top of previously emergent Devonian reefs.

5.3. Sequences 3 and 4 (latest Hastarian and Ivorian)

The latest Hastarian and Ivorian (late Tournaisian) sequences 3-4 are well developed in the shallow water facies of southern Belgium, southwestern England, and southern Poland. The bases of the sequences are affected by regionally differing sedimentary gaps; e.g. relatively close to the southern margin of the London-Brabant Massif. Sequence 3 is completely missing in the Namur Sedimentary Area (Hance et al., 2001).

In the RKB the interval is difficult to access in sequence stratigraphic terms except for the HST of sequence 4. In most parts of the basin, the black alum shales of the Kahlenberg Fm pass gradually into the black bedded cherts and siliceous shales of the Hardt Fm (formerly Hardt Mb of Oberrödinghausen Fm, Korn 2003a), i.e. into the classical 'Schwarze Kieselschiefer', respectively 'Black Lydites'. In spite of the major sea-level variations and resulting gaps on the adjoining carbonate platforms during sequences 3-4, the condensed sedimentation during the preceding sequence and concomitant subsidence of the foreland basin caused further deepening of the basin and almost complete shut-down of the input of fine-grained detrital material; anoxic conditions like in the underlying alum shales continued. This relationship between sedimentation and subsidence was already noted by Krebs (1968a) and termed 'leptogeosynclinal conditions'. However, Kalvoda (1989, 1991, 1994) stressed condensation, dissolution, erosion and reworking of fauna between Kahlenberg and Hardt formations (see e.g. description of the Drewer section, 5.3.3.) and related a major faunal turnover in conodonts and calcareous foraminifers to the 'Middle-Upper Tournaisian boundary', i.e. the Hastarian-Ivorian boundary. A major global sea-level fall at that boundary was already depicted by Ross & Ross (1987a, 1988).

5.3.1. Western basin margin – Velbert Anticline

A key region to understand the development of the latest Hastarian and Ivorian sea-level within the RKB is the Velbert Anticline (Fig. 6). From the southwesternmost outcrop Ratingen-Cromford that represents the northeastern margin of the Northwest European carbonate platform, an enigmatic, very localized and not longer accessible occurrence of 17.6 m of upper Tournaisian limestone with conodonts of the 'Tn3' had been described (Paproth et al., 1976; see also Franke et al., 1975). Amler & Herbig (2006) included it into the Richrath Mb of the Heiligenhaus Fm. However, as the Richrath Mb is an undeniable transgressive uppermost Tournaisian unit (see 5.4.4.), it would be desirable to exclude the 'Tn3' limestone from Ratingen-Cromford. According to the stratigraphic relationships, it represents the undifferentiated sequence 3 (Fig. 6). This interpretation is supported by the succession from the core Velbert 4 from the northern edge of the Velbert Anticline. There, a 0.25 m thick sparsely packed bioclastic limestone with conodonts from the *Gn. typicus* Zone (Park, 1983) overlies with sharp basal contact the Pont d'Arcole Fm. Its top is a rugged and bored erosional surface (Fig. 8) overlain by the Richrath Mb (Herbig et al., 2013, 2014b). According to the sharp basal contact, the limestone is not the HST of sequence 2, but in analogy to the 'Tn3' limestone from Ratingen-Cromford the undifferentiated sequence 3 including a SB1 at the top. Elsewhere in the Velbert Anticline, e.g. in the Zippenhaus section (Paproth et al., 1976; Amler & Herbig, 2006), the Pont d'Arcole Fm is overlain with sharp contact by the transgressive Richrath Mb and sequence 3 is missing (Fig. 6; Fig. 7E). The paradoxon that the limestone of sequence 3 is thickest at the platform edge (Ratingen-Cromford) and only relictic preserved or completely missing in sections of the platform slope (Velbert 4, Zippenhaus, cf. Fig. 6) is not solved.

According to the core Velbert 4 and the Zippenhaus section, the bioclastic limestone of the up to one metre thick Richrath Mb with abundant detrital quartz and phosphate grains, unequivocally represents sequence 4. TST and HST are not differentiated. The SB at the base of sequence 5 is located within the basal bed of the Zippenhaus Mb still below the biostratigraphically proved Tournaisian-Viséan boundary (see 5.4.4.).

The Richrath Mb wedges out towards the Herzkamp Syncline, where it is not any more formally recognized. In the Riescheid section, a 0.2 m thick phosphate and detrital quartz bearing horizon at the base of sequence 4 is the lateral equivalent (Fig. 7D; see 5.3.3).

5.3.2. High rising intrabasinal swells

A second key area are the high-rising intrabasinal swells on the top of drowned Devonian reefs in the eastern part of the RKB, which display strongly differentiated, discontinuous stratigraphic successions. Their interpretation, however, is hampered by complicated relationships of different lithofacies, preserved only in fissures and lens-like erosional relics, and by old, mostly conodont-based stratigraphic data.

For example, Krebs (1966, 1968b) only differentiated '*Siphonodella crenulata* Zone' and '*Scaliognathus anchoralis* Zone' concerning the middle and upper Tournaisian of the Langenaubach-Breitscheid reef. Despite that, his detailed descriptions allow a sequence stratigraphic interpretation (Fig. 9). Important lithostratigraphic key elements are three limestone intervals termed 'Erdbach Limestone I-III', each only some decimetres thick, and two intervening breccia horizons. These are the bipartite breccia horizon of the 'Langenaubach Tuffbrekzie I-II' separating Erdbach Limestone I and II, and an unnamed limestone breccia separating Erdbach Limestone II and III. Interbedded layers of volcanic rocks ('Deckdiabas I-IV') are not of importance herein. Except for the Erdbach Limestone III, which already yielded conodonts of the Viséan *Ps. homopunctatus* Zone (Herbig & Stoppel, 2006; Krebs, 1966, 1968b: *Sc. anchoralis*-*Gn. bilineatus* Interregnum), the limestones yielded *Sc. anchoralis*. Hence, they should be latest Tournaisian in age and, like the intervening units, would plot into sequence 4 (Poty et al., 2006, fig. 15; see also Poty et al., 2014). Later, Bender & Stoppel (2006) placed the Erdbach Limestone I without further discussion into the underlying *Gn. typicus* Zone. *In situ*, it is only known from crevasses within and in depressions on the top of the Frasnian reef limestone. Reworked reef blocks with crevasses filled by Erdbach Limestone I are also preserved within the Langenaubach Tuff breccia I, which overlies the Kahlenberg Alum Shales. Within the breccia, also a reworked, several cubicmetre-sized block of alum shales was recorded (Krebs 1966). Hence, according to biostratigraphic data and lithostratigraphic relations, the Erdbach Limestone I is younger than the Kahlenberg Fm, but older than the Langenaubach Tuff Breccia I. As a sequence boundary is associated with the top of the Kahlenberg Fm (Fig. 3), and in some cases even within its upper part (e.g. in the Drewer section; see 5.3.3), the Erdbach Limestone I most probably represents the HST of sequence 3. Reworking within the Langenaubach Tuff Breccia I indicates that the latter is the subsequent LST of sequence 4.

Above, the 3-15 m thick, only locally developed Langenaubach Tuff Breccia II is separated from the lower breccia by about three metres of black siliceous shales, bedded cherts and alum shales containing phosphorite nodules. Clasts are finer grained than in the lower breccia; in the thickest section limestone beds are intercalated. On top black bedded cherts reappear. The succession indicates the gradual waning of debrite formation and transition into the TST of sequence 4.

The Erdbach Limestone II is known (1) from depressions and crevasses within the Devonian reef limestone, (2) from depressions on top of the Langenaubach Tuff Breccia I, and (3), it overlies black, tuffite-bearing shales and tuffites, which in turn overly Erdbach Limestone I (sections west of Medebach; Krebs 1966). According to the stratigraphic position, this is the HST deposit of sequence 4 (Fig. 9).

Further occurrences of equivalents of the Erdbach Limestone II with conodont faunas of the late Tournaisian *anchoralis* Zone, that unconformably overly Devonian reef limestone are known e.g. from the Brilon reef area (Bär, 1968; Heuer et al., 2015), from the Warstein reef area (Uffenorde, 1977; Clausen et al., 1982; Clausen & Leuteritz, 1989) and, in the northeastern prolongation of the RKB, from the Iberg Reef in the Harz Mountains (Franke, 1973; Gischler, 1992, 1996). For the latter, stratigraphic equivalence is well proved by ammonoids and trilobites (see compilation in Krebs, 1968b, and references therein).

5.3.3. Deep intrabasinal swells

Bedded limestones of equivalent age to the Erdbach II Limestone also occur on intrabasinal deeper-water swells. Best known are examples from the the Warstein and Belecke anticlines (Kattensiepen Formation, e.g. Drewer section), and from the

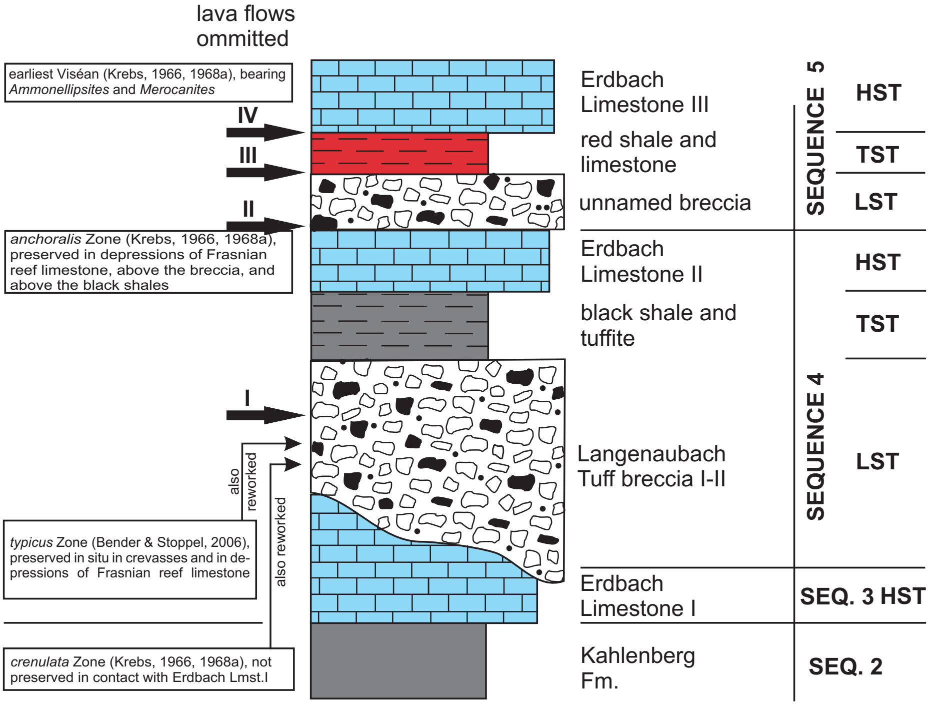

Figure 9. Idealized synthetic section of the Hastarian to early Moliniacian sequences 2-5 from the high-rising swell on top of the Erdbach-Langenaubach reef, southwestern Dill Syncline, eastern Rhenish Kulm Basin. Ages of the Erdbach Limestone I-III and further important relations between the units as seen in the outcrops are indicated. Based on Krebs (1968b).

Herzkamp Syncline (Kohleiche Fm, e.g. Kohleiche and Riescheid sections).

In the eastern Drewer quarry, the most informative section is located at the northwestern quarry wall close to the ancient quarry entrance (Fig. 4). Like elsewhere, the strongly condensed, phosphorite bearing, black shales of the Kahlenberg Fm are attributed to the Lower *Si. crenulata* and *Si. isosticha*-Upper *Si. crenulata* Zones (Clausen et al., 1989; Korn et al., 1994). The upper part of the 0.5 m thick Fm is formed by a conglomerate- to breccia-like horizon consisting of mostly flattened, up to 2 cm thick and 10 cm long phosphorite clasts, which are layered and in places imbricated. Additionally, up to centimetre thick, laterally more or less continuous phophorite crusts should occur (Struckmeier, 1982). According to own observations, a single, only partially preserved crust restricted to the base of the conglomeratic portion of the Kahlenberg Fm exists (Fig. 5B, G, H). Siegmund et al. (2002) described an erosional surface at the base of this "phosphoclastic floatstone" which is another indication for the reworking of phosphatic crusts and concretions from below. Moreover, opposed to the strongly fissile black shale in the lower part of the Kahlenberg Fm, the upper part consists of dark grey, slightly siliceous shale in some millimetres thick, in the topmost part undulating beds (Fig. 5B, F-H).

The phosphatic crust indicates omission at the top of sequence 2 and the phosphoclastic floatstone above subsequent reworking of parts of the sequence. This had to take place during the *Gn. typicus* Zone, though it is not proved in this section. However, along the northeastern quarry wall, the Kahlenberg Fm wedges out towards a local synsedimentary swell. There, it is substituted by a strongly condensed limestone with a mixed conodont fauna bearing elements of this Zone (Clausen et al., 1989). As a result, the upper part of the Kahlenberg Fm in Drewer is the faint vestige of sequence 3.

In Drewer, the phosphorite conglomerate and breccia of the upper Kahlenberg Fm is overlain with sharp contact by the 0.7-0.8 m thick limestone of the Kattensiepen Fm (formerly Kattensiepen Mb of the discarded Eichenberg Fm of Korn, 2003a). In the section at the northwestern quarry wall an erosional surface could be observed at its base (Fig. 5B, E). Bioclastic and peloidal wackestone and mudstone/wackestone with radiolarian-rich laminae in the upper bed indicate deposition in deeper water (Herbig et al., 2006). According to rich conodont faunas from the *Scaliognathus anchoralis* Zone (Clausen et al., 1989) and rich macrofossils, among them goniatites including *Merocanites* (Schmidt, 1922), the Kattensiepen Fm is an equivalent of 'Erdbach Limestone II' (see also Krebs, 1968b). Therefore, it represents the HST of sequence 4.

The top of the Kattensiepen Fm records the sequence boundary at the top of sequence 4 (Fig.4; Fig. 5A-B).

An almost analogous succession from the Kohleiche section (Herzkamp Syncline; Fig. 6) shows (1) a thin, 10 cm thick sandstone bed with slightly erosional base in the upper part of the Kahlenberg Fm, overlain by (2) black alum shale with lenses and layers of phosphate (Thomas & Zimmerle, 1992, p. 43: "Schicht 8/10" and "Schicht 8/11"; see also the separately enclosed section). (3) Above, 4-5 m of flasered to nodular limestone of the uppermost Tournaisian Kohleiche Fm follow (formerly Kohleiche Mb of the discarded Steinberg Fm; of Korn, 2003a). The three lithological units indicate LST, TST and HST of sequence 4. The fate of sequence 3 remains unclear. As in the adjacent Zippenhaus section (see 5.3.1) it is apparently completely eroded (Fig. 6).

In the likewise condensed Riescheid section, some kilometres further northeast, strata belonging to sequence 3 are recognizable. As already elucidated (see 5.2.3), sequence 2 ends at the top of HST calciturbidites of the flinz type. Above, a 1.7 m thick package of organic-rich black shale that form the lowermost part of the lower Hardt Fm (Hartenfels et al., 2016), is regarded as TST of sequence 3 (Fig. 6; Fig. 7A). The LST is not observed. The black shale grades rapidly into a 7 m thick package of laminated, siliceous black shale and minor bedded chert containing phosphorite nodules near its base and in the middle part; C_{org} values are still high (lower part of Hardt Fm). The package documents the continuing transgression and reduced terrestrial influx. As deeper-water conditions continued during the HST, different facies did not develop.

Above, sequence 4 starts with an about 0.2 m thick horizon consisting at its base of fine-grained sandy black shale containing pyrite and phosphate nodules; fine-grained sandy greenish shales with densely packed, in part angular to subangular (broken) phosphate nodules, up to 3 cm in length overly (Fig.6; Fig. 7D). This horizon ('Richrath Beds': Franke et al., 1975; Amler & Herbig, 2006; Aretz et al., 2006; Hartenfels et al., 2016; transitional beds of Zimmerle et al., 1980) represents the LST/TST of the sequence. The HST above consists of 2.7 m thick flasered, rarely nodular limestone (Kohleiche Fm), still bearing sparse detrital quartz silt in the lower beds (Fig. 7B). Conodonts, rare ammonoids and a single trilobite record correlate it with the Erdbach II Limestone. The Tournaisian-Viséan boundary is documented in the upper part of the Formation (Hartenfels et al., 2016, and references therein). As the boundary between sequences 4 and 5 is in the uppermost Tournaisian (see e.g. Bábek et al., 2010 for the Velbert Anticline and other sections around the Wales-Brabant Massif; Poty et al., 2014 for Belgium), it remains undetected within the limestone.

5.3.4. Calciturbidite facies

During the latest Hastarian and Ivorian, calciturbidites are missing in most parts of the basin. In the Waldeck Syncline, black calciturbidite beds yielding conodonts of the *Scaliognathus anchoralis* Zone (Witten, 1979) are intercalated within the black bedded cherts of the upper Hardt Fm. The succession (Bömighausen Mb, Korn 2003a, see also Jackson, 1985) represents the highstand shedding of sequence 4 from a no longer preserved platform in the northeastern RKB.

5.3.5. Biotic response

The HST of sequence 4 is a remarkable bioevent, called Avins event (Poty et al., 2006: coral subzone RC4β1; Poty 2007). On shallow water platforms, high sea-levels globally caused the radiation of rugose corals. In the RKB, the Avins event is well represented in the Erdbach Limestone II (Herbig, 2011), which is famous for its diversified macrofauna, first described by Holzapfel (1889). Besides ammonoids, which need revision (see compilations in Krebs, 1968b; Korn, 2006b), the fauna mostly consists of well-studied trilobites (see compliations in Hahn et al., 1996 and Amler et al., 2008), gastropods (Amler, 2006; Amler et al., 2008) and bivalves (Amler et al., 2008). Brachiopods and ahermatypic deeper-water corals are minor constituents in the Erdbach Limestone II of the type region, but the corals from the drowned Iberg Reef (Harz Mountains) constitute a unique fauna (see compilations in Weyer, 2000, 2006).

5.3.6. General evaluation

The former interpretation of Siegmund et al. (2002) that a single third order sequence comprises the Hangenberg Limestone (LST), the Kahlenberg Fm (TST including mfs) and the Richrath Mb (HST), has to be rejected. A sequence boundary can be demonstrated at the top of sequence 2, i.e. at the top of the Kahlenberg Fm or even within the Formation, e.g. in the Drewer section. On high rising and deep intrabasinal swells also at least relictic records of the Ivorian sequence 3 are recognized. Rising sea-level and intensified carbonate production on the platforms occurred not until the late Ivorian during the HST of sequence 4, i.e. during the Avins event. This caused the transport of periplatform carbonate oozes towards different intrabasinal swells and the onset of local carbonate production as seen in the 'Erdbach Limestone II' and equivalents.

In basinal areas, the sequences 2, 3 and 4 cannot be separated and are amalgamated; the Kahlenberg Fm grades without apparent interruption into the Hardt Fm. However, an important general conclusion has to be drawn concerning the depositional regime of the latter. Hitherto, it was generally assumed that the black bedded cherts record continuous deepening of the basin after deposition of the Kahlenberg Fm and correspondingly the highest sea-levels of the Tournaisian. The regional recognition of the sequence boundaries at the bases of sequences 3 and 4 in the RKB show the need for a more differentiated evaluation. It has to be stressed that according to the general upper Tournaisian sea-level development on the Northwest European and Polish carbonate platforms, the Hardt Fm is related to low sea-levels. This is well demonstrated by condensation, non-deposition, and erosion of the Formation on intrabasinal swells and at the western margin of the RKB.

From that evidence, the anoxic environment of the 'Black Lydites' has to be explained by deposition within an elongate, deeper basin with restricted communication across shallow gateways to adjacent marine realms and, especially, to the Palaeotethys. Relatively deep environments in the starved basin facies of the RKB resulted from continued low sedimentation rates, which were outpaced by the subsidence of the foreland basin since the deposition of the Kahlenberg Alum Shales. Almost missing detrital siliciclastic input into the basin with its predominantly biogenic siliceous sedimentation appears to result from the wide, partly emergent carbonate platforms in its surroundings. Such peritidal dolomitic environments are e.g. widely developed in the Aachen region (westernmost Germany) and adjoining eastern Belgium (Vesdre Fm; Amler & Herbig, 2006, and references therein).

According to Randon & Caridroit (2008) time-equivalent black bedded cherts ("lydites") from the Pyrenees developed on the outer shelf or upper slope in water depths of less than 300 m after progressive deepening that is recorded in the underlying nodular limestones. According to their results, main factors of the formation of the black bedded cherts in the Pyrenees might be changes in the oceanic circulation due to the general relative deepening (transgression) and eutrophication caused by upwelling. In fact, the formation of radiolarian-rich deposits is not necessarily bathymetry-related, but also might occur in relatively shallow water and proximal conditions depending on the preservation rate of radiolarians relative to calcareous biota, preferentially in cold seas or in upwelling zones: in general, outbursts of radiolarians are related to high productivity, i.e. the availability of nutrients, and the availability of dissolved silica (De Wever et al., 2001). Among others, nutrients and silica input might derive from the surrounding continents. For the late Tournaisan of the RKB, all these observations support the interpretation of a general regressive regime, although, as a paradoxon, deep water conditions continued within the basin.

5.4. Sequences 5-8 (latest Ivorian-early Warnantian/early Asbian)

Sequence 5 that straddles the Tournaisian-Viséan boundary (latest Ivorian-early Moliniacian) is missing in Belgium and Southwest England in all inner shelf areas bordering the Wales-Brabant Massif. Regionally, the erosional hiatus extends into the TST of sequence 6 (Hance et al., 2001, 2002). Also in southern Poland sequence 5 and the TST of sequence 6 is missing (Poty et al., 2007). This indicates a major sea-level drop during the earliest Viséan (Hance et al., 2002). In fact, sequence 5 is only complete in the outer shelf areas of Belgium, mostly within the Dinant sedimentation area. Bábek et al. (2010) were able to correlate such deeper water sections containing the sequence boundary between sequences 4 and 5 between the Dublin Basin, southern Belgium and the Zippenhaus section in the westernmost RKB and to demonstrate its isochronous nature. Sequences 6-8 are separated by minor gaps. They are well represented in southern Belgium and southwestern England; in southern Poland the published record ends with the HST of sequence 6 (Poty et al., 2007).

In the RKB, the time slice embracing the sequences 5-8 is difficult to access. Biostratigraphic data are scarce or completely missing. Relatively uniform, mostly light grey coloured calciturbidites and intercalated light grey and varicoloured cherts of the Hillershausen Fm and its lithostratigraphic equivalents (Becke-Oese Fm, Hellefeld Fm) spread across most of the basin, except the southeasternmost parts. There, sedimentation of varicoloured, mostly light bedded cherts (Laisa Fm) took place. Detailed biostratigraphic, sedimentological and microfacies analyses might reveal differences in composition of the turbidite beds, bed thicknesses, and turbidite abundances, and thus might allow recognition of sequences. Witten (1979) made a first approach for the Hillershausen Fm, but paid more attention to sedimentology and to the change of the source areas in space and time. Later, Korn (2008) presented a detailed study of the calciturbidites systems further west from the Remscheid-Altena Anticline and the Lüdenscheid Syncline (Fig. 1) but focused on the late Viséan formations. Besides lateral variations, he described the more or less synchronously, vertically varying carbonate contents and bed thicknesses within the sections. Herbig et al. (2013, 2014b) initiated a promising approach concerning the variations in carbonate microfacies from the calciturbidites of the Heiligenhaus Fm in the core Velbert 4 They related repeated changes in the component spectra to different flooding stages of the platform source, as earlier described e.g. by Reijmer & Everaars (1991) and Reijmer et al. (1991).

5.4.1. Deep intrabasinal swells

The TST of sequence 5 appears to be well-documented only on the top of deeper intrabasinal swells. A LST was nowhere recognized. In the Drewer section, the TST consists of an up to 1.5 m thick black alum shale package with phosphorite nodules following on top of the limestone of the Kattensiepen Fm (HST of sequence 4; Fig. 4; Fig. 5B). The alum shale is overlain by thin-bedded black cherts, siliceous shales and alum shales, which might become slightly calcareous (upper Hardt Fm, formerly Külben Mb of the now discarded Eichenberg Fm, Korn, 2003a, 2006a, 2010). They are attributed to the undifferentiated later TST and HST.

Almost analogous successions are known from the Devonian Brilon reef complex (core Nehden 2) and from the Herzkamp Syncline (Riescheid and Kohleiche sections). In the core Nehden 2, equivalents of the Kattensiepen Fm consist of at least two fossiliferous limestone horizons yielding conodonts of the *Scaliognathus anchoralis* Zone and interbedded black alum shales (Stoppel in Luppold et al., 1994). Above, black alum shales with phosphate nodules are assigned to the TST of sequence 5. Also in the Riescheid section (Zimmerle et al., 1980; Aretz et al., 2006; Hartenfels et al., 2015), a thin black shale horizon rapidly substituted by black bedded radiolarian cherts with phosphorite nodules in certain horizons record the TST and the undifferentiated later TST/HST of sequence 5 (Fig. 6; Fig. 7B,F; upper part of Hardt Fm). The succession (upper Hardt Fm, formerly Kothen Mb of the now discarded Steinberg Fm, Korn, 2003a, 2006a, 2010) overlies with sharp contact the nodular limestone of the Kohleiche Fm, which contain the boundary between sequences 4 and 5. In the Kohleiche section, some kilometres further southwest (Thomas & Zimmerle, 1992, p. 48: lithological unit 010), the base of the about two metre thick "lydite" succession following above the Kohleiche Fm consists of a mudstone/siltstone. The latter yielded abundant and diverse fauna (trilobites, brachiopods, corals) as well as phosphate nodules that unequivocally stress the interpretation as TST. Moreover, attribution to the TST is underlined by the presence of abundant, partly permineralized, up to one metre long plant fragments (Thomas & Zimmerle, 1992; Rowe, 1992b). Permineralized plants from an isolated outcrop in the Herzkamp Syncline near Wuppertal presumably have been derived from the same horizon (Braun & Gosny, 2000). In that paper, also the older age of the plants is stressed, which were formerly described as late Viséan by Rowe (1992b).

5.4.2. High rising intrabasinal swells

Another critical region for recognition of sequence 5 is the Langenaubach-Breitscheid reef area. Above the Erdbach Limestones I-II (see 5.3.2), Krebs (1966, 1968b) differentiated an uppermost Erdbach Limestone III from the '*anchoralis-bilineatus* Interregnum' (= *Gn. homopunctatus* Zone, Herbig & Stoppel, 2006). It still contains goniatites also known from the Erdbach Limestone II, such as *Ammonellipsites* and *Merocanites*.

These are the index fossils for the *Fascipericyclus-Merocanites* Ammonoid Genozone, which straddles the Tournaisian-Viséan boundary (Korn et al., 2007; Ebbighausen et al., 2010, and references therein). Therefore, the Erdbach Limestone III should be of earliest Viséan age and most probably represents the HST of sequence 5 (Fig. 9). Youngest clasts from a few metres thick, unnamed polymictic limestone-diabase breccia separating Erdbach Limestone II and Erdbach Limestone III (Krebs, 1966, 'Kalk-Diabas-Brekzie', 'Kalk-Brekzie') yielded conodonts of the *Scaliognathus anchoralis* Zone. Hence, in analogy to the preceding sequence 4, the breccia might represent the LST of sequence 5, although complicated outcrop conditions and an intervening volcanic flow of the 'Deckdiabas' prevent an unequivocal interpretation.

5.4.3. Calciturbidite and starved basin facies

In most parts of the RKB the black bedded cherts of the Hardt Fm grade quite rapidly, within about one metre, into light grey and varicoloured cherts and intercalated light grey calciturbidites of the Hillershausen Fm and lateral equivalent formations. According to Voges (1960), already the lowermost calciturbidites contain '*Gn. homopunctatus'* (= *Lochriea homopunctatus*, Atakul-Özdemir et al., 2012), and thus, the base of the formations is generally considered to coincide with the Tournaisian-Viséan boundary (e.g. Korn, 2003a, 2006, 2010).

Except for the Velbert Anticline (Conil & Paproth, 1968; Paproth et al., 1976; Bábek et al., 2010) foraminifer data do not support this biostratigraphic datum. The oldest faunas that were reworked from pencontemporaneous platform deposits are from 'Cf4δ' (= most of MFZ 11, except its base, latest Moliniacian; see Fig. 3). Associated are reworked taxa from zones 'Cf3-Cf4' (= MFZ 6-11). They are also known from stratigraphically younger samples and indicate reworking of calcareous beds from strata as old as the late Ivorian *Sc. anchoralis* Zone (Herbig, 2006a), i.e. from the extended HST deposits of sequence 4. Besides the fragmentary knowledge of foraminifers in the Viséan calciturbidite successions, the discrepancy between foraminifer and conodont ages for the base of the Hillershausen Fm and its equivalents is mostly facies-related. Thin, very fine-grained, macroscopically 'micritic' calciturbidite beds predominate in the lower part of the formations. They contained conodonts, but no calcareous foraminifers due to different habitats of both groups and the hydraulic sorting of shallow-water bioclasts (Herbig & Mamet, 1994). It seems reasonable that the faint development of calciturbidite beds and their facies mirrors the generally low sea-levels and extended stratigraphic gaps during sequence 5 and the lower part of sequence 6 on the Northwest European carbonate platform.

In the southeastern Wittgenstein Syncline, e.g. in the well-documented section Wallau, near Biedenkopf (upper Lahn valley, Bender et al., 1993; Herbig et al., 2006, and references therein), some rhodochrositic Fe-Mn ore beds (Fig. 10) mark the transition between the dark siliceous sediments of the Hardt Fm and light coloured sediments of the Hillershausen Fm. They demonstrate the first influx of carbonate ions bearing, oxic water into the previously anoxic, restricted basin (Huckriede & Meischner, 1996). The process preceded the first calciturbidite shedding. Hence, this marker horizon indicates the first flooding of the platform and has to be associated with the base of sequence 5.

As mentioned, the oldest Viséan calciturbidites outside the Velbert calciturbidite system (Fig. 1) are latest Moliniacian ('Cf4δ', Conil & Paproth, 1983: Hillershausen Fm., Bromberg section). Their shedding is related to the first major Viséan flooding of the Northwest European carbonate platforms. In Belgium, this datum is documented by the Neffe Fm, which for the first time during the Viséan shows a homogenized carbonate deposition across the Namur-Dinant Basin. Thus, these calciturbidites indicate the HST of sequence 6. Foraminifers from 'Cf5' to 'Cf6β' (MFZ 12 and MFZ 13, Poty et al., 2006) document continued calciturbidite shedding in the Hillershausen Fm. Hence, hitherto only an amalgamated sequence from the HST of sequence 6 to the HST of sequence 8 is recognized (Herbig, 2011).

Figure 10. Rhodochrositic Mn-Fe ore bed. The facies indicate the first influx of oxygenated, carbonate-bearing water into the starved basin at the base of the basal Viséan (early Moliniacian) sequence 5. Wallau section, southeastern Wittgenstein Syncline. Diameter of coin 16 mm.

Along the northern rim of the RKB Korn (2008) studied the lateral equivalents of the Hillershausen Fm. These are the Hellefeld Fm, fed from the Hellefeld Calciturbidite System (Fig. 1), and separated into lower Stemmberg and upper Oberröhre Mb (southern flank of Lüdenscheid Syncline), and the Becke-Oese Fm, fed from the Herdringen Calciturbidite System (Fig. 1), and separated into lower Deinstrop and upper Holzen Mb (eastern Remscheid-Altena Anticline). Both lower members consist of thick-bedded calciturbidites including thick-bedded oolitic beds. Both upper members are characterized by cherty shales, thin-bedded siliceous calciturbidites and beds of "detrital limestone", which are coarse-grained in the Oberröhre Mb. The base of the Hellefeld Fm is close to the Tournaisian-Viséan boundary according to conodonts (Voges, 1960; Gauglitz, 1967); oldest calcareous foraminifers probably date from the MFZ 11 ('Cf4δ', Herbig, 2006a, based on Conil & Paproth, 1968 and translated herein: "most of the encountered foraminifers appear in Belgium first in V2a and V2b and continue into V3b"). Therefore, in analogy to the Hillershausen Fm, it is tempting to relate the lower members (Stemmberg and Deinstrop Mbs) to sequences 5-6, with most calciturbidites shed during the HST of sequence 6, and the upper members (Oberröhre and Holzen Mbs) to the undifferentiated sequences 7-8.

5.4.4. Western basin margin – Velbert Anticline

In the Velbert Anticline, the Heiligenhaus Fm consists of an almost pure limestone succession of latest Tournaisian to late Viséan age (Fig. 11). Above the Richrath Mb (beds 3-6, sequence 4, see 5.3.1.), the some tens of metres thick calciturbidite succession (Zippenhaus Mb) contains the Tournaisian-Viséan boundary in its lowermost parts. This is proved by foraminifers in the Zippenhaus section (entry of *Eoparastaffella simplex* at the base of bed 9, Dvořák et al., 2009; Bábek et al. 2010) and by conodonts in the core Velbert 4 (entry of '*Gn. homopunctatus'*, Herbig et al. 2013, 2014b, based on Park, 1983). Earlier assumptions that the Richrath Mb reaches into the lowermost Viséan (Paproth et al., 1976; Amler & Herbig, 2006) are therefore not correct. Correlation of biostratigraphic data and outcrop gamma-ray logs (GRS) with sections from Belgium and the British Isles (Bábek et al., 2010) enabled to draw the boundary between sequences 4 and 5 just below the Tournaisian-Viséan boundary, coinciding with the last occurrence of the conodont *Sc. anchoralis* in bed 7 of the Zippenhaus section, i.e. at the base of the Zippenhaus Mb

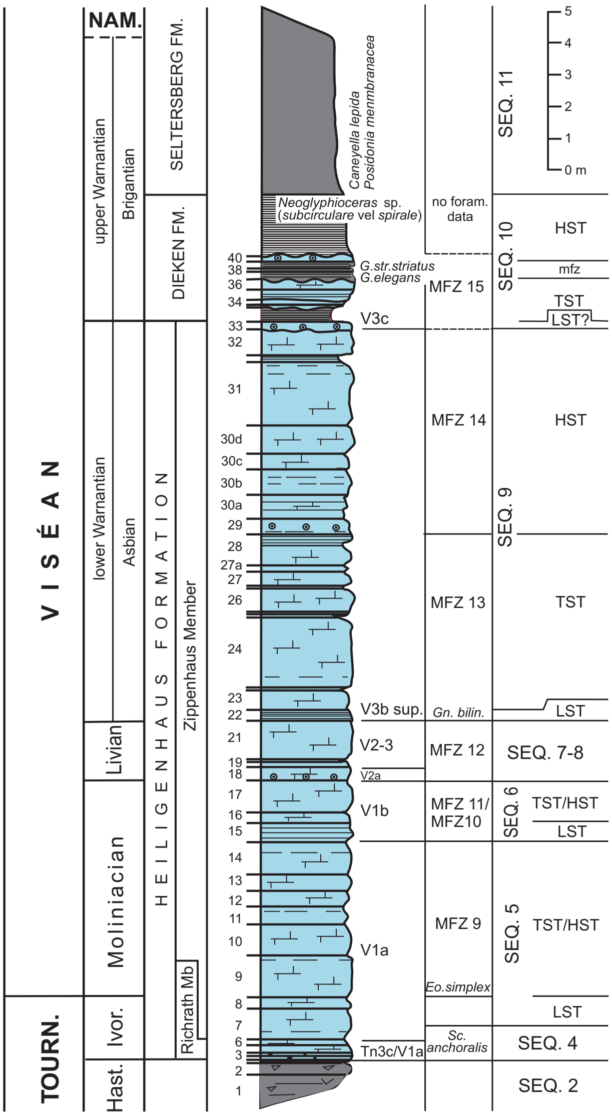

Figure 11. Depositional sequences from the Tournaisan-Viséan of the Zippenhaus section, Velbert Anticline, western margin of the Rhenish Kulm Basin. Based on data of Paproth et al. (1976) and Pille et al. (2006). Drawing modified from Amler & Herbig (2006).

(Fig. 11). The LST of sequence 5 extends upsection just below the first occurrence of *E. simplex* in bed 9 (Dvořák et al., 2009; Bábek et al., 2010, fig. 10). However, interpretation is somewhat hampered by the extreme condensation of that part of the section and a further basinward facies shift is indicated by decreasing GRS values up to the base of bed 13, where a last significant drop was recorded (Bábek et al., 2010, fig. 9). This might indicate a somewhat more extended LST to a level shortly above the entry of *'Gn. homopunctatus'* in bed 11.

Herbig et al. (2013, 2014b) presented comparable results using variations of the carbonate microfacies in the some kilometres distant well Velbert 4. They related calciturbidites with fine-grained peloidal-bioclastic grainstone to packstone and low diverse bioclasts to the LST, as this facies indicates reworking of carbonate mud mostly from the platform slope and a narrow, poorly developed carbonate platform. Coarse-grained grainstone to packstone with diverse shallow-water biota, which grade into thin ooid- and cortoid-bearing levels indicate a well-differentiated platform that finally developed into an oolite-rimmed platform-lagoon system and, therefore, indicate the HST. In the core Velbert 4, the lowermost cortoid-bearing calciturbidites (i.e. the HST) are still latest Tournaisian in age, following above the TST of the Richrath Mb. This is in accordance with the petrophysical interpretation from the Zippenhaus section and allows their attribution to sequence 4.

Further upsection, two imprecisely dated early-middle Viséan (Moliniacian-Livian) sequences were recognized in Velbert 4 by identical microfacies successions. In analogy to the time equivalent calciturbidite formations from the northern rim of the RKB, they might be correlated to sequences 5-6 and 7-8.

In the Zippenhaus section (Fig. 11) biostratigraphic data contribute to a better sequence stratigraphic subdivision of the Viséan calciturbidites of the Velbert Anticline. As outlined above, sequences 4 and 5 are differentiated by modern high-resolution biostratigraphy and gamma-ray data (Dvořák et al., 2009; Bábek et al., 2010). Further upsection, data from gamma-ray and magnetic susceptibility appear to be not very indicative. However, the extremely reduced thickness of Livian calciturbidites is obvious, as indicated by biostratigraphic data based on smaller foraminifers (beds 18-21: Pille et al., 2006: MFZ 12, see already Conil & Paproth, 1968; Paproth et al., 1976: "V2a" and "V2-3"). Important faunal mixing was recorded by all authors in bed 18 that apparently represents the base of the Livian and, hence, the base of sequence 7 (Fig. 11; Fig.12G). The short sequence 8 that straddles the Livian-Warnantian boundary, is not recognized and probably also contained in beds 18-21. Beds above are attributed to sequence 9 (see 5.5.3).

The distinctive low thickness of the Livian calciturbidites in the Zippenhaus section was related to reduced calciturbidite shedding from a platform area covered only by a thin sediment veneer (Aretz et al., 2006; Pille et al., 2006). In fact, in southern Belgium Livian and lower Warnantian deposits of sequences 7-8 form thin successions with predominant deposition in restricted marine environments (e.g. Hance et al., 2001; Poty et al., 2014). In the autochthonous platform deposits in westernmost Germany these deposits are not known (Amler & Herbig, 2006). They either were never deposited or the presumably thin deposits were completely removed by erosion at the Viséan-Namurian transition.

With identification of the marker horizon of bed 18, the presumed base of sequence 7, sequence 6 might comprise the calcareous shale of bed 15 (LST/TST) and the overlying well-developed calciturbidite beds 16-17; both beds contained besides reworked older fauna foraminifers from the late Moliniacian MFZ 11, i.e. from the later part (HST) of sequence 6. If that interpretation is correct, beds below, from the uppermost Tournaisian base of the Zippenhaus Mb (bed 7) (Bábek et al., 2010) to bed 14 might indicate sequence 5 (Fig. 11).

5.5. Sequence 9 (early Warnantian/"Asbian")

Sequence 9 is one of the best documented Mississippian sequences in the RKB (Herbig, 2011). In Belgium, the sequence is well developed in southern and eastern Belgium (Hance et al., 2001; Poty et al., 2014).

5.5.1. General development – the calciturbidite and starved basin facies

Apparent minor biostratigraphic discrepancies between the base of the sequence in Belgium and the RKB (Herbig, 2011) are solved herein. On the Belgian carbonate platform, the base of sequence 9 is within the foraminifer zone MFZ 13 (Fig. 3). It is approximated by the base of the *Gn. bilineatus* conodont Zone. In the RKB, the base of the sequence was placed somewhat higher at the base of MFZ 14 ('Cf6γ', 'late Asbian'). The lithostratigraphic base was considered to be the base of the Bromberg Fm (Korn, 2003b), i.e. at the base of the traditional 'Kieselige Übergangsschichten' (Nicolaus, 1963). The Formation includes the former Retringen and Linnepe formations (Korn, 2003a) from the Herdringen and Hellefeld calciturbidite systems (Fig. 1), which due to their location within the calciturbidite facies are more calcareous, but now are included as members within the Bromberg Formation.

The Bromberg Formation consists of an alternation of black alum shale packages, light greenish-grey to black cherty shales, and intercalated calciturbidite beds. It records a pulsed transgression (Herbig, 1998), which led to a remarkable homogenization of the sedimentation with prevailing dark sediments within the RKB.

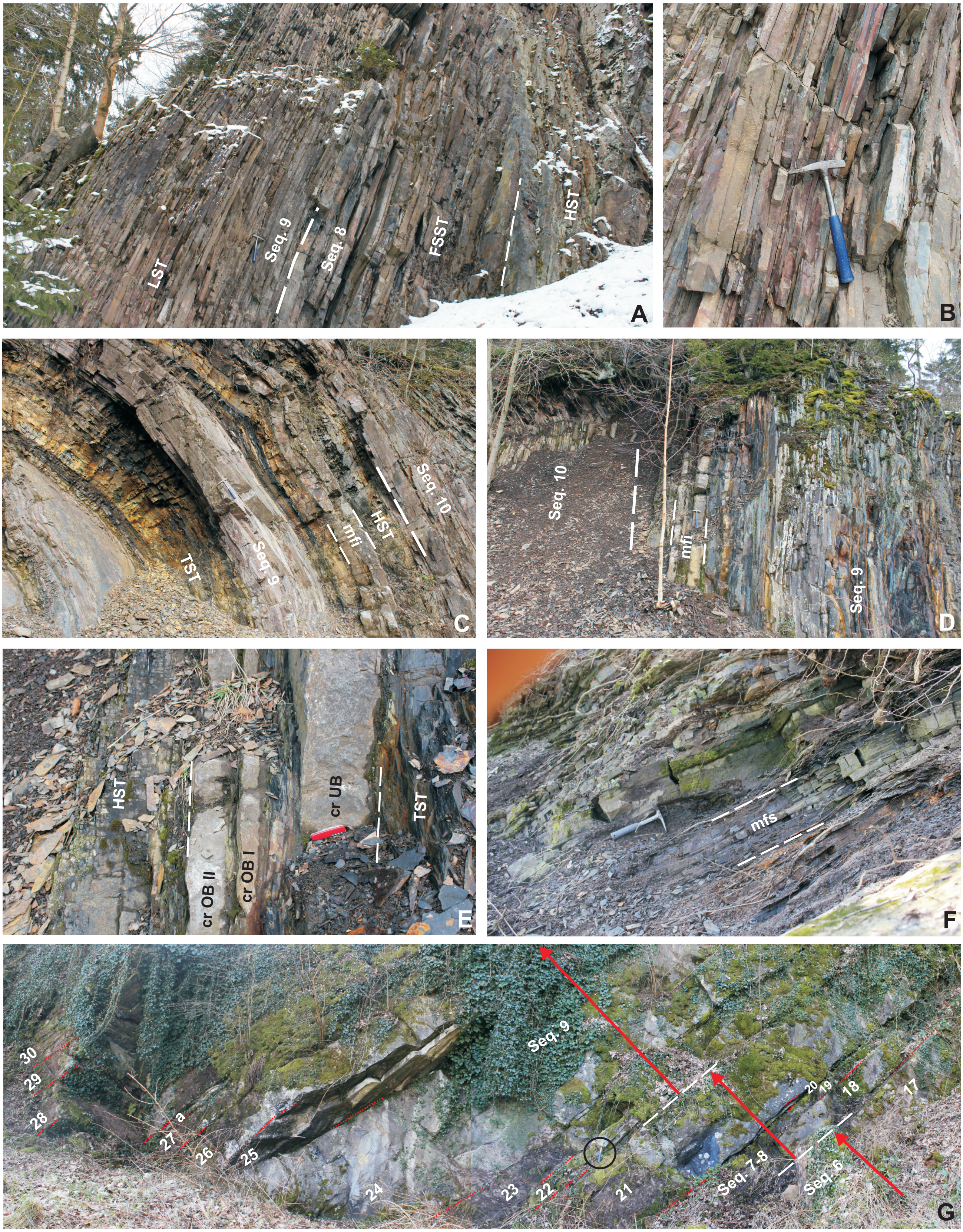

Figure 12. Late Viséan sequences from the starved basin facies (Fig. A-B, D-E: Bromberg section, C: Düdinghausen section, both Waldeck Syncline), and from the western margin of the Rhenish Kulm Basin (Fig. F-G, Zippenhaus section, Velbert Anticline). A: Transition between sequences 8 and 9, uppermost Hillershausen Fm. Calciturbidite beds with episodically changing, irregular bed thicknesses (HST) overlain by regular thin-bedded calciturbidites in topmost sequence 8 (FSST). Above sharp boundary basal sequence 9 with extraordinary thin, lightly marly calciturbidites (LST). Hammer for scale (close to base of sequence 9). B: Detail of the macroscopically dense, slightly marly calciturbidites from Fig. A. C: Sequences 9-10. TST of sequence 9 consisting of alum shale packages and intercalated light greenish-grey, siliceous shale and calciturbidite beds. mfi: *crenistria* Limestone horizon. Above an uppermost alum shale package (HST), sequence 10 starts with shale (Lelbach Fm). D: Sequences 9-10. Succession as in Fig. C, but less developed calciturbidite beds in the TST of sequence 9. Most of the HST of sequence 9 and boundary to sequence 10 not exposed. E: mfi of sequence 9 showing the three *crenistria* Limestone beds (cr UB – Unterbank, cr OB I – Oberbank I, cr OB II – Oberbank II) and separating black shale layers. F: mfi of sequence 10. mfs sensu strictu indicated by few thin siliceous shale/chert beds within the black shale. Note lithological similarity to mfs of sequence 11 (Fig. 15E). G: Top of late Moliniacian sequence 6. Undifferentiated Livian sequences 7-8 with extremely reduced calciturbidite shedding. Opposed, thick Asbian sequence 9 (bed 22-32, ?33; uppermost beds not visible in photograph). Sequence boundaries amalgamated and mostly based on biostratigraphic data; few thin beds at the base of sequence 9 (bed 22, hammer encircled for scale) probably indicate the LST.

The facies is indicative of the TST of sequence 9. However, the base of the sequence, i.e. the LST, therefore has to be close to the top of the underlying lithological units (Hillershausen Fm and lateral equivalents). In fact, calciturbidites are rare or extremely thin-bedded and fine-grained in the uppermost part of the Hillershausen Fm, thus pointing to strongly reduced carbonate sedimentation on the platform source. This was well documented e.g. in the Bromberg section (Korn, 2003b) (Fig. 12A, B) and in the Riescheid section (e.g. Korn, 2010; Hartenfels et al., 2016). Witten (1979) noted the generally increased thickness of turbidite interbeds, this means decreased turbidite shedding, in the uppermost Hillershausen Fm.

The LST of sequence 9 coincides approximately with the proposed base of the *Gn. bilineatus* Zone few metres below the base of the Bromberg Fm (Meischner & Nemyrovska, 1999; see also Herbig & Stoppel, 2006). Herbig (2006a) attributed the complete Bromberg Fm to ‘Cf6γ’ (MFZ 14), but the foraminifer assemblages derived from the upper part of the Formation, whereas the lower part yielded only undifferentiated ‘Cf6’ faunas (Conil & Paproth, 1983; see also Herbig, 2006a). Hence, the existence of ‘Cf6α-β’ (MFZ 13) appears reasonable and was already assumed by Herbig (1998, fig. 2), who placed the *Entogonites grimmeri* Zone in the sense of Korn (1996) at the base of the Bromberg Fm into the ‘Cf6α-β’ (MFZ13).

In summary, the redefined base of sequence 9 in the uppermost Hillershausen Fm and its equivalents, the approximate entry of *Gn. bilineatus* at this level, and reevaluation of foraminifer data strongly point to the stratigraphic equivalence of the base of sequence 9 on the northwest European carbonate platform and in the RKB.

Further clarification is needed concerning the usage of “late Asbian”, which generally was used in description of sequence 9 in the RKB. Conventionally, the foraminifer zone MFZ 14 (Cf6γ) was correlated with the upper Asbian (e.g. Riley, 1993; Jones & Somerville, 1996; Herbig, 1998, 2006a; Somerville, 2008). Moreover, the bases of the Asbian and Warnantian stages were mostly considered to coincide (e.g. Jones & Somerville, 1996; Somerville, 2008). However, Aretz & Nudds (2005) showed the absence of the Asbian index fossils in the lower part of the stratotype. As a result, the “*de facto* Asbian” in the stratotype starts high up in the lower Warnantian with coral subzone RC7β, i.e. within foraminifer zone MFZ 14 (see also Poty et al., 2014). For reasons of nomenclatural stability “upper Asbian” and respectively “late Asbian” is still used for the time slice of MFZ 14 in the RKB.

In the upper part of the Bromberg Fm, the TST of sequence 9 ends below three peculiar black cephalopod limestone beds and interbedded black shales, termed *crenistria* Horizon after the mass occurrence of *Goniatites crenistria* Phillips, 1836 (Fig. 12C-E; Fig. 13). The autochthonous deeper-water limestone is the best index horizon in the Mississippian of the RKB, lacking any shallow water components. It represents the maximum flooding interval (mfi) (Herbig, 1994, 1998). The horizon and stratigraphic adjacent strata were intensely studied (Warnke, 1997; Mestermann, 1998; Herbig et al., 1999; Piecha et al., 2004). It is traced in almost identical facies and comparable thickness across the Rhenohercynian Zone from the Harz Mountains and the RKB to the Dinant region, southern Belgium, Devonshire, southwestern England, and to the hemipelagic platform of the external South Portuguese Zone (Korn & Horn, 1997, and older references therein; Mestermann 1998, Herbig et al., 1999).

Above the *crenistria* Horizon, a thin, maximum about 1.5 m metre thick HST consisting mostly of black alum shales is developed in the topmost part of the Bromberg Fm (Korn & Kaufmann, 2009). This is another example that within basinal sequences the HST still records exaggerated water depth. Opposed, it shows a differentiated lithological development in the hemipelagic carbonate platform environment of the South Portuguese Zone (Herbig et al., 1999).

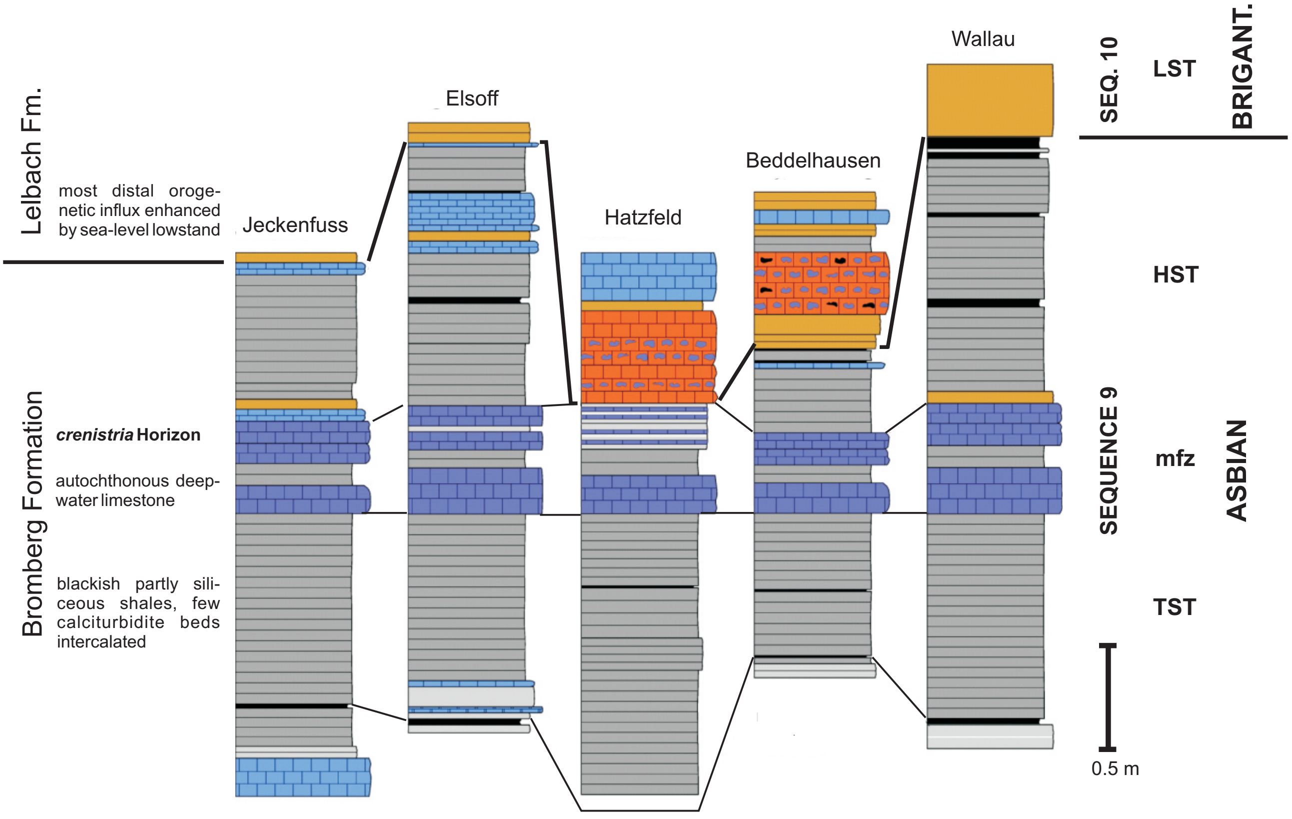

Figure 13. Asbian to early Brigantian sequences 9-10 from sections in the upper Eder valley, Witttgenstein Syncline, eastern Rhenish Kulm Basin. Note partly to complete erosion of the HST of sequence 9 in the Hatzfeld and Beddelhausen sections. Dark blue: autochthonous deep-water limestone (*crenistria* Limestone beds), light blue: calciturbidites, grey: partly siliceous blackish shales, black: black alum shales, yellow: silty shales, red: debrites reworking *crenistria* limestone. Modified from Piecha et al. (2004).

5.5.2. Flysch facies

The *crenistria* limestone is not developed within the siliciclastic flysch facies of the easternmost RKB. However, at least parts of sequence 9 can be traced in certain sections.

A key section is Dainrode, type locality of the Dainrode Formation (Korn, 2003a), which was thoroughly described by Schrader (2000) and van Amerom et al. (2002); additional interpretations are from Herbig et al. (2006). The TST of sequence 9 is contained in 'unit 1' in the lowermost part of the section. It consists of silty shales and siltstones. The mfs is recorded by mass occurrences of *G. crenistria* in all growth stages, preserved as internal moulds on the bedding plane of a thickly laminated, greenish grey, decalcified mudstone layer. The uppermost TST and the HST are characterized by some fine-grained calciturbidite beds within the continuing silty succession (see description in van Amerom et al., 2002). Also in Eckelshausen, northern Dill Syncline, the mfi/HST is indicated by calciturbidite lenses within dark shales, which yielded goniatites of the 'cd III$\alpha_{3\text{-}4}$' (Nicolaus, 1963), i.e. from the *G. crenistria* and *G. fimbriatus* Zones (Korn, 1996). The calciturbidites also yielded foraminifers from zone MFZ 14 (Cf6γ) (Amler, 1987; Herbig, 1998). Presumably, further isolated calciturbiditic limestone beds and lenses from other sections within the flysch facies can be attributed to the HST of sequence 9 (Amler, 1987).

5.5.3. Western basin margin – Velbert Anticline

As in the siliciclastic flysch facies, the *crenistria* limestone is not developed within the calciturbidite succession of the Velbert Anticline. Sequence 9 records the maximum turbidite shedding within the Heiligenhaus Fm, resulting in up to 2.5 m thick, probably amalgamated calciturbidite beds in the Zippenhaus section (Figs 11, 12G). According to lithofacies and biostratigraphic data (Conil & Paproth, 1968; Paproth et al., 1976; Pille et al. 2006), the sequence contains beds 22-33, altogether about 12.6 m thick, and thus representing somewhat more than half of the Formation. This indicates a profound reorganization of the platform source after the extremely reduced late Moliniacian and Livian calciturbidite shedding. Bed 22 represents the LST. Characteristically, it consists of thin calciturbidite subbeds partly separated by marly interbeds. Its attribution to the base of sequence 9 is supported by the entry of *Gn. bilineatus* (Paproth et al. 1976), and the disappearance of all Livian foraminifers still known from the bed below. The impoverished calcareous microbiota within beds 23-28, noted by all workers, and in generally characteristic for early Warnantian platform carbonates, is apparently related to the TST of the sequence, although the great thickness of the calciturbidite beds is surprising. Above, the HST is easily recognized by repeated shedding of oolitic material (e.g. in bed 29 and in the topmost bed 32 of the Heiligenhaus Fm, as already noted by Paproth et al., 1976). This clearly indicates the development if a rimmed carbonate platform during highstand. Again, biostratigraphy strongly supports the interpretation, as MFZ 14, i.e. the HST of sequence 9 (see Poty et al., 2006, 2014) is unequivocally proved from beds 29 to 32/33 (Pille et al., 2006). The boundary between sequences 9 and 10 is discussed in 5.6.2.

Also in the well Velbert 4, sequence 9 records the maximum calciturbidite shedding. It consists of a 14 m thick succession of up to 1.3 m thick beds with lithoclastic-bioclastic rudstone at their bases (Herbig et al., 2014b).

5.5.4. Biotic response

Outside the flysch facies and the Velbert Calciturbidite System, sequence 9 is exceptional because of its fauna. The base of the TST, i.e. the base of the Bromberg Fm, is marked by the *E. grimmeri* bed. In most sections, it is characterized by the abundance of the name-bearing ammonoid, that, however, also occurs somewhat below and above the bed (see Korn, 2003b for the detailed record of the taxon in the Bromberg section). The *E. grimmeri* bed is traced in the Harz Mountains and throughout the RKB (Korn, 2003b, 2010) and is herein classified as a proliferation epibole (Brett & Baird, 1997) caused by favourable, though unknown ecological conditions during the beginning transgression. It has to be stressed that *Entogonites* is almost globally distributed and, therefore, indicates widely connected marine realms already at the base of sequence 9 (Korn et al., 2012). Above, a rapid evolution and diversification of ammonoids is known from the RKB (Korn, 1996, 2006b). The obviously successive breakdown of barriers due to the rising sea-level caused a pandemic distribution of the genus *Goniatites* during the HST of sequence 9 (*G. fimbriatus* Zone), which continued through the following LST of sequence 10 (*G. spirifer* Zone) (Korn, 1997). In general, a distinct biogeographic pattern of ammonoids is missing during the Asbian (Korn et al., 2012), thus indicating that sequence 9 was a major transgressive interval without important marine barriers.

G. crenistria enters below and continues somewhat above the *crenistria* Horizon (Korn, 1996, 2003b). However, an outburst is recorded in the limestone beds of the horizon with specimens from embryonic to adult growth stages ("*crenistria* Event"). Herbig et al. (2014a, 2015) considered this mass occurrence as an ecological epibole. The authors speculated that opposed to other ammonoids only this taxon survived in the extremely nutrient-poor environments that developed during the maximum flooding interval due to maximum coastal onlap and the resulting fading of fine-grained detrital and nutrient input from the terrigenous hinterlands.

5.6. Sequence 10 (late Warnantian/early Brigantian)

The existence of a sequence 10 in Belgium, the British Isles and the Montagne Noire was already indicated by Hance et al. (2001; see also Poty & Hance, 2006; Poty et al., 2011b, 2014), but not elucidated in greater detail. The major erosional unconformity on top of sequence 9 in the Belgian Namur and Condroz Sedimentation areas (Hance et al., 2001), i.e. at the top of the Lower Member of the Anhée Fm, is correlated with the important sea-level drop between sequences 9 and 10 in the

Figure 14. Debris-flow sediment indicating the LST at the base of the Early Brigantian sequence 10, Hatzfeld section, Wittgenstein Syncline, eastern Rhenish Kulm Basin (base of Lelbach Fm; see Fig. 13). Clasts consist of *crenistria* Limestone, which forms the mfi o sequence 9.

RKB. Biostratigraphic uncertainties remain. In the RKB, the base of sequence 10 coincides with the base of the *G. spirifer* Zone, which is considered to indicate the base of the Brigantian (see discussion in Herbig et al., 1999, Korn, 2010). In Belgium, the base of the sequence is drawn somewhat higher, above the base of the upper Warnantian, and respectively, above the approximately coinciding base of the Brigantian (Poty & Hance, 2006; Poty et al., 2014). This is due to the the guide foraminifer *Janischewskina typica* that defines the base of the upper Warnantian (= base of MFZ 15), and that on the platform already enters in the uppermost part of sequence 9.

5.6.1. Calciturbidite and starved basin facies

The LST of sequence 10 is well seen in the starved basin and calciturbidite facies in sections that were deposited adjacent to deeper intrabasinal swells. There, different debrites bearing clasts of the *crenistria* limestone are seen in conglomerates and debris-flow sediments. This was first noted by Mestermann (1998) and well-documented from the Hatzfeld section, but also from sections in southern Belgium and southwestern England (Mestermann, 1998; for the latter see already Matthews & Thomas, 1974), and from the South Portuguese Zone (Herbig et al., 1999). Hatzfeld and adjacent sections (Fig. 13) were studied in detail by Piecha et al. (2004). Besides the 0.3-0.4 m thick debris-flow bed reworking

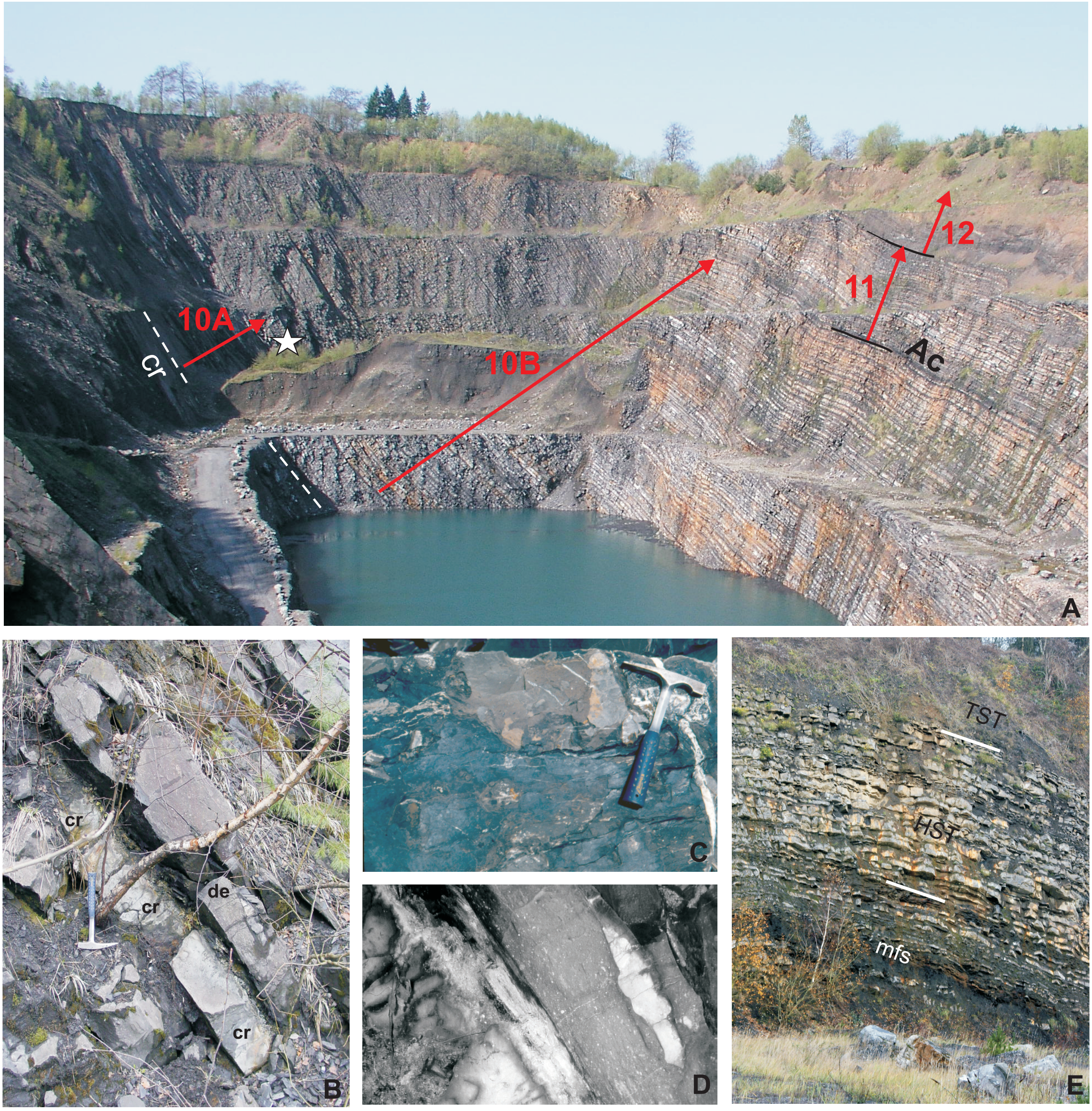

Figure 15. Brigantian sequences 10-11 (Herdringen Fm) and Pendleian sequence 12 (Seltersberg Fm) in the Becke-Oese quarry, Remscheid-Altena Anticline. Calciturbidite facies (Herdringen Calciturbidite System). A: General view. Early Brigantian bipartite sequence 10 starting shortly above the *crenistria* Horizon (cr, mfi of sequence 9): Sequence 10A corresponds to Griesenbrauck Mb, base of sequence 10 B coincides with major debrite horizon at the base of Wicheln Mb (asterisk). Late Brigantian sequence 11 (Edelburg Mb) with basal TST consisting of the black alum shales of the *Actinopteria* Shale interval (Ac). Above pronounced sequence boundary lowermost part of the Pendleian sequence 12. Photograph (M. Piecha, Krefeld) showing situation in 2006. Lowermost floor now flooded. B-D: Debrite horizon at the base of sequence 10B (for location see asterisk in Fig. 10A). B: More than one metre long *crenistria* Limestone olistolite (cr) and overlying coarse-grained calciturbidite with floating *crenistria* Limestone clast (de); hammer for scale). C: Debris-flow sediment with large *crenistria* Limestone clast and shale clasts. D: *crenistria* clast in coarse-grained calciturbidite, detail of Figure 10B). E: *Actinopteria* Shale interval at base of sequence 11 (TST), mfs characterized by more intense silicification. Black shale of the basal Seltersberg Fm indicates TST of sequence 12.

the *crenistria* limestone in Hatzfeld (Fig. 14), they proved an analogous, less well-developed debrite bed in the Beddelhausen section, some kilometres further west. A gap was noted in Hatzfeld, removing the uppermost unit M9 of the Bromberg Fm; a minor gap is apparently developed in Beddelhausen due to the reduced thickness of M9 compared with other sections of the region (Fig. 13). The debrites in both sections occur in the basal beds of the Lelbach Fm. They are from the basal Brigantian *G. spirifer* Zone with the oldest *G. spirifer* occurring 2.7 m below the debrite in Hatzfeld, but co-occurring within the debrite in Beddelhausen. Brigantian foraminifers (MFZ 15) from rare, fine-grained calciturbidite beds intercalated within shales occur about five metres above.

Further sections with debrites bearing reworked *crenistria* limestone clasts are known from the well Rüthen-2 northeast of Brilon (Scheuch, 1999) and from the Herdringen Calciturbidite System (Korn, 2008; Herbig et al., 2006). In the latter area, the debrites occur in several sections at the base or very close to the base of the Herdringen Fm, closely above the *crenistria* Horizon. They are thickest in the western Griesenbrauck section. There, as in Hatzfeld, the uppermost unit M9 of the Bromberg Fm and even the upper part of *crenistria* Horizon are eroded. Also in Becke-Oese unit M9 is only fragmentarily preserved with reduced thickness; the overlying, laterally rapidly wedging debrites account for repeated successive erosion and redeposition (Korn, 2008).

In Becke-Oese, an uppermost quite spectacular debrite horizon occurs about 25 m above the *crenistria* Horizon yielding various clasts of limestone, mudstone, and alum shale floating in a coarse-grained matrix (Fig. 15A-D). Among them, a more than two metre long slab of the *crenistria* limestone has been recognized (Korn, 2008). The debrite occurs at the base of the Wicheln Mb of the Herdringen Fm, i.e. at the base of the *Neoglyphioceras spirale* Zone. The relatively thin, up to 25 m thick Griesenbrauck Mb below predominantly consists of grey shales deriving from turbiditic fines with increasing abundance of calciturbidite beds up-section. However, the total carbonate content and the thickness of calciturbidites remain low (Korn, 2008, figs 9-10). According to the general lithofacies development of the Griesenbrauck Mb and the spectacular uppermost debrite horizon just above its upper boundary, this succession hitherto was regarded as the LST of sequence 10 (Herbig et al., 2006). The overlying, up to 110 m thick Wicheln Mb, almost completely consists of calciturbidites and, hence, would represents the TST(?) and HST of sequence 10. In its upper part, a falling sea-level (FSST?) might be indicated by the thinning of calciturbidite beds (Korn, 2008).

However, doubts remain because of the extended thickness of the LST, which would end above the spectacular debris-flow horizon at the base of the *N. spirale* Zone and, therefore, would extend across four ammonoid zones. In fact, a conspicuous '*spirale* conglomerate' is widespread in the Waldeck Syncline (Kulick, 1960; Sadler, 1983). From that time slice also debris-flow sediments bearing reworked shallow-water limestones are known ('Kohlenkalk von Schreufa', 'Kohlenkalk-Schollen' from the southern slope of the Waldeck Schlossberg; see Amler, 1987 and older references therein; see also Stoppel et al., 2006). Moreover, two well-known calciturbidite successions within the Waldeck Syncline are separated by the conglomerate. These are the older Hesseberg Mb (the traditional *Posidonia* Limestone) that reaches into the *N. spirale* Zone (e.g. Korn, 1993), and the younger Rhena Mb above (Meischner, 1962). Hence, the *spirale* conglomerate is an important eustatic signal, as already expressed by Herbig (1993) and Bender et al. (1993) which favours the subdivision of sequence 10 into two transgressive-regressive cycles of lower order (sequence 10A, 10B). As a result, the Griesenbrauck Mb of the Retringen calciturbidite System represents sequence 10A, the Wicheln Mb sequence 10B (Fig. 15A). In the Hellefeld calciturbidite System the undivided sequence 10 is contained in the Geitenberg Mb of the Wennemen Fm.

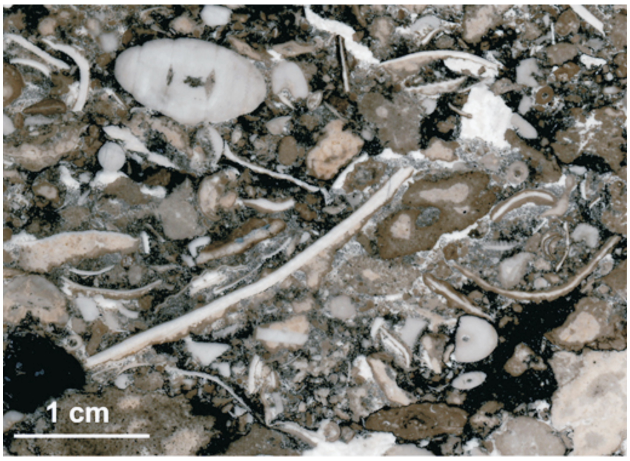

Figure 16. LST breccia from the base of the early Brigantian sequence 10. Base of Dieken Fm, core Velbert 4, depth 25.7-26.0 m, western margin of the Rhenish Kulm Basin, Velbert Anticline. Bioclastic-lithoclastic rudstone reworking diverse shallow-water biota.

5.6.2. Western basin margin – Velbert Anticline

In the Velbert Anticline, sequence 10 is recorded in the core Velbert 4 and in the Zippenhaus section. In the latter, the base of the TST coincides with the base of the Dieken Fm, which according to Amler & Herbig (2006) and Aretz et al. (2006) is drawn at the base of the 0.42 m thick black alum shale above bed 33 (Fig. 11). The LST is not reliably recognized, but might be represented in the calciturbidite bed 33 below, which shows an ambiguous erosional unconformity at its base. This would be in accordance with the core Velbert 4, where the base of the Dieken Fm is drawn at the base of a 0.35 m thick conspicuous carbonate breccia (Fig. 16). It supposedly records the generally well-documented platform-margin collapse at the Asbian-Brigantian boundary and, hence, represents the LST. In the core, a 1.65 m thick TST consisting of calciturbidites and intercalated, in part black, silicified shales is overlying. Subsequent drowning of the adjoining platform is recorded in the mfi that consists of 2.15 m of laminated cherts. The HST above shows calciturbidites with rapidly changing grain sizes and highly diverse biota (Herbig et al., 2014b).

In Zippenhaus, biostratigraphic data support the existence of the lower Brigantian sequence 10. Certain foraminifers from the calciturbidite beds above the basal black shale interval indicate MFZ 15, although most taxa are obviously reworked from MFZ 14 (Cf6γ) (Pille et al., 2006; see also review in Herbig, 2006a). In addition, ammonoids from the Dieken Fm in the Zippenhaus section indicate the Brigantian (Amler & Herbig, 2006, based on data from Paproth et al., 1976) (Fig. 11). 1.35 m further upsection, a 0.55 m thick intercalation of thin-bedded black cherts, siliceous shales and black shales (beds 37-39) indicate analogous to the core Velbert 4 the mfi (Fig. 12 F). The HST above consists of the two uppermost calciturbidite beds (bed 40) of the section, followed by few metres of dark grey shales. They are overlain by a monotonous succession of black alum shales (Seltersberg Fm, formerly Eisenberg Fm of Korn 2003a). The pseudoplanctic bivalve '*Caneyella lepida*', one of the names given to *Ptychopteria* (*Actinopteria*) *lepida* (Goldfuss) (Amler, 2004) occurs in the basal parts of the Formation in the Zippenhaus section. Mass occurrences of this taxon occur in the *Actinopteria* Shale interval at the base of the overlying sequence 11 (see 5.7.1). As Korn (2010) noted this guide horizon in a temporarily accessible section in the adjacent Herzkamp Syncline at the base of the Seltersberg Fm, it is tempting also to correlate in the Zippenhaus section the boundary between Dieken and Seltersberg formations with the boundary between sequences 10 and 11 (Fig. 11).

5.6.3. Flysch facies

In the flysch facies of the eastern RKB, the lowstand of sequence 10 is documented in polymicitic debris-flow sediments from Königsberg (Lahn Syncline) (Herbig, 1998). Ammonoids indicate an age of 'late cd IIIα/early cd IIIβ' (around the

Asbian-Brigantian boundary). The debris-flow sediments contain reworked exotic shallow-water macrofauna (Amler, 1987) and isolated calcareous microbiota, shallow-water carbonate bioclasts, radiolarian-bearing cherts and partly plastically deformed mudstones. Reworked calcareous microbiota are slightly older than the host sediment. They have been derived from the late Asbian Zone 'Cf6γ' (MFZ 14) and, hence, indicate erosion and redeposition of the strata of the immediately preceding highstand. The presence of radiolarian-bearing cherts indicates also erosion of older parts of the Carboniferous succession. Analogous debrites are known from further localities (Amler, 1987), but age control is less detailed.

An excellent record of the lowermost sequence 10 is documented within the greywacke succession of the Dainrode Fm in its type locality. Above the HST of sequence 9 that is characterized by the predominance of mudstone and siltstone and some intercalated calciturbidite beds (unit 1 of the section, see 5.5.2), the LST of sequence 10, the 165 m thick unit 2, mostly consists of coarse-grained to micro-conglomeratic greywackes. Except for the lowermost part, this is a thinning- and fining-upward macrocycle. Like the HST of the preceding sequence 9, the following 40 m thick unit 3 consists of mudstone, siltstone, some thin greywacke beds, and rare calciturbidite beds. Above, some tens of metres of coarse-grained, very thick-bedded greywackes (unit 4) follow with erosional contact. However, according to ammonoids and the trilobite *Cyrtoproetus moravicus* (Přibyl, 1950), the unit 3 is still from the basal Brigantian *G. spirifer* Zone (van Amerom et al., 2002; Herbig et al., 2006) and thus still from the LST of sequence 10. Therefore, the fine-grained facies of unit 3 either might be related to an autocyclic origin, i.e. to a switch of turbidite lobes, or, more probable, represents a smaller allocycle. Like the pronounced small cyclic development of late Asbian and Brigantian shallow-water successions, such allocycles could be related to the onset of the Gondwana glaciation (Herbig et al., 2006).

5.6.4. General evaluation

In wide parts of the RKB, the base of the Brigantian is characterized by the onset of fine-grained terrigeneous deposits as seen in the Lelbach Fm (the former 'Kulm-Tonschiefer' from the eastern RKB, Fig. 12C-D; Fig. 13). Further northwest, time-equivalent, more fossiliferous mudstone/siltstone successions that might include some calciturbidite beds were named Dieken Fm (the former 'Posidonien-Schiefer'). The changing sedimentary regime documents the end of the starved basin phase and the beginning of the flysch phase, characterized by the influx of the most distal detritus from the prograding Variscan Orogen. The simultaneous onset of muddy and silty sediments in wide parts of the basin was enhanced by the sea-level fall at the Asbian-Brigantian boundary, due to the rising erosional gradient and progradation of the coastline (Herbig, 1998; Herbig et al., 2006).

5.6.5. Biotic response

Opposed to the differentiated trilobite fauna from the late Asbian TST/HST of sequence 9, the trilobite fauna from the earliest Brigantian *G. spirifer* Zone is characterized by the almost monospecific distribution of *Cyrtoproetus moravicus.* The genus first appeared in the HST of sequence 9 and substituted *Archegonus* that is the index genus throughout the Asbian (Brauckmann & Tilsley, 1987; Brauckmann & Hahn, 2006). Change and impoverishment of the benthic trilobite fauna between sequences 9 and 10 are obvious in the RKB, although definite reasons remain unknown.

5.7. Sequence 11 (late Warnantian/late Brigantian)

Sequence 11 is well-represented in the latest Viséan of the RKB. It is not preserved in Belgium due to the extended erosional gap below the transgressive lower Namurian (Arnsbergian) Chokier Fm (e.g. Hance et al., 2001; Poty et al., 2014, Nyhuis et al., 2014).

5.7.1. Generalized basin wide development

The TST of sequence 11 is the isochronous *Actinopteria* Shale in the sense of Nyhuis et al. (2015). It consists mostly of black alum shales and, as a first order index horizon (Korn, 2008; Korn & Kaufmann, 2009), forms the base of the Medebach Group (Korn, 2003a). The base coincides with the base of the *N. suerlandense* Zone (e.g. Korn 2010). The *Actinopteria* Shale *sensu strictu* (Ruprecht, 1937; Kulick, 1960; Korn, 1993, 2008; Korn & Kaufmann, 2009) adjoins directly above within the *N. suerlandense* Zone (Korn, 1996, 2006b). According to lithofacies, both horizons merge and judging from existing descriptions, some confusion seems to exist in their differentiation and, respectively, in well-defined usage. The base of the *Actinopteria* Shale in its wider sense ('*Actinopteria* Shale interval') coincides with the conventional mid-Brigantian boundary. New biostratigraphic data indicate that this biostratigraphic level might be close to the still unsettled base of the Serpukhovian (Sevastopulo & Barham, 2014; Cózar & Somerville, 2014, 2016). The LST of sequence 11 is not recognized. This might be due to sediment starvation, like e.g. at the base of sequence 2.

The *Actinopteria* Shale interval (Fig. 15A, E) is related to a transgression (Bender et al., 1993; Korn, 2008; Herbig, 2011). Maximum thicknesses of up to three metres are attained within the Herdringen and Hellefeld calciturbidite systems (Korn, 2008). The usually thin horizon is also recognized within greywackes from the Harz Mountains (Figge, 1964) and all along the northern margin of the Rhenish Mountains. Outcrops in the western part of the basin are poor. Grewing et al. (2000; see also Korn, 2010) recorded the *Actinopteria* Shale from a pipeline trench in the Herzkamp Syncline near Kohleiche. A three metres thick unit bearing phosphate nodules and a rich radiolarian fauna from the adjacent Kohleiche road cut most probably also represents the interval (Thomas & Zimmerle, 1992: bed 8/17). It also might be present in the subsurface of the eastern Campine Basin in the southern Netherlands (Nyhuis et al., 2016).

Mass occurrences of *Actinopteria* within the horizon as described by Nyhuis et al. (2015) are restricted to a very thin, more siliceous interval (see 5.4.4.). It is interpreted to be the mfs (Fig. 15E). According to the lithofacies, it resembles the mfs of sequence 10 from the Velbert Anticline (see 5.6.2 and Fig. 12F). The TST of sequence 11 is extremely thin and in addition to the not recognized LST of the sequence, this points to major sediment starvation. The relatively extended calciturbidite successions above the mfs are the HST of sequence 11. These are the calciturbidites of the Berge Mb (upper Wennemen Fm, Hellefeld Calciturbidite System), and the Edelburg Mb (upper Herdringen Fm, Herdringen Calciturbidite System) (Korn, 2003a, 2008).

On top of the intrabasinal swells of the Warstein and Brilon anticlines, and in the Herzkamp Syncline, undifferentiated shales commonly yielding the bivalve *Posidonia* predominate in an undifferentiated sequence 10 below the *Actinopteria* Shale (Dieken Fm, Korn & Kaufmann, 2009; Korn, 2010). In these areas, as well as in the Velbert Anticline (see 5.6.2.), the *Actinopteria* Shale forms the base of a thick succession of black alum shales that reaches up into the Namurian (Seltersberg Fm, former Eisenberg Fm of Korn 2003a). Hence, the TST of sequence 11 is the uppermost sequence stratigraphic level that can be observed there; the Seltersberg Fm forms an amalgamated sequence comprising the late Brigantian HST of sequence 11 and the basal Namurian (Pendleian) sequence 12. Opposed, in the Herdringen and Hellefeld calciturbidite systems, the base of the Formation is more or less connected with the basal Namurian transgression (see 5.8).

Only in its type area at the southwestern end of the Lüdenscheid Syncline, the Dieken Fm continues above the *Actinopteria* Shale with differentiated shales, partly bearing carbonate laminae, and few intercalated, thin calciturbidite beds (Korn & Kaufmann, 2009). According to their stratigraphic position they can be attributed to the HST of sequence 11.

In the eastern RKB (within the Waldeck Syncline and further east), the *Actinopteria* Shale is not recognized hitherto. Hence, the boundary between sequence 10 and 11 is not recognizable and parts of sequence 10 (see 5.6.3.) and sequence 11 are hidden in shales and, further east, in the earliest greywackes of the prograding flysch front.

5.7.2. Biotic response

'Actinopteria' [= *Ptychopteria* (*Actinopteria*)] *lepida* (Goldfuss), Amler, 2004] is known from the late Viséan *N. spirale* to the basal early Namurian *Tumulites pseudobilinguis* zones, but 'mass occurrences' are apparently restricted to some bedding planes within the *Actinopteria* Shale interval (Korn & Kaufmann, 2009; Nyhuis et al., 2015). Based on a detailed study of a section in the Hellefeld calciturbidite System, Nyhuis et al. (2015) interpreted the only some centimetre thick *Ptychopteria*-bearing interval in the upper part of the *Actinopteria* Shale in their sense as mfs. According to the microfacies of the shales and bioturbation features, the abundant preservation of the flimsy paper pecten is obviously related to minimum sedimentary input during the maximum flooding and missing bottom currents that could rework the shells. For that type of bioevent Herbig et al. (2014a, 2015) coined the term "maximum completeness epibole".

Moreover, the break-down of barriers during the highest sea-levels in sequence 11 is documented by the spread of *Lusitanoceras poststriatum* in the interval above the *Actinopteria* Shale interval throughout most European platforms and basins. The very short ranging genus *Lusitanoceras* itself even reached an almost global distribution with morphological extremely similar species (Korn, 1997).

5.8. Higher sequences (lower Namurian)

In the RKB, sequences above sequence 11 are not reliably recognized due to the progradation of the Variscan orogen front and concomitant downwarp of the foreland basin. Outside of the Herdringen and Hellefeld calciturbidite systems the formation of the black alum shales constituting the Seltersberg Fm already started in the late Brigantian (see. 5.7.1). Within the Herdringen Calciturbidite System, Korn (1993) demonstrated the diachronous onset of the Formation on top of the Herdringen Fm. In the eastern sections, calciturbidite sedimentation terminated in the latest Brigantian, but further west three ammonoid zones later in the basal Namurian (Pendleian). However, already Krebs (1968a, 1969) stressed the transgressive nature of the 'Hangende Alaunschiefer' and an important general basal Namurian (Pendleian) transgression was depicted by Ross & Ross (1987a, 1988). Hence, a major sequence boundary, masked by the general tectonic downwarp of the foreland basin, is related to the Viséan-Namurian boundary. In the eastern Campine Basin (southern Netherlands), the TST of this sequence 12 is documented by the bituminous black shale of the Geverik Mb (lower Epen Fm), that conformably overlies upper Viséan limestone (Goeree Mb, upper Zeeland Fm) (van Adrichem Boogaert & Kouwe, 1993; Nyhuis et al., 2016). An analogous succession is known from the subsurface of the Lower Rhine Embayment (Mathes-Schmidt & Elfers, 1998; Mathes-Schmidt, 2000; Nyhuis et al., 2015).

It appears reasonable that in spite of the observed diachroneities, the basal Namurian (Pendleian) transgression, (1), caused the general shutdown of the latest Viséan calciturbidite shedding within the Retringen and Hellefeld calciturbidite systems, (2), retarded the continuous northwestern progradation of synorogenic greywackes (Dainrode Fm), and, (3), resulted in the anoxic, thick black alum shale succession of the Seltersberg Fm. The alum shales are, according to their microfacies, the product of extremely fine-grained mud turbidites (C. Nyhuis, pers. comm.) due to the wide inundation of the hinterland and damping of the coarse-grained sediment influx.

In most parts of southern Belgium, the early Namurian sedimentation started later, above a major erosional gap at the base of the Arnsbergian (Chokier Fm, see review in Delmer et al., 2001). In the Arnsberg region, at the northeastern tip of the Remscheid-Altena Anticline, this sequence 13 is well recognizable. The LST is represented by an about 12-35 m thick greywacke succession ('Erste Grauwacke' Schmidt, 1934, see also Patteisky, 1959; Horn, 1960). It constitutes the base of the Arnsberg Fm (formerly Lüsenberg Fm, Korn 2003a) and is separated by an SB type 1 from the the black shales of the Seltersberg Fm below. The TST (and mfi?) can be related to the the black siliceous horizon of the '*bisulcatum* Kieselschiefer' (Schmidt, 1934). Its base marks the base of the Arnsbergian, i.e. the *Eumorphoceras-Cravenoceratoides* Genus Zone ('E2', e.g. Korn, 2006b, 2010).

5.9. Relictic late Viséan-basal Namurian sequences on high rising intrabasinal swells

Heuer et al. (2015) described the sedimentary fill of a neptunian dyke from the Brilon reef area. The results show the controlling factor of sea-level for the late Viséan-basal Namurian sedimentary history on top of a high rising intrabasinal swell and the applicability of sequence stratigraphy in this setting. The dyke yielded clasts of the pelagic *crenistria* limestone deposited during the maximum flooding interval of sequence 9 and clasts of tempestitic limestone from the slightly younger *G. imbriatus* or *G. spirifer* Zone. The shallow-water facies and the age of the latter clasts unequivocally indicate deposition during the LST of sequence 10. Together, they prove flooding of the reef area during the latest Asbian and earliest Brigantian. Afterwards, karstification, dyke formation, erosion and infill of the clasts started in the later Brigantian. Time equivalence with the major gap affecting the Belgian carbonate platform is evident, as sequence 10 is regionally eroded in Belgium and sequence 11, which is regionally recognized in the RKB, is not preserved at all. The basal Namurian transgression (sequence 12) again flooded the reef area and caused deposition of shales that yielded lower Serpukhovian conodonts and finally encased the limestone clasts.

6. Conclusions

The review and interpretation of published data enabled for the first time to recognize a comprehensive sequence stratigraphic subdivision of the Mississippian succession of the Rhenish Kulm Basin. The results demonstrate that key sections allow a successful sequence stratigraphic analysis of deeper-water successions, in the presented case of a foreland basin. However, sequence boundaries might be masked and, hence, sequences might be amalgamated in certain facies realms, e.g. on palaeobathymetrically undifferentiated basin plains outside the reach of gravitative sediment redeposition.

The comparison with the sequences known from the latest Devonian to latest Viséan of the Belgian shallow-water carbonate platform shows the presence of all nine sequences recognized there, and, additionally, the presence of two further sequences in the latest Viséan (Brigantian). In spite of the tectonic downwarp of the basin due to the prograding Variscan orogen front and the concomitant prograding flysch facies, regionally two lower Namurian sequences are discernible. These are the Pendleian sequence 12 with a partly masked and, therefore, apparent diachronous base, and the lower part of the Arnsbergian sequence 13. In summary, sequence stratigraphy backed-up by biostratigraphic data, is a most valuable tool for the correlation of basin and platform successions.

The earlier successful correlation of the Belgian sequences with successions in southwestern England, southern Poland, and southern China proves that Mississippian sedimentation is – at least wide-spread – governed by sea-level changes. They account for the relatively short, synchronous and parallel facies variations deduced from the stratigraphic sequences (Vail et al., 1991; for the RKB see Herbig, 1998; Herbig et al., 2014b). The general basin evolution of the RKB, and origin, migration and demise of its megafacies realms (flysch facies, starved basin facies, calciturbidite facies adjacent to shallow marine platform sources, facies of intrabasinal swells and slopes) are controlled by tectonic processes during longer time scales. Also (in part rapid) synsedimentary block faulting, e.g. in the Visé-Maastricht area (Poty & Delculée, 2011) only overprints the primary sequence stratigraphic pattern.

The best documented sequences in the RKB are the Hastarian sequences 1 and 2, the late Ivorian sequence 4, and the Warnantian (Asbian-Brigantian) sequences 9-11. The early Ivorian sequence 3 is mostly masked or missing. The Moliniacian and Livian sequences 5-8 are observed, but due to rare biostratigraphic data and lithological uniformity are not very well known. Biotic developments like preferential occurrence of plant fragments during transgressive phases, diversity peaks (HST of sequence 4 = Avins event), faunal breaks (e.g. trilobite overturn at SB 9-10), short pandemic distributions of ammonoid genera (basal TST of sequence 9, HST of sequence 9 and LST of sequence 10; early HST of sequence 11), proliferation epiboles (*E. grimmeri* bed), ecological epiboles (*crenistria* Event) and maximum completeness epiboles (*Actinopteria* Black Shale Event) support sequence stratigraphic interpretations.

Concerning the relative heights of sea-level of the sequences, four maximum sea-level rises are documented.

- During the early Ivorian sequence 2, which resulted in the extended formation of black alum shale within the RKB (Kahlenberg Fm). Exaggerated sea-levels during this time are stressed by the almost complete shut-down of the carbonate sedimentation in Belgium (Pont d'Arcole Fm), which is a remarkable exception from the general Mississippian carbonate facies development on the Northwest European shallow-water platforms.
- During the latest Ivorian HST of sequence 4, which resulted in a major diversification of benthic taxa on intrabasinal swells of the Rhenish Basin (Erdbach Limestone II), and immigration and diversification on the Belgian carbonate platform (Avins event).
- During the late Asbian mfi of sequence 9, which resulted in an extremely reduced input of hinterland material into the basin and resulted in the remarkable homogeneous deposition of the *crenistria* Horizon throughout the Rhenohercynian Zone from Southern Portugal to the Harz Mountains.
- During the basal Namurian (Pendleian) sequence 12, which caused the end of carbonate production in all external calciturbidite sources of the RKB, and in adjoining platform areas in the Niederrhein Embayment and the Netherlands (Campine Basin).

Opposed, only a minor sea-level rise is attributed to the early Moliniacian sequence 5, which is characterized by minor calciturbidite deposition in the Rhenish Basin and a widespread gap on the Belgian and Southwest English platforms. The upper Moliniacian and Livian sequences 5-8 record moderate sea-level rises and minor gaps on the platform.

The Brigantian sequences 10-11 are remarkable, as widespread gaps are recorded on the Southern Belgian carbonate platform, but at least regionally well-expressed sequences are recognized in the RKB due to the increased tectonic downwarp of the basin.

Of special interest is the sedimentary history of the latest Hastarian-lower Ivorian sequence 3. Although recording generally low sea-levels, as seen by widespread non-deposition/erosion at the western margin and on intrabasinal swells of the RKB, it witnessed the deposition of the black siliceous muds, which formed the bedded cherts of the Hardt Fm. In consequence they were deposited in a confined, more or less landlocked, and according to the general palaeogeography, elongate basin. The basin itself might have been relatively deep, as starved sedimentation continued throughout the interval from the preceding Kahlenberg Fm and most probably did not outpace subsidence.

With the successful application of diagnostic lithofacies elements to decipher the sequence stratigraphy of the RKB, perspectives are opened to transfer the method to other Kulm basins of the European and North African Variscides, in order to achieve a more dynamic and process-oriented stratigraphy. A first indication that this should yield promising results is seen from Herbig (1998) concerning the late Asbian Kulm succession of the Bardo Mountains (Sudetes) and Nízký Jesenik Mountains (northern Moravo-Silesian Zone). In the Bardo Mountains, the HST of sequence 9 consists of a fossiliferous, mixed fine-grained siliciclastic-carbonate succession (Paprotnia Series). It ends abruptly below polymictic conglomerates (Wilcza Fm) attributed to the basal Brigantian LST of sequence 10; an almost identical succession is seen in the Sowie Góry. In the Nízký Jesenik Mountains, the late Asbian limestone lenses from Dívcí Hrad are encased in shales with siltstone laminae and fine-grained greywacke beds and according to facies and biostratigraphy indicate the HST of sequence 9.

Similarities between time-equivalent facies developments of the RKB and the Montagne Noire were already indicated by Engel et al. (1981) and stressed by Aretz (2016, this volume). They are especially well recognized during Tournaisian and earliest Viséan time, as seen by the analogous facies of the Hangenberg Limestone and the 'upper supragriottes' (HST of sequence 1), by the Lydiennes Formation with and without phosphatic nodules, which is an analogue to the Kahlenberg and Hardt formations (sequences 2, 3). Similar time-equivalent calcareous facies is observed in the Erdbach Limestone, Kattensiepen, and Kohleiche formations from the RKB and the southern French Faugères Fm (sequence 4, lower part of sequence 5), and also in the following Viséan calciturbidites of the Colonnes Fm. Although more detailed studies are necessary, this is an important indication that the sequence stratigraphic subdivision of the RKB can be transferred to the basinal environments of the foreland basins of the southern branch of the European Variscides.

7. Acknowledgements

First ideas of the eustatic control of the lower Carboniferous successions in the RKB date back into the early 1990's. Over the years many students and colleagues contributed to the topic by theses, publications, and discussions. Especially helpful were excursions and discussions during the annual meetings of the German Subcommission on Carboniferous Stratigraphy, and during field meetings and symposia on Carboniferous topics abroad. My thanks go to all who helped to decipher the fascinating story of Carboniferous stratigraphy and facies. However, the work and character of four researchers that throughout their careers were intimately related with stratigraphy and regional geology of the Rhenish Mountains especially influenced my work. These are Peter Bender (Marburg), Dieter Meischner (†, Göttingen), Eva Paproth (Krefeld), and Dieter Stoppel (Hannover). I am especially obliged to D. Korn (Berlin) and M. Aretz (Toulouse) for thoughtful reviews and further discussions that strongly improved the manuscript, M. Amler (Köln) gave additional advice. D. Korn (Berlin) also discovered and demonstrated the debrite at the base of sequence 10B in the Becke-Oese quarry. The photographic overview of the quarry (Fig. 10A) is a courtesy of M. Piecha (Krefeld). Last but not least special thanks go to Julien Denayer for his careful editorial work.

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Manuscript received 24.02.2016, accepted in revised form 27.04.2016, available on line 31.10.2016.