3 Material

The data used in this study consists of data from literature sources as well as unpublished data. The unpublished data comes from collections stored at the Museum für Naturkunde Berlin. The ammonoid species from the unpublished collections were determined by Dieter Korn, who also provided the columnar sections.

3.1 Fossil species

The Devonian and Carboniferous datasets contain a total of 64 and 52 ammonoid species, respectively. The original datasets needed to be corrected to improve the results of the Unitary Associations method: Species with open nomenclature were omitted to avoid stratigraphical uncertainties caused by taxonomic uncertainties (Monnet et al. 2011). The datasets were also checked for taxa, whose occurrence can not be explained in some horizons and were therefore either incorrectly identified or incorrectly assigned to the horizon. Finally, taxa, which exclusively define a UA, which does not coincide with the empirical stratigraphical ordering, were deleted, because they do not provide information for correlation and also add uncertainties to the datasets.

Devonian

The Devonian dataset (which includes the *Clymenia laevigata* Zone to the *Wocklumeria denckmanni* Zone) contains 27 genera (Tab. 4).

Order	Suborder	Superfamily	Family	Genus	Species	n
Goniatitida	Tornoceratina	Prionoceratoidea	Posttornoceratidae	*Discoclymenia*	*cucullata*	4
			Prionoceratidae	*Mimimitoceras*	*alternum*	2
					fuerstenbergi	8
					geminum	32
					lentum	19
					lineare	6
					liratum	50
					nageli	6
					pompeckji	1
					rotersi	2
					trizonatum	10
				Effenbergia	*falx*	39
					lens	32
					minutula	13
				Kenseyoceras	*biforme*	14
					nucleus	25
				Balvia	*globulare*	11
						...

C. Klein, *Testing Modern Biostratigraphical Methods*,
BestMasters, DOI 10.1007/978-3-658-15345-8_2

Order	Suborder	Superfamily	Family	Genus	Species	n
...						
Clymeniida	Clymeniina	Platy-clymeniaceae	Platy-clymeniidae	*Progonio-clymenia*	*acuticostata*	1
			Piriclymeniidae	*Piriclymenia*	*piriformis*	6
				Ornatoclymenia	*ornata*	3
			Glatziellidae	*Glatziella*	*glaucopis*	19
				Soliclymenia	*paradoxa*	2
				Postglatziella	*carinata*	11
		Clymeniaceae	Clymeniidae	*Clymenia*	*laevigata*	10
			Kosmo-clymeniidae	*Kosmoclymenia*	*effenbergensis*	8
					inaequistriata	15
					lamellosa	1
					schindewolfi	30
					undulata	19
				Lissoclymenia	*wocklumeri*	37
				Muessenbergia	*ademmeri*	5
					bisulcata	8
					coronata	3
					diversa	1
					galeata	7
					parundulata	9
					sublaevis	58
					xenostriata	3
				Linguaclymenia	*clauseni*	33
					similis	98
		Wocklumeria-ceae	Para-wocklumeriidae	*Kamptoclymenia*	*endogona*	9
					trigona	3
				Parawocklumeria	*distorta*	11
					paprothae	23
					paradoxa	40
					patens	11
			Wocklumeriidae	*Wocklumeria*	*denckmanni*	34
		Gonio-clymeniaceae	Gonio-clymeniidae	*Kalloclymenia*	*pessoides*	3
					subarmata	32
					uhligi	3
				Finiclymenia	*wocklumensis*	41
				Gonioclymenia	*speciosa*	10
			Sellaclymeniidae	*Sellaclymenia*	*torleyi*	1
	Cyrto-clymeniina	Cyrto-clymeniaceae	Cyrtoclymeniidae	*Cyrtoclymenia*	*angustiseptata*	44
					plicata	4
			Cymaclymeniidae	*Cymaclymenia*	*camerata*	2
					cordata	13
					costellata	32
					curvicosta	1
					involvens	10
					striata	109
					tricarinata	1
						...

Order	Suborder	Superfamily	Family	Genus	Species	n
...						
					warsteinensis	20
				Rodachia	*dorsocostata*	2

Tab. 4: Taxa of the Devonian dataset [n=number of occurrences].

Carboniferous

The Carboniferous dataset (which includes the latest Devonian *Acutimitoceras prorsum* Zone to the Carboniferous *Paragattendorfia patens* Zone) contains 17 genera (Tab. 5).

Order	Suborder	Superfamily	Family	Genus	Species	n
Goniatitida	Tornoceratina	Priono-cerataceae	Prionoceratidae	*Mimimitoceras*	*hoennense*	7
					varicosum	4
				Globimitoceras	*globiforme*	9
				Paragattendorfia	*globiformis*	7
					patens	1
				Acutimitoceras	*acutum*	9
					antecedens	7
					convexum	3
					depressum	4
					exile	4
					intermedium	15
					kleinerae	11
					prorsum	2
					procedens	1
					simile	5
					stockumense	2
					subbilobatum	14
					undulatum	3
				Costimitoceras	*ornatum*	3
				Hasselbachia	*gracilis*	2
					multisulcata	7
					sphaeroidalis	10
				Nicimitoceras	*acre*	3
					caesari	1
					carinatum	4
					heterolobatum	9
					subacre	7
					trochiforme	9
				Voehringerites	*peracutus*	4
				Paralytoceras	*serratum*	1
				Paprothites	*dorsoplanus*	13
					raricostatus	1
					ruzhencevi	1
				Pseudoarietites	*planissimus*	1
					subtilis	3
					westfalicus	9
			Gattendorfiidae	*Gattendorfia*	*costata*	14
					crassa	5
					subinvoluta	9
						...

Order	Suborder	Superfamily	Family	Genus	Species	n
..						
					tenuis	11
				Kazakhstania	*evoluta*	2
				Weyerella	*concava*	5
					molaris	13
					reticulum	3
Prolecanitida	Prolecanitina	Prole-canitaceae	Prolecanitidae	*Eocanites*	*brevis*	4
					carinatus	1
					nodosus	13
					planus	1
					spiratissimus	1
					supradevonicus	4
					tener	2
Clymeniida	Clymeniina	Cyrto-clymeniaceae	Cymaclymeniidae	*Postclymenia*	*evoluta*	3

Tab. 5: Taxa of the Carboniferous dataset [n=number of occurrences].

3.2 Localities

The Late Devonian dataset includes 13 sections (Tab. 6); the Early Carboniferous dataset includes 7 sections (Tab. 7) in a total of 8 localities (Fig. 6).

Section	Short	Reference	n species	n horizons
Oberrödinghausen railway cutting	ORBK	Korn (unpublished)	21 species	13 horizons
Oberrödinghausen road cutting	ORSK	Korn (unpublished)	34 species	13 horizons
Oberrödinghausen road cutting alpha	ORSTA	Thiem (unpublished)	29 species	29 horizons
Oberrödinghausen road cutting beta	ORSTB	Thiem (unpublished)	30 species	27 horizons
Effenberg 1977	E77	Korn (unpublished)	27 species	15 horizons
Effenberg 1987	E87	Korn (unpublished)	7 species	16 horizons
Müssenberg 1	M1	Korn (unpublished)	44 species	78 horizons
Müssenberg 3	M3	Korn (unpublished)	9 species	7 horizons
Müssenberg 4	M4	Korn (unpublished)	23 species	20 horizons
Dasberg Middle	DASM	Korn (unpublished)	13 species	9 horizons
Dasberg North	DASN	Korn (unpublished)	5 species	10 horizons
Dasberg South	DASS	Korn (unpublished)	30 species	41 horizons
Drewer	DD	Korn et al. (1994)	11 species	7 horizons

Tab. 6: The Late Devonian sections with number of species and number of horizons.

Section	Short	Reference	n species	n horizons
Hasselbach	H	Korn and Weyer (2003)	20 species	16 horizons
Becke-Oese	BO	Korn and Weyer (2003)	9 species	6 horizons
Oberrödinghausen railway cutting	ORBW	Weyer (unpublished)	23 species	15 horizons
Oberrödinghausen railway cutting	ORBV	Vöhringer (1960)	45 species	10 horizons
Müssenberg	M2	Korn (unpublished)	7 species	3 horizons
				...

Section	Short	Reference	n species	n horizons
...				
Stockum	SK	Korn (1984)	7 species	1 horizon
Drewer	DK	Korn et al. (1994)	7 species	8 horizons

Tab. 7: The Early Carboniferous sections with number of species and number of horizons.

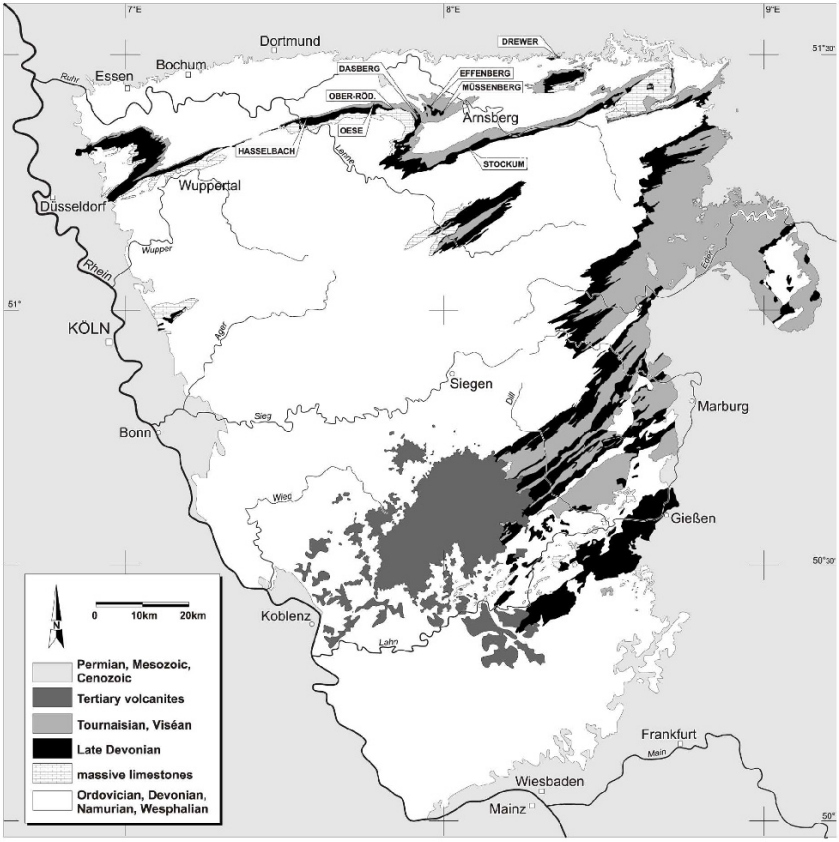


Fig. 6: Geographical positions of section localities (from Korn 2002).

Hasselbach

Geographical position: The Hasselbach section is located at the banks of the Hassel rivulet between Hagen-Reh and Hagen-Henkhausen (51.37388° N, 7.57247° E).

Analysed section: Only the Carboniferous part of the section is analysed with the bed

numbers H-83 to H-45 in ascending order. Twenty species compose the total data set, of which 16 are represented by a single occurrence. Two species (*Acutimitoceras intermedium* and *Paprothites dorsoplanus*) are best represented and occur in four horizons.

Stratigraphical frame: *Gattendorfia subinvoluta* Zone to *Pseudarietites westfalicus* Zone.

Previous studies: Schmidt (1924) was the first, who described the rock succession of the outcrop. He distinguished between the Dasberg and Wocklum limestones, the Hangenberg Black Shale and the Hangenberg Limestone. Becker et al. (1984) used conodonts and ammonoids for a detailed description of the Hangenberg Limestone and the Hangenberg Shale. Becker (1988) presented columnar sections of a part of the Wocklum and Hangenberg limestones. He misleadingly postulated an overlap of *Kalloclymenia* and *Wocklumeria*, which was later corrected by Luppold et al. (1994). Korn and Weyer (2003) provided a detailed lithological description of the section.

Lithology: Only the Hangenberg Limestone is used in this study. It is composed of interbedded thin nodular limestones, which contain only a limited number of fossils, and shales. Metabentonite horizons can be used for detailed dating of the section. (Claoué-Long et al. 1992; Claoué-Long 1995; Trapp et al. 2004). The base of the Hangenberg Limestone is formed by a platy turbiditic limestone (Korn and Weyer 2003).

Becke-Oese

Geographical position: Three outcrops at the western side of the B7 between Hemer and Menden have been combined across the Devonian-Carboniferous boundary beds; the first is located in a road cutting (51.40082° N, 7.78680° E) and displays the Devonian limestone formations as well as the Hangenberg Black Shale, the second is exposed in a small abandoned quarry (51.40106° N, 7.78704° E) and exposes the Hangenberg Sandstone and the Hangenberg Limestone and the third is again located at the road cutting (51.40132° N, 7.78751° E) and exposes the Hangenberg Limestone and following formations.

Analysed sections: One combined section of the three outcrops is analysed with the bed numbers BO-11 to BO-37 in ascending order. Eight of the nine species are represented by only one occurrence and the ninth species by 2 occurrences.

Stratigraphical frame: The compound section exposes a complete late Famennian to middle Tournaisian section. Only the Early Carboniferous ammonoids of the Hangenberg Limestone (*Gattendorfia subinvoluta* Zone to *Paragattendorfia patens* Zone) were used in this analysis. The sparse occurrence of ammonoids and conodonts does not allow for a precise determination of the Devonian-Carboniferous boundary (Luppold et al. 1994).

Previous studies: Schmidt (1924) presented the first lithological subdivision: He found the Hangenberg Sandstone as a thick bedded greywacke with shale at its top, followed by the Hangenberg Limestone. Kullmann (in Paproth and Streel 1982) published a compilation of the ammonoid faunas of the Hangenberg Limestone in this section. Luppold et al. (1994) and Korn and Weyer (2003) published descriptions of the ammonoid fauna of the *Clymenia* Stufe and the *Wocklum* Stufe as well as a conodont stratigraphy and a facies analysis.

Lithology: The Hangenberg Limestone begins with a platy limestone bed, which shows characteristics of a distal turbidite rich in mica (Luppold et al. 1994; Korn and Weyer 2003).

Oberrödinghausen railway cutting

Geographical position: The Oberrödinghausen railway cutting section is located in the Hönne Valley between Menden and Balve, at the western margin of the large cement works of Ober-Rödinghausen (51.39429° N, 7.84113° E).

Analysed sections:

(1) The unpublished bed-by-bed sampling of the section by Korn (ORBK; bed numbers ORBK-11B to ORBK-1A in ascending order) from the eastern side of the railway cutting.

(2) The unpublished bed-by-bed sampling of the section by Weyer (ORBW; bed numbers ORBW-6b to ORBW-2a in ascending order) from the eastern side of the railway cutting.

(3) The bed-by-bed sampling of the section by Vöhringer (1960) (ORBV; bed numbers ORBV-6 to ORBV-1 in ascending order) from the western side of the railway cutting.

ORBV is the best of the Carboniferous sections in this analysis and is hence used as a reference. The section sampled by Weyer was taken only about five meters away from Vöhringer's section. Vöhringer (1960) subdivided the section into six beds, of which he subdivided bed 3 into five subunits. Weyer used the same bed numbering. He did not sample bed 1, but subdivided beds 2, 3c, 3d, 4 and 6 into two subunits and bed 5 into four subunits. Weyer's section has a higher resolution, but his collections were smaller and hence less diverse than Vöhringer's collections.

Stratigraphical frame:

ORBK: Wocklum Limestone from the *Kamptoclymenia endogona* Zone to the *Wocklumeria denckmani* Zone

ORBW and ORBV: Hangenberg Limestone from the *Gattendorfia subinvoluta* Zone to the *Paragattendorfia patens* Zone (Fig. 7)

Previous studies: This famous locality is, for fossils, one of the richest Devonian-Carboniferous boundary sections worldwide. Schmidt (1924) found a rich cephalopod assemblage in the Hangenberg Limestone. The global subdivisions of the *Wocklumeria* and *Gattendorfia* Stufen are based on investigations of this section (Schindewolf 1937; Vöhringer 1960). Luppold et al. (1994) found ammonoids in the Hangenberg Black Shale.

Lithology: The Wocklum Limestone and the Hangenberg Limestone are composed of alternating shales and nodular limestone (Korn and Weyer 2003). The clay content of the Hangenberg Limestone is remarkably high.

Oberrödinghausen road cutting

Geographical position: The Oberrödinghausen road cutting section is located at the eastern side of the Hönne Valley between Menden and Balve, east of the large cement works of Ober-Rödinghausen (51.39385° N, 7.84478° E).

Analysed sections:

(1) The unpublished bed-by-bed sampling of the section by Korn (ORSK; bed numbers ORSK-20 to ORSK-1 in ascending order)

(2) The unpublished bed-by-bed sampling of the section by Thiem (ORSTA; bed numbers ORSTA-7a(3) to ORSTA-1(1) in ascending order)

(3) The unpublished bed-by-bed sampling of the section by Thiem (ORSTB; bed numbers ORSTB-12(4) to ORSTB-6b(1) in ascending order)

ORSTB represents the lower part of the succession, ORSTA the upper part, with an overlapping part in the middle.

Stratigraphical frame:

ORSK: *Kamptoclymenia endogona* Zone to *Wocklumeria denckmani* Zone

ORSTA: *Effenbergia lens* Zone to *Wocklumeria denckmani* Zone (Fig. 8)

ORSTB: *Effenbergia lens* Zone to *Kamptoclymenia endogona* Zone

Lithology: The difference between the Oberrödinghausen railway cutting and the Oberrödinghausen road cutting is the presence of the approximately 15 m thick Hagenberg Shale, with intercalated thick-bedded sandstone beds, which belong to the Hangenberg Sandstone (Luppold et al. 1994; Korn and Weyer 2003).

Previous studies: Ziegler (1962) was the first to publish a detailed description of the Late

Devonian sections and its conodont fauna. Thiem and later Korn sampled this locality intensively for ammonoids, but the results were never published. Luppold et al. (1994) found the Wocklum Limestone to be rich in ammonoids and the Hangenberg Limestone moderately rich in ammonoids. Korn and Weyer (2003) noticed a close resemblance to the Oberrödinghausen railway cutting section, which is located approximately 200 meters away.

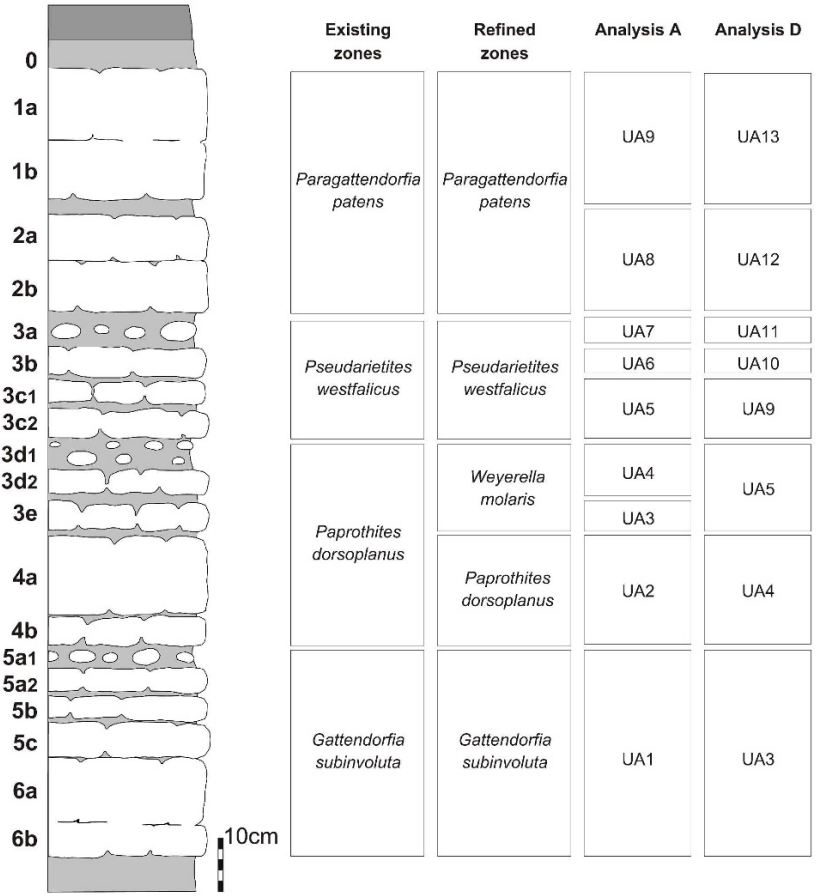


Fig. 7: Columnar section of the Oberrödinghausen railway cutting including ammonoid zonation.

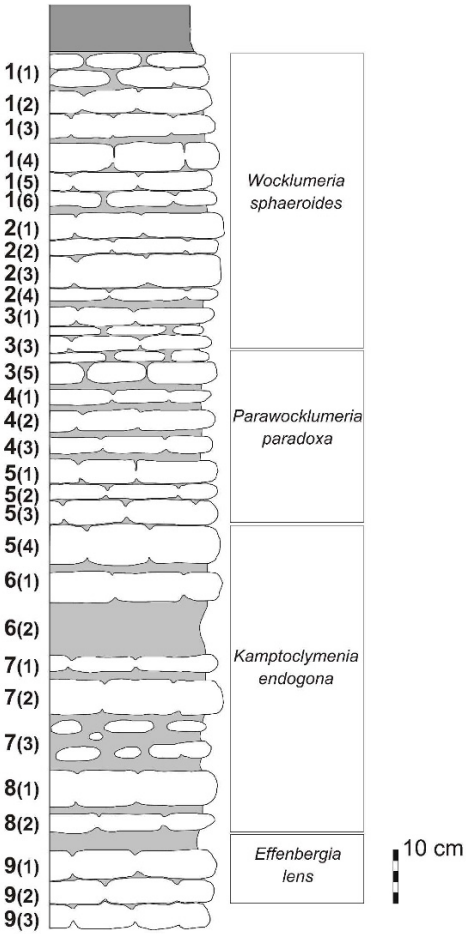


Fig. 8: Columnar section of the Oberrödinghausen road cutting including ammonoid zonation.

Effenberg

Geographical position: The Effenberg section is located at the large active quarry on the Effenberg northwest of Hachen (51.39080° N, 7.96120° E).

Analysed sections:

(1) The unpublished bed-by-bed sampling of the section by Korn in 1977 (E77; bed numbers E77-B to E77-V in ascending order)

(2) The unpublished bed-by-bed sampling of the section by Korn in 1987 (E87; bed numbers E87-J4 to E87-R in ascending order)

Stratigraphical frame: *Clymenia* Stufe and *Wocklumeria* Stufe

Effenberg 77: *Clymenia laevigata* Zone to *Effenbergia lens* Zone

Effenberg 87: *Piriclymenia piriformis* Zone to *Muessenbiaergia parundulata* Zone

Previous studies: Korn and Luppold (1987) gave a detailed lithological description from the *Cheiloceras* Stufe to the middle part of the *Wocklumeria* Stufe. The *Clymenia* Stufe and the *Wocklumeria* Stufe are rich in fossils. The authors considered the section as one of the best sections for Late Devonian cephalopod limestones in the Rhenish Mountains. Luppold et al. (1994) described the section in detail, including an ammonoid and conodont stratigraphy, a microfacies analysis and the bathymetric development.

Lithology: Nodular limestones with intercalated shales are exposed from the *Cheiloceras* to the *Gattendorfia* Stufe (Luppold et al. 1994).

Müssenberg

Geographical position: The locality Müssenberg is composed of trenches on the southern slope of the Müssenberg, 1.2 km N of Sundern-Hachen (51.38831° N, 7.98502° E).

Analysed sections (bed numbers are given in ascending order):

(1) Müssenberg 1 (M1; bed numbers M1-4 to M1-109)

(2) Müssenberg 2 (M2; bed numbers M2-3A to M2-3C in ascending order; Müssenberg 2 represents the three youngest horizons of the section Müssenberg 1, which are Carboniferous in age)

(3) Müssenberg 3 (M3; bed numbers M3-7 to M3-1)

(4) Müssenberg 4A (M4A; bed numbers M4A-18 to M4A-4)

(5) Müssenberg 4B (M4B; bed numbers M4B-16 to M4B-1)

(6) Müssenberg 4C (M4C; bed numbers M4C-15 to M4C-8)

Stratigraphical frame:

Müssenberg 1: *Clymenia laevigata* Zone to *Wocklumeria denckmanni* Zone (Fig. 9)

Müssenberg 2: *Acutimitoceras prorsum* Zone to *Gattendorfia subinvoluta* Zone

Müssenberg 3: *Clymenia laevigata* Zone to *Piriclymenia piriformis* Zone

Müssenberg 4A-4C: *Kamptoclymenia endogona* Zone to *Wocklumeria denckmanni* Zone

Previous studies: Korn (1981) was the first to describe the Müssenberg locality and particularly investigated the small part of the section, which embraces the Hangenberg Event. Luppold et al. (1984) stated that the section includes the ammonoid zones from the *subarmata* Zone to the *subinvoluta* Zone (*Muessenbiaergia sublaevis* Zone to *Gattendorfia subinvoluta* Zone in new terminology), hence bridging the Devonian- Carboniferous boundary. Korn (2002) found all ammonoid zones from the *Clymenia laevigata* Zone to *Gattendorfia subinvoluta* Zone except for the *Cymaclymenia nigra* Zone, because the Hangenberg Black Shale is absent.

Lithology: The limestone succession appears to be complete without major gaps. Only a few shale and siltstone layers interrupt the carbonate sedimentation. The lithofacies and carbonate microfacies were investigated by Luppold et al. (1994); they showed that biomicrites and biosparites dominate the lower part of the section, while biomicrudites and biosparrudites are more common in the upper part. The presence of micrites indicates calm and deep water conditions during deposition.

Dasberg

Geographical position: The locality Dasberg contains trenches and a road cutting 1 km WNW of Hövel (Dasberg S: 51.37174° N, 7.91031° E; Dasberg M: 51.37211° N, 7.91029° E;

Dasberg N: 51.37229° N, 7.91010° E).

Analysed sections: Three unpublished bed-by-bed samplings of the section by Korn are analysed:

(1) Dasberg Middle (DASM; bed numbers DASM-6 to DASM-1 in ascending order; represents the upper part of the succession)

(2) Dasberg North (DASN; bed numbers DASN-9 to DASN-26 in ascending order; represents the lower part of the succession)

(3) Dasberg South (DASS; bed numbers DASS-55 to DASS-1 in ascending order; represents the medium part of the succession)

Stratigraphical frame:

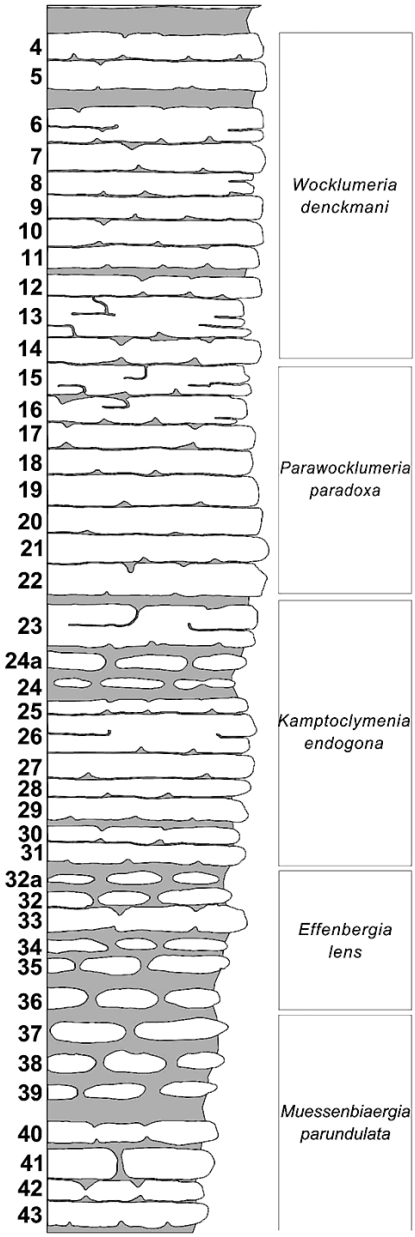
Dasberg Middle: *Parawocklumeria paradoxa* Zone to *Wocklumeria denckmani* Zone

Dasberg North: *Clymeina laevigata* Zone to *Ornatoclymenia ornat*a Zone

Dasberg South: *Ornatoclymenia ornat*a Zone to *Kamptoclymenia endogona* Zone (Fig. 10)

Previous studies: The mapping geologist Denckmann (1901) was the first author, who noted the fossil-rich nodular limestones in the Dasberg area. Wedekind (1914) distinguished ammonoid species at this locality. Because of the disadvantageous outcrop conditions, some authors (Schmidt 1924; Lange 1929) only collected surface material. In the late 1980s Korn dug trenches, where he collected 1600 late Famennian ammonoid specimens. Korn and Luppold (1987) subdivided the section into a lower part (*Clymenia* Stufe), which is rich in shale, and an upper part *(Muessenbiaergia sublaevis* Zone to *Effenbergia lens* Zone), which is poor in shale. Korn (2002) found all ammonoid zones from the *Francoclymenia serpentina* Zone to the *Kamptoclymenia endogona* Zone.

Lithology: The lithological development is similar to the neighbouring sections Effenberg and Müssenberg.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Wocklumeria denckmani
Parawocklumeria paradoxa
Kamptoclymenia endogona
Effenbergia lens
Muessenbiaergia parundulata

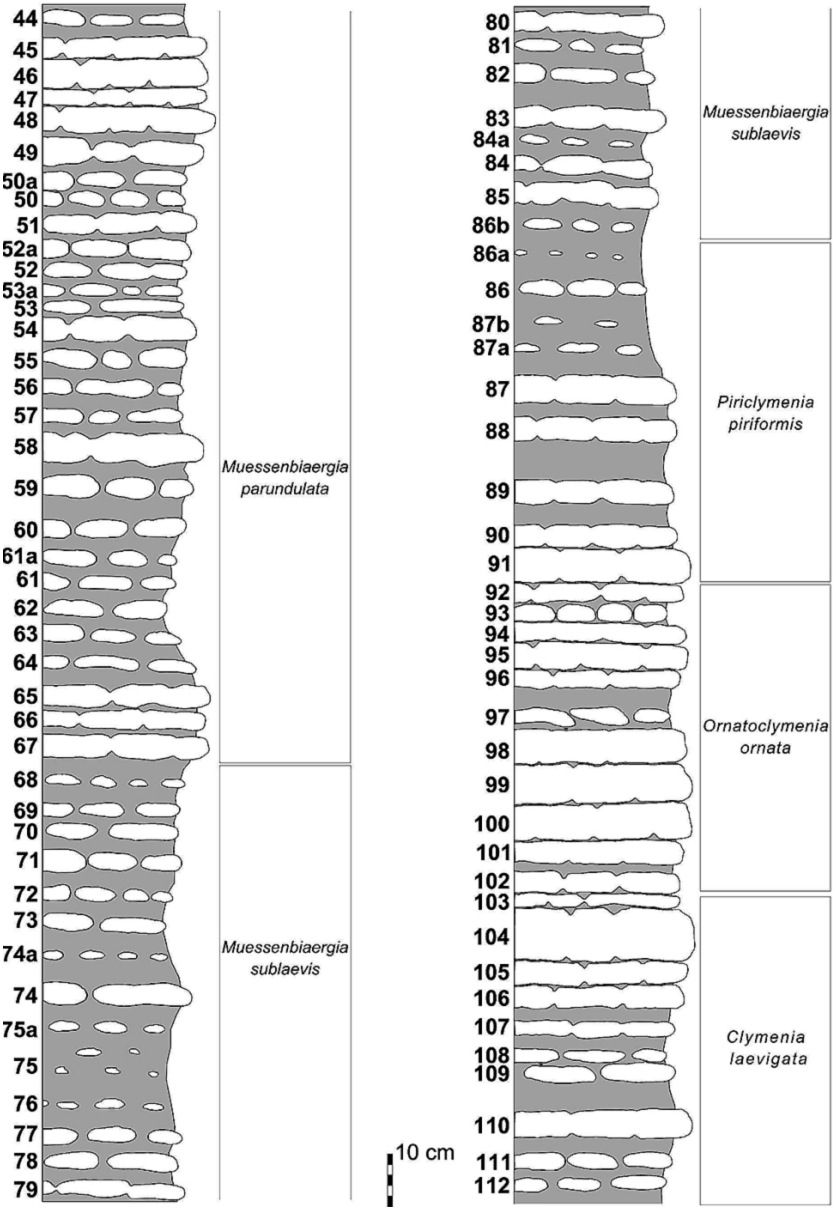

Fig. 9: Columnar section of Müssenberg including ammonoid zonation (by Luppuld et al. 1994).

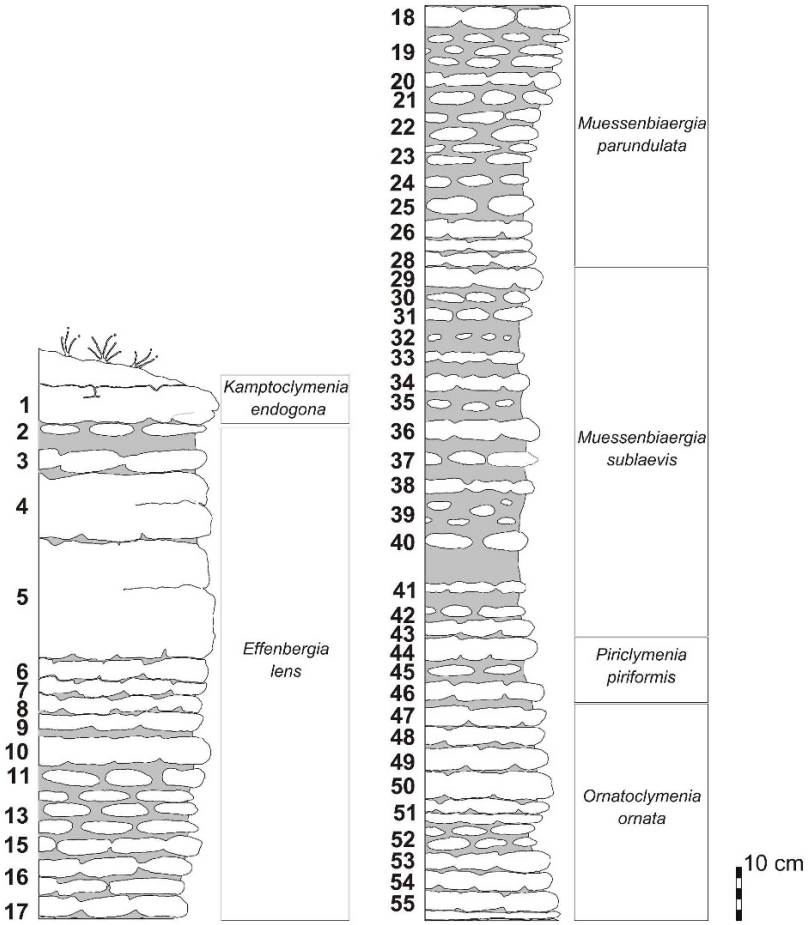

Fig. 10: Columnar section of Dasberg South including ammonoid zonation (by Clausen & Korn 2008).

Stockum

Geographical position: The section of the Stockum locality was taken at a trench 250 m SSW of the Spitzer Kahlenberg near Stockum (51.29185° N, 7.99832°).

Analysed section: The only horizon in this section (SK), which yielded ammonoids and is therefore used in this analysis, is the Stockum Limestone, which is located in the Hangenberg Sandstone.

Stratigraphical frame: Index fossils for the Stockum Limestone are Nici*mitoceras carinatum*, *Acutimitoceras stockumense*, *Acutimitoceras prosum* and *Nicimitoceras caesari*, which are all limited to the *Acutimitoceras prorsum* Zone. No clymeniids occur in the *Acutimitoceras*

prorsum Zone.

Previous studies: The calcareous lenses, found at Stockum, containing goniatites were first described by Henke (1924) and Schmidt (1924). Vöhringer (1960) pointed out that the lenses are older than the Hangenberg Limestone. The term Stockum Limestone was coined by Alberti et al. (1974). Korn (1984) found numerous well preserved species of the genus *Acutimitoceras* at this locality. Clausen et al. (1994) provided a detailed biostratigraphy based on ammonoids, trilobites, ostracods, conodonts and spores.

Lithology: The complete section is mainly composed of shales, siltstone and sandstone with intercalated limestone nodules (Clausen et al. 1994). The limestone lenses of Stockum are grey in colour up to 8 cm thick and 50 cm in diameter.

Drewer

Geographical position: The section Drewer was examined at the north-western face of the abandoned Provinzialsteinbruch Drewer 40 m south the road between Belecke and Drewer (51.49430° N, 8.35680° E).

Analysed sections:

(1) Devonian part of the section (DD; bed numbers DD-1,2 to DD-93 in ascending order)

(2) Carboniferous part of the section (DK; bed numbers from DK-99 to DK-5 in ascending order)

Stratigraphical frame:

Devonian part of the section: *Wocklumeria* Stufe

Carboniferous part of the section: *Gattendorfia* Stufe

Previous studies: Schmidt (1922) was the first, who described this section and Ziegler (1971) presented a lithological section. Korn et al. (1994) found *Postclymenia evoluta* above the Hangenberg Black Shale in the *Acutimitoceras prorsum* Zone.

Lithology: The north-western face of the quarry shows silty mudstones with calcareous nodules and thinly bedded nodular limestones. Fine biomicrites are proof of a calm sedimentation environment, where the fine components were not washed away by currents. The nodular Dasberg and Wocklum limestones are bluish grey in colour. The Hangenberg Black Shale is overlain by the Hangenberg Sandstone (Korn et al. 1994).

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