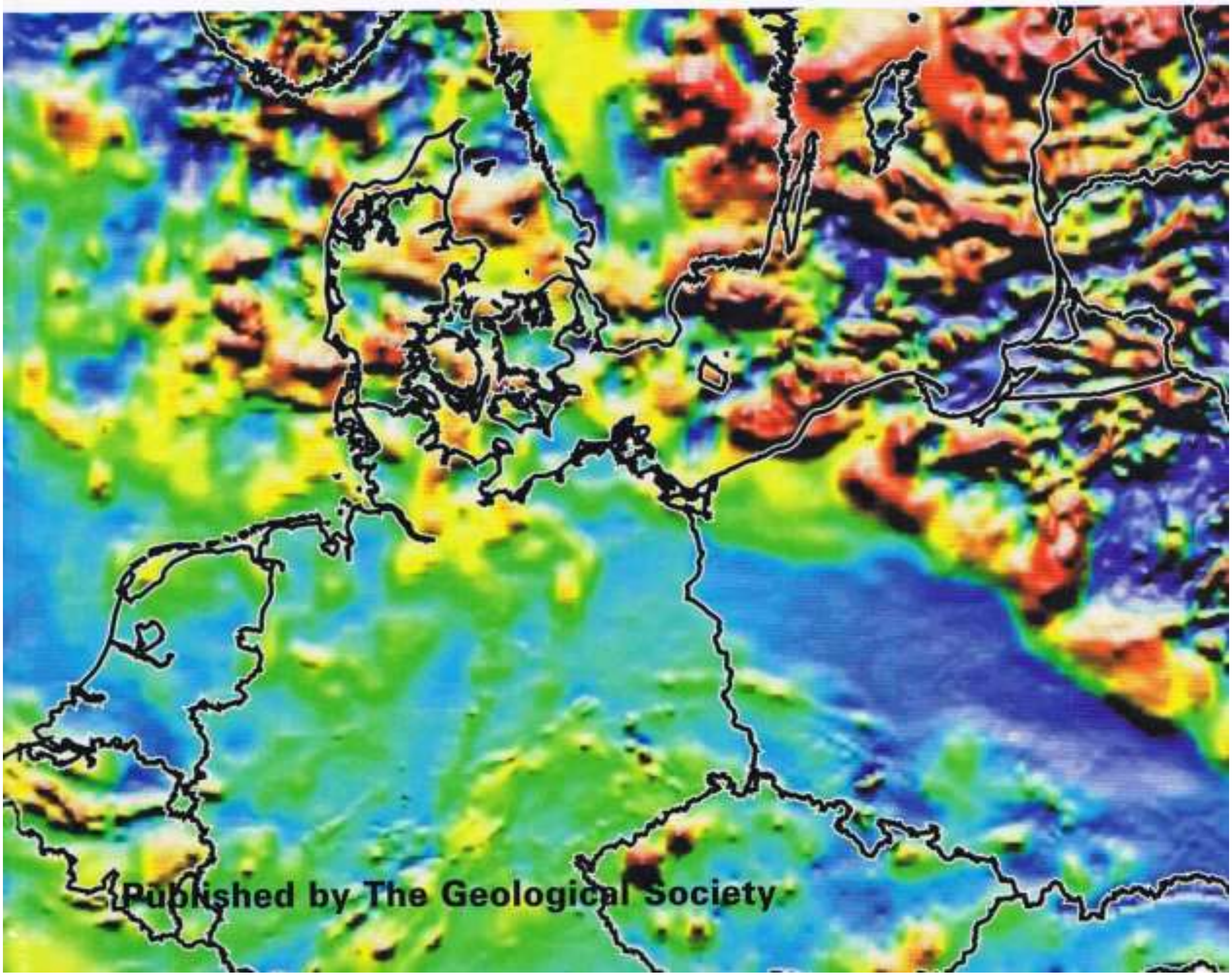
Palaeozoic Amalgamation of Central Europe

edited by J. A. Winchester, T. C. Pharaoh and J. Verniers

Geological Society Special Publication No. 201



Published by The Geological Society

Chitinozoa and Nd isotope stratigraphy of the Ordovician rocks in the Ebbe Anticline, NW Germany

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Abstract: Strongly tectonized Ordovician rocks appear in the Ebbe Anticline (Rheinisches Schiefergebirge), West Germany. These fine-grained detrital rocks of the Herscheider Schichten are divided into the Plettenberger Bänderschiefer, Unterer (Kiesberter) Tonschiefer, (Rahlenberger) Grauwackenschiefer, and the Oberer (Solinger) Tonschiefer. The scope of this investigation was to improve the dating of the entire Ordovician succession, but especially the Oberer (Solinger) Tonschiefer. We used chitinozoans, Palaeozoic microfossils of high biostratigraphic value, and Nd isotopes, which previously have been used for correlation and terrane affinity analysis. Chitinozoan preservation is poor, but some taxa could be confidentially identified to the species level. The $\varepsilon Nd(t)$ values obtained from the Ordovician succession range from –8.0 to –9.2. Joint evaluation of chitinozoan and Nd isotope data together with previously known age-ranges suggest the following ages for the Herscheider Schichten: Plettenberger Bänderschiefer (early Abereiddian, earliest Llanvirn), Unterer (Kiesberter) Tonschiefer (early to mid Abereiddian, early Llanvirn), (Rahlenberger) Grauwackenschiefer (Aurelucian, earliest Caradoc), and Oberer (Solinger) Tonschiefer (late Caradoc). The Ebbe $\varepsilon Nd(t)$ values are most readily compared with $\varepsilon Nd(t)$ values from Avalonia, and we therefore support the inclusion of the Ordovician rocks of the Ebbe Anticline in that palaeocontinent.

The Rheno-Hercynian belt to the south and east of the Ardennes has few outcrops in its geographic extension from the Rheinisches Schiefergebirge through the Harz Mountains in central Europe. Ordovician rocks appear in small isolated outcrops located in the north-eastern part of the Rheinisches Schiefergebirge, West Germany in the Ebbe and Solingen–Remscheid–Altena anticlines in the Sauerland region, east of Cologne (Fig. 1). Near the towns of Plettenberg and Herscheid, about 25 km SE of Hagen, in the Ebbe Anticline a strongly tectonized succession of monotonous black and grey mudstones and siltstones occur. These rocks were referred to the Herscheider Schichten by Fuchs (1912, 1935). Similar rocks crop out 3 km SW of Solingen (Solingen–Remscheid–Altena Anticline). In the Ordovician successions that constitute the Ebbe Anticline e.g. trilobite faunas comparable to the Mediterranean faunal province occur (Siegfried 1969; Koch 1999*a*). The Ebbe Anticline sediments are usually interpreted as belonging to the palaeocontinent Avalonia, together with most of the autochthonous parts of the Rheno-Hercynian Belt (e.g. Pharaoh 1999).

The Herscheider Schichten of the Ebbe Anticline are subdivided in four lithological units, from bottom to top: the Plettenberger Bänderschiefer, the Unterer (Kiesberter) Tonschiefer, the (Rahlenberger) Grauwackenschiefer and the Oberer (Solinger) Tonschiefer (Beyer 1941*a*,*b*,*c*). The ages of the two lower units, the Plettenberger Bänderschiefer and the Unterer (Kiesberter) Tonschiefer, are fairly well-constrained by graptolites, and the age of the (Rahlenberger) Grauwackenschiefer is constrained by previously known chitinozoan data,

From: WINCHESTER, J. A., PHARAOH, T. C. & VERNIERS, J. 2002. *Palaeozoic Amalgamation of Central Europe.* Geological Society, London, Special Publications, **201**, 115–131. 0305-8719/02/$15.00

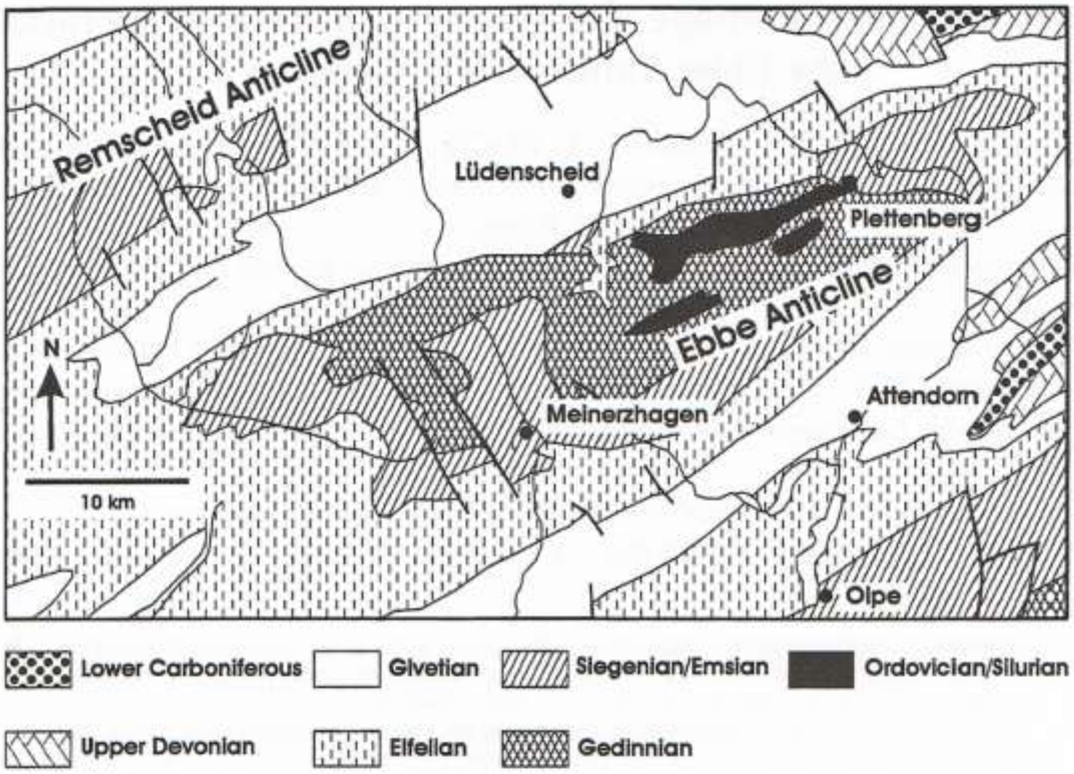


Fig. 1. Geological overview map of the Ebbe Anticline and its surroundings in the Rheinisches Schiefergebirge. Modified from Koch *et al.* (1990).

but the age of the Oberer (Solinger) Tonschiefer is only broadly assumed to be Late Ordovician.

Chitinozoans are organic-walled Palaeozoic microfossils of unknown biological affinity that are extremely useful for biostratigraphy, but also palaeobiogeography (e.g. Miller 1996; Paris 1996). A number of studies carried out in recent years has demonstrated the applicability of this fossil group for detailed stratigraphy and palaeobiogeography also for successions deposited on Eastern Avalonia (Samuelsson & Verniers 2000; Samuelsson *et al.* 2000, 2002; Samuelsson & Servais 2001; Vecoli & Samuelsson 2001).

Results from Nd-isotope studies can, under certain circumstances, act as a powerful tool for correlation and dating of clastic sedimentary rocks. Furthermore, Nd-isotope ratios of fine-grained clastic sedimentary rocks reflect their average detritus composition and can help to identify potential source regions from which they were originally derived (e.g. Thorogood 1990; Evans 1992). Changes in the supply of detritus due to orogenic and magmatic activity will cause variation of the sedimentary Nd-isotope composition through time. These changes, if significant enough, can be traced over wide areas, e.g. a micro-continent (Gerdes *et al.* 2001) or even a major continent (Patchett *et al.* 1999). Avalonia and some Variscan crustal blocks, where the latter are sometimes grouped together as the Armorican Terrane Assemblage (ATA; Tait *et al.* 1997), are a result of the Early Palaeozoic break-up of northern Gondwana. The geological record indicates differences in their rift, drift and subsequent amalgamation history and their crustal provenance (e.g. Nance & Murphy 1996; Tait *et al.* 1997; Winchester *et al.* 2002). Distinct supply of juvenile detritus to the marginal basins and distinct basement lithologies yield characteristic Nd-isotope trends of these terranes. Eastern Avalonia probably has the best studied and dated sediment successions and the most complete Nd-isotope data set. New and published analyses of about 200 Cambrian to Silurian sediments from the Brabant Massif, the Ardennes, the Welsh Basin, the Welsh Borderland and the English Lake District show that Nd isotopes can be used as a powerful tool to correlate different well-dated sedimentary successions of a specific palaeogeographic unit (Gerdes *et al.* 2001). Local variation can be seen usually only in the amount of juvenile, volcanogenic detritus supplied during the Ordovician drift stage. Thus, when a specific isotope trend from a terrane is known, Nd isotopes may even give some constraints for the deposition time of poorly dated terrigenous sediments.

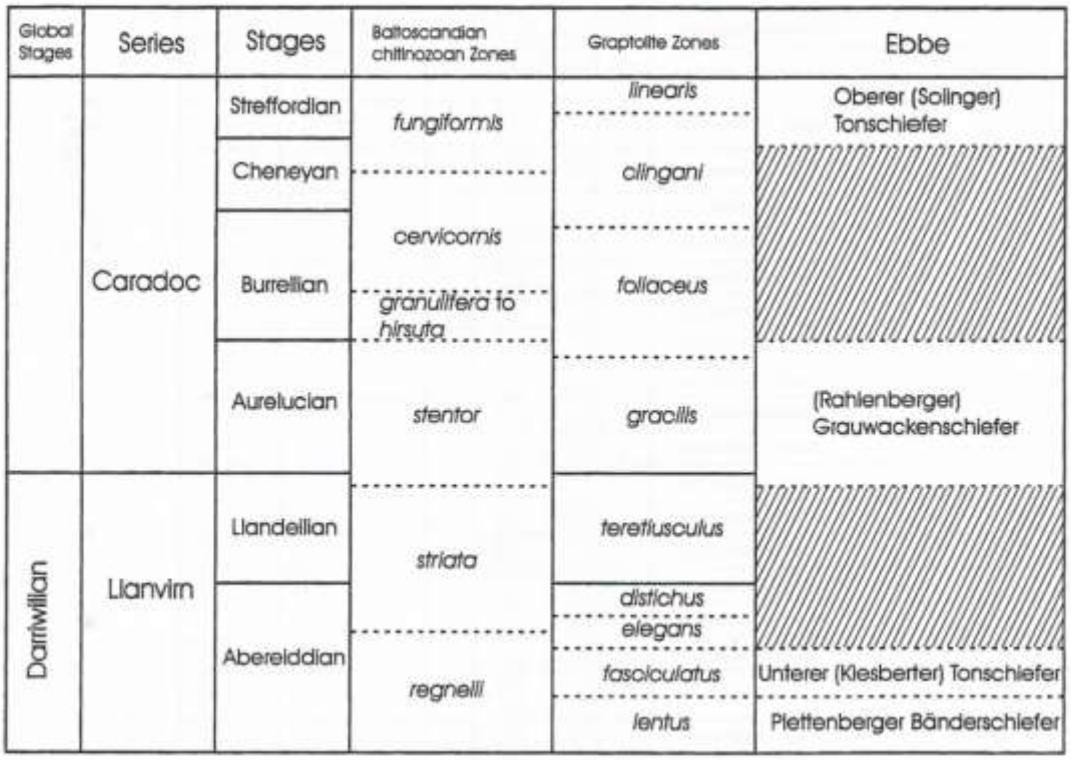


Fig. 2. Simplified stratigraphic outline and the ages as suggested in this paper of the four units of the Herscheider Schichten in relation to British Series (and the single defined global Stage), British Stages, Baltoscandian chitinozoan biozonation (Nõlvak & Grahn 1993), and graptolite biozonation (Fortey *et al.* 1995; Maletz 1995), respectively. Stratigraphical terminology follows Eiserhardt *et al.* (2001). Vertical thickness not drawn to scale. Oblique lines indicate lack of evidence for deposition.

The scope of the present study is to place age constraints on the Oberer (Solinger) Tonschiefer, and also to provide further stratigraphic constraints on the previously suggested ages of the other Ordovician units of the Ebbe Anticline. By doing this, we will obtain further indirect evidence for the deposition of these sediments on the microcontinent Avalonia. Based on chitinozoan and Nd-isotope data, we suggest a late Caradoc age for the Oberer (Solinger) Tonschiefer, and confirm earlier suggested ages for the other units.

Previous palaeontological studies

Whereas a number of papers have reported on fossils from the Ebbe Anticline, e.g. trilobites (e.g. Richter & Richter 1937, 1954; Siegfried 1969; Koch & Lemke 1994, 1995*a,b*, 1997, 1998*a,b*, 2000; Koch 1999*a,b*), graptolites (e.g. Jentsch & Stein 1961; Maletz & Servais 1993), phyllocarids (Beyer 1941*a,b,c*; Koch & Brauckmann 1998), foraminiferans (Riegraf & Niemeyer 1996), ostracodes (Schallreuter 1996; Schallreuter & Koch 1999), and trace fossils (Richter & Richter 1939*a,b*, 1941; Beyer 1941*a*; Eiserhardt *et al.* 2001) very few papers deal with the organic-walled microfossil assemblages. Eisenack (1939) demonstrated the presence of acritarchs and chitinozoans from siliceous concretions ('Kieselknollen', or 'Kieselgallen') in an unknown level in the (Rahlenberger) Grauwackenschiefer, that has now been built over, in the town of Rahlenberg (Herscheid). His paper is the only previous publication dealing in detail with chitinozoans from the Ebbe Anticline and he reported and originally described a number of chitinozoan species in that study. Acritarchs from the Plettenberger Bänderschiefer and the Unterer (Kiesberter) Tonschiefer were dealt with in Maletz & Servais (1993).

Geological overview and previously obtained ages

A graphic summary of the stratigraphy of the Herscheider Schichten can be found in Figure 2. After the original studies by Beyer in the early

Ebbe	unit	*? Belonechitina ? capitata*	*Belonechitina capitata*	*Cyathochitina* sp. A	*Belonechitina ? micracantha*	*Desmochitina cocca*	*Conochitina ? minnesotensis*	*Desmochitina minor*	*Pistillachitina ? pistillifrons*	*Rhabdochitina ? magna*	*Euconochitina ? conulus*	*Desmochitina* cf. *piriformis*	*Conochitina* sp. A	*Conochitina* ?sp. A	*Cyathochitina calix*	*Rhabdochitina ? gracilis*	*Laufeldochitina ? clavata*	*Cyathochitina ? campanulaeformis*	*Cyathochitina campanulaeformis*	*Lagenochitina ? ponceti*	CONOCHITININAE indet.	*? Lagenochitina* spp.	*Conochitina* spp.	*Desmochitina* spp.	*? Rhabdochitina* spp.	*Belonechitina* spp.	*Cyathochitina* spp.	*? Conochitina* spp.	*? Cyathochitina* spp.	*Euconochitina* spp.	*Lagenochitina* spp.	*? Laufeldochitina* spp.	*Rhabdochitina* spp.	*? Eisenackitina* spp.	*? Belonechitina* spp.	*? Pistillachitina* sp.	*? Euconochitina* sp.	undetermined	total number of Chitinozoa	sample weight (g)	Chitinozoa / g sample
EA99-1	Oberer (Sol.) Tonschiefer	4	1	3	1	2	2														2	2	2	2														15	36	144	0.2
EA99-2			1				1	4													3		2		1	1	1											9	23	101	0.2
EA99-5	(Rahlenberger) Grauwacken Schiefer																																						0	12	0
EA99-6								2	3														1					1										1	8	58	0.1
EA99-15					1																							1	1									3	6	54	0.1
EA99-16																																							0	12	0
EA99-17						1				3	1										4		3				2											10	24	54	0.4
EA99-3A	U. Tonsch./ Grauwackens.																										2											4	6	54	0.1
EA99-4		1										2													1			6										2	12	52	0.2
EA99-9	Unterer (Kiesberter) Tonschiefer		23			4			3				5	74	8	16					21		100			1				10	1							27	293	13	22
EA99-10																													2		1	3						5	11	13	0.8
EA99-12																						2	24					1				1						10	38	12	3.3
EA99-13						4											5				12		3							7	3							15	49	12	4.0
EA99-14						3											13				27		10				1			2	12		1	3				48	120	14	8.5
EA99-18																						2	4												1			2	9	13	0.7
EA99-7	Plettenberger Bändersch.								12						1			1				1	6		1					1								7	30	12	2.5
EA99-8																			4			1	1		2											1	1	1	11	12	0.9
EA99-19		1			1	3					2						1				11		14				1		2		2			2				16	56	12	4.5
EA99-20			1								2									5	10		11	4						7	3			10				13	66	13	5.1

Fig. 3. Chitinozoan taxa recovered from the Herscheider Schichten, Ebbe Anticline, in absolute numbers.

1940s, a multidisciplinary group of geologists from the University of Hamburg investigated the Ebbe Anticline in the late 1970s (Degens *et al.* 1981). The history of Ebbe Anticline research and the geology of the Ebbe Anticline Ordovician successions have recently been reviewed by Maletz (2000) and Eiserhardt *et al.* (2001). In the latter paper, the terminology is reviewed according to the modern usage of stratigraphical nomenclature. This new stratigraphical terminology is also adopted here (see Fig. 2).

The Ebbe Anticline rocks, referred to as the Herscheider Schichten, consist of a monotonous thick clastic succession of shales and siltstones without any carbonate content in total some 800 m thick (Timm 1981). The lithological monotony of the succession makes it difficult to distinguish between the four different lithological units that Beyer (1941*a,b,c*) established (Degens *et al.* 1981). The base of the Ordovician rocks is not known, and the contact with the overlying late Silurian and Devonian rocks is obscure (Degens *et al.* 1981).

The Plettenberger Bänderschiefer is up to 65 m thick and is a monotonous dark grey to bluish compact shale with abundant thin silty layers where pyrite is common (Eiserhardt *et al.* 1981). The overlying 150–200 m thick Unterer (Kiesberter) Tonschiefer incorporate dark grey to bluish and black shale with infrequent sandy layers. The (Rahlenberger) Grauwackenschiefer is about 300 m thick, and consists of massive black to grey and bluish-grey silty shale with sandy layers and true thin-bedded greywacke. In the upper part, siliceous concretions are common in places. Presumably the youngest of the Herscheider Schichten units is the Oberer (Solinger) Tonschiefer, a dark grey to bluish and black shale with coarser silty or sandy bands, which reaches some 200 m thickness in the Ebbe Anticline.

Graptolites from the Plettenberger Bänderschiefer belong to the *Holmograptus lentus* Zone and indicate an early Abereiddian (earliest Llanvirn/mid Darriwilian) age. This age assignment is corroborated by the presence of early Llanvirn acritarchs (Maletz & Servais 1993). The overlying Unterer (Kiesberter) Tonschiefer yielded graptolites typical of the *Nicholsonograptus fasciculatus* Zone, which is stratigraphically positioned immediately above the *lentus* Zone, also indicative of an Abereiddian age, although somewhat younger. In the Unterer (Kiesberter) Tonschiefer, early Llanvirn/mid Darriwilian acritarchs occur as well (Maletz & Servais 1993). Hitherto, the youngest confidentially dated strata in the Herscheider Schichten are the (Rahlenberger) Grauwackenschiefer, which yielded the biostratigraphically significant chitinozoan species *Laufeldochitina stentor* (Eisenack) and *Eisenackitina rhenana* (Eisenack) from siliceous concretions within the Grauwackenschiefer (Eisenack 1939). In Baltoscandia, *E. rhenana* is the index species of a subzone within the *L. stentor* biozone which has an age limited to the Kukruse Stage (Nõlvak & Grahn 1993), corresponding to the Aurelucian Stage (lowermost Caradoc) in Britain. Ages obtained from poorly preserved graptolites in the (Rahlenberger) Grauwackenschiefer are less precise, and indicate a Llandeilian (latest Llanvirn/latest Darriwilian) or younger age (Maletz 2000). For the Oberer (Solinger) Tonschiefer an undiagnosed post-Llanvirn Ordovician age was suggested, based on the presence of a few trilobites (Koch 1999*a*; Maletz 2000).

Material and methods

The studied material consists of 19 outcrop samples collected by the authors in November 1999 from the four lithological units that together constitute the Herscheider Schichten in the Ebbe Anticline (Fig. 1). The samples were not taken in strict stratigraphic order, but can be described as spot samples. Samples are referred in the text with the field sample numbers (Fig. 3). For the exact location of the samples, see the Appendix. For the Nd-isotope analyses, two samples from the Oberer (Solinger) Tonschiefer were analysed and one sample each from the other three units (Table 1).

Palynological extraction

Laboratory extraction and concentration of palynomorphs were carried out using the standard palynological method described by Paris (1981). Slides for optical microscopy were prepared using Canada Balsam as the embedding medium. Scanning electron microscope (SEM) study and photography of chitinozoans was carried out at the Department of Geology and Pedology, Ghent University, Belgium, with a JEOL scanning microscope 6400 at 10 kV. All illustrated specimens are deposited in the collection of the Research Unit Palaeontology, Department of Geology and Pedology, Ghent University, Belgium.

Nd-isotopes

Approximately 200 mg of powdered sample were combined with a ^{149}Sm–^{150}Nd mixed spike, digested at *c.* 120 °C in a HF-HNO_3 mixture over 4 days, evaporated to dryness, attacked with

Table 1. *Nd-isotope values obtained from the Herscheider Schichten, Ebbe Anticline, Germany*

Sample	Formation	Age* (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma_m$)	$^{143}Nd/^{144}Nd$ Initial	εNd Initial
EA99-1	Oberer (Solinger) Tonschiefer	452	6.752	40.55	0.1007	0.511911 ± 0.000003	0.511613	–8.7
EA99-2	Oberer (Solinger) Tonschiefer	452	6.768	40.67	0.1006	0.511893 ± 0.000003	0.511595	–9.0
EA99-5	(Rahlenberger) Grauwackenschiefer	457	8.244	46.75	0.1066	0.511956 ± 0.000003	0.511637	–8.0
EA99-9	Unterer (Kiesberter) Tonschiefer	465	9.787	50.65	0.1168	0.511927 ± 0.000003	0.511571	–9.1
EA99-19	Plettenberger Bänderschiefer	465	9.307	49.19	0.1144	0.511917 ± 0.000003	0.511569	–9.2

*Estimated ages (see text) using time scale proposed by McKerrow & van Staal (2000).

HNO_3 and after evaporation re-dissolved overnight in 6 M HCl, once again evaporated to dryness and finally dissolved in 2.5 M HCl. Sm and Nd concentrations and Nd isotope ratios were analysed in static mode on a Finnegan MAT 262 multicollector mass spectrometer at the NERC Isotope Geosciences Laboratory (NIGL) after standard chromatographic separation. $^{143}Nd/^{144}Nd$ was normalized to a $^{146}Nd/^{144}Nd$ ratio of 0.7219. Nd blanks were less than 0.5 ng and remained negligible.

The NIGL in-house J&M standard gave a $^{143}Nd/^{144}Nd$ of 0.511185 ± 12 (2σ, n = 15) during the course of this study. Sample data are reported relative to a J&M value of 0.511126, which corresponds to the accepted $^{143}Nd/^{144}Nd$ of 0.511860 for La Jolla. Nine analyses of the rock standard BCR-1 at NIGL over a period of 8 months yielded $^{147}Sm/^{144}Nd$ of 0.13867 ± 0.2 (2σ) and $^{143}Nd/^{144}Nd$ of 0.512638 ± 15 (2σ). Results are reported as εNd-values, the derivations in parts per 10^4 from chondritic Nd at time of sedimentation.

Results

Palynological results

Almost all recovered specimens are broken and in a poor state of preservation, but some are nevertheless preserved in three dimensions. Thus, the abundance of chitinozoans in each processed sample as indicated by a number of specimens per gram of rock must be regarded only as approximate. These numbers vary between 0.1 and 22 (EA99–9) chitinozoans per gram of rock (Fig. 3). Two samples from the (Rahlenberger) Grauwackenschiefer proved to be barren. Because of the poor state of preservation, a large number of specimens remain undetermined or are determined to the generic level only; sometimes the classification even at this level proved difficult. The chitinozoans which are reasonably well preserved are all attributed to well-known taxa, hence, no formal taxonomic descriptions have been made, and no synonymy lists are provided. In the following section, abbreviations for the biometric measurements are as follows: L = total length; Lp = chamber length; Dp = chamber diameter, Dc = diameter of oral tube, and n = number of specimens included in the calculation. The terminology and the generic assignments of the observed chitinozoans correspond to the new generic classification proposed by Paris *et al.* (1999). Because of the poor preservation of the chitinozoans, open nomenclature has been used for numerous taxa.

Plettenberger Bänderschiefer Four investigated samples from around the village of Herscheid and the small town of Plettenberg yielded few chitinozoans in a poor state of preservation that nevertheless allowed recognition of some chitinozoan species, i.e. *Belonechitina capitata* (Eisenack), *Cyathochitina calix* (Eisenack), *Cyathochitina campanulaeformis* (Eisenack) and *Desmochitina cocca* Eisenack. A number of other chitinozoans are uncertainly determined to the specific level, i.e. *Euconochitina ?conulus*, *Pistillachitina ?pistillifrons*, *Laufeldochitina ?clavata*, *Belonechitina ?micracantha* and *Lagenochitina ?ponceti* (Fig. 3). The specimen attributed to *C. calix* (in EA99–7) is reasonably well-preserved (L = 185 µm; Dp = 65 µm; Dc = 40 µm; Lp = 135 µm) and a weakly developed carina is clearly visible (Fig. 4c). Twelve incomplete chitinozoans (average: L > 135 µm; Dp = 63.3 µm, n = 12; Dc = 41.2 µm, n = 9) are similar to *P. pistillifrons* (Eisenack), with long weakly conical necks, and pronounced aboral swellings, here attributed to *P. ?pistillifrons* (Fig. 4c). Five specimens in EA99–20 are attributed to *L. ?ponceti* (Rauscher). The general morphology and the biometry (average: Dp = 90 µm, n = 5; Dc = 66.5 µm, n = 4; Lp = 114.5 µm, n = 4) fits well with that of those illustrated by Paris (1981) from the Domfront Synclinal, Orne, France, but the specific assignment is far from certain as these specimens are flattened, and their necks are missing (Fig. 4i).

Unterer (Kiesberter) Tonschiefer Six samples yielded a few complete, three-dimensionally preserved specimens. The most fossiliferous sample that we encountered from the entire Ebbe Anticline comes from the Unterer (Kiesberter) Tonschiefer (EA99–9). This particular sample produced a great number of specimens which belong to the subfamily Conochitininae. However most of these specimens were very difficult to determine even to the generic level, as only very general characters can be observed. Some fossils were attributed to *Rhabdochitina ?gracilis*, and five other are treated as *Conochitina* sp. A. The latter are characterized by a short vesicle, a flat base with a sharp margin and a short mucron-like structure (average: L = 154 µm, n = 3; Dp = 53 µm, n = 5; Dc = 33.5 µm, n = 2). One hundred specimens in the same sample (EA99–9) are only determined as *Conochitina* spp. These specimens can be compared to poorly diagnostic species such as *Conochitina claviformis* Eisenack and *Conochitina incerta* Eisenack. Several specimens of *Belonechitina capitata* (Eisenack) were also observed in this sample. Two other samples (EA99-13 and -14) yielded some specimens similar to *Laufeldochitina clavata* (Jenkins). Because all of them are incomplete (Fig. 4h), we formally refer to them as *L. ?clavata* (average in EA99–14: Dp = 95.5 µm, n = 4; Dcarina > 80 µm).

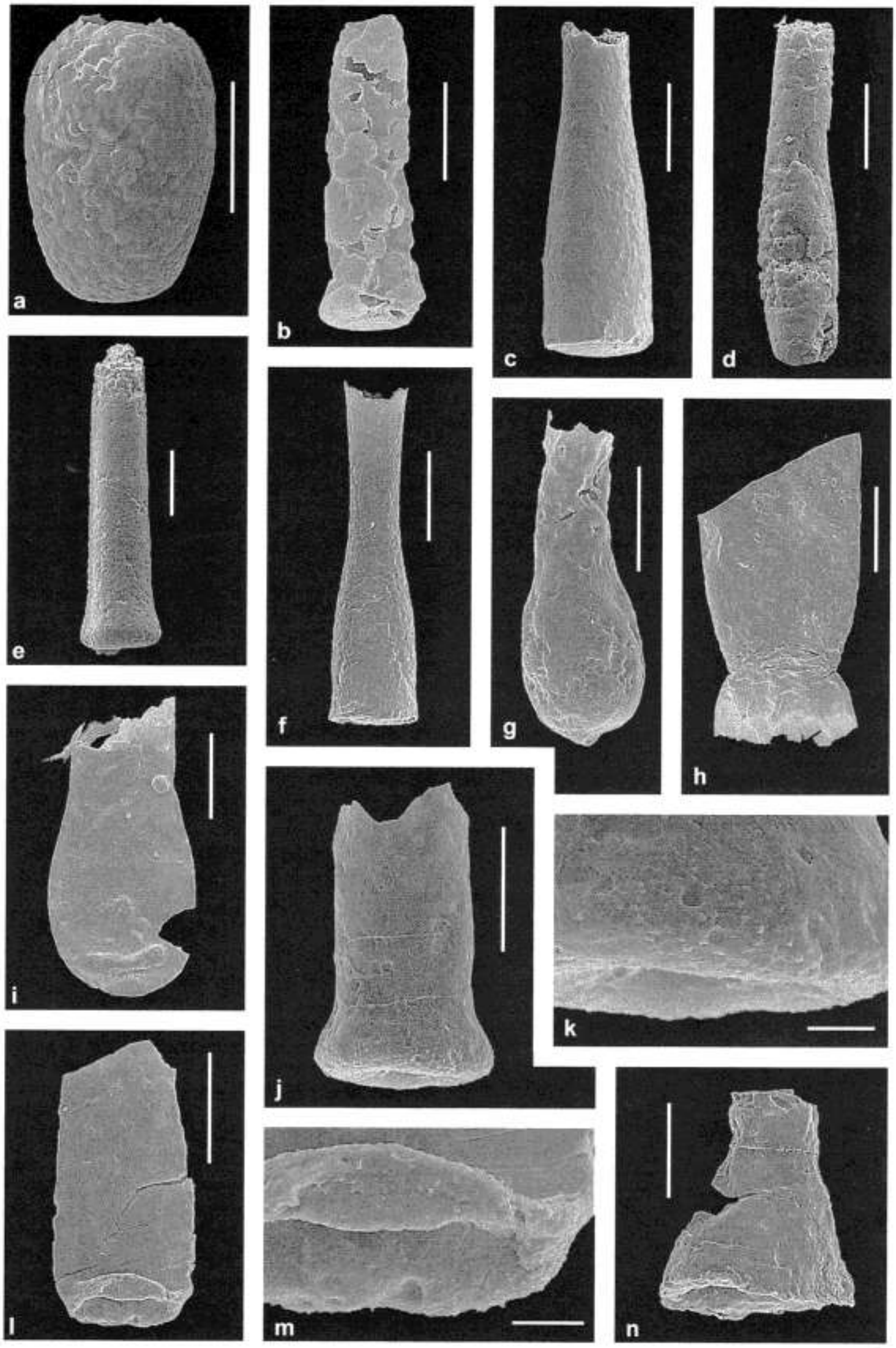
(Rahlenberger) Grauwackenschiefer In the three fossiliferous samples from Rahlenberg, the Hangweg of Kiesbert-Höh and the village of Frehlinghausen (see Appendix) a few fragmentary chitinozoans in a very poor state of preservation were observed. These were attributed to *Belonechitina ?micracantha*, *Desmochitina minor* Eisenack, *Euconochitina ?conulus*, *Pistillachitina ?pistillifrons* (Fig. 4b) and *Rhabdochitina ?magna*, but most were determined to the generic level only, or could not be attributed even to that level (Fig. 3).

Two samples from a temporary excavation at Herscheid (see Appendix), EA99-3A and -4, come from an outcrop mapped as Unterer (Kiesberter) Tonschiefer (Degens *et al.* 1981), but because of the difficulty in separating the Unterer (Kiesberter) Tonschiefer from the overlying (Rahlenberger) Grauwackenschiefer, the possibility exists that they belong to the latter unit. From these samples, only three specimens could be tentatively determined to two species: *?Belonechitina ?capitata* and *Desmochitina* cf. *piriformis* (Fig. 4a), both in EA99–4 (Fig. 3).

Oberer (Solinger) Tonschiefer The two samples that were obtained close to the village of Hohl (see Appendix) yielded inadequately preserved and broken chitinozoans only. In addition, the small number of reasonably preserved chitinozoans possess few discriminate characters that permit a definite attribution to the specific level of these fossils. The following taxa were determined to the specific level: *Belonechitina capitata* (Eisenack), *Desmochitina cocca* Eisenack and *Desmochitina minor* Eisenack. Attribution of specimens to the following taxa were less certain: *Cyathochitina* sp. A, *Belonechitina ?micracantha* (Figs 4l, 4m), and *Conochitina ?minnesotensis*. The two specimens of *B. capitata* (average: L > 117 µm; Dp = 65 µm, n = 2; Dc = 52 µm, n = 2) show clear although worn aboral spines (Figs 4j, 4k), and the shapes of the incomplete vesicles are identical to the holotype (Eisenack 1962). The specimens called *Cyathochitina* sp. A herein (Fig. 4n) have a conspicuous flexure and a short neck (average: L = 127.5 µm, n = 2; Dp = 101.7 µm, n = 3; Dc = 46.5 µm, n = 2; Lp = 95 µm, n = 2) and are very similar to those also referred to *Cyathochitina* sp. A in deep drillholes in Pomerania (Samuelsson *et al.* 2002). Two specimens are designated to *?Lagenochitina* spp., and one of them, although even the generic attribution is uncertain due to the poor preservation, is similar to *Lagenochitina dalbyensis* (Laufeld), both in terms of shape, e.g. the flat base typical for *L. dalbyensis* which is present, and size (L > 130 µm; Dp = 65 µm). Unfortunately, no further *L. dalbyensis*-like specimens were observed despite several renewed macerations and investigation of additional sample material.

Nd-isotope results

Nd-isotope data are listed in Table 1 and plotted in comparison to Lower Palaeozoic sediments from Avalonia and the ATA in Figure 5. The obtained εNd(t) values from the Ebbe Anticline range from –8.0 to –9.2 and thus show less variation than e.g. the Ordovician Brabant Massif sediments. However, samples from the Plettenberger Bänderschiefer and the Unterer (Kiesberter) Tonschiefer have εNd(t) values of –9.1 to –9.2, which is comparable to values from the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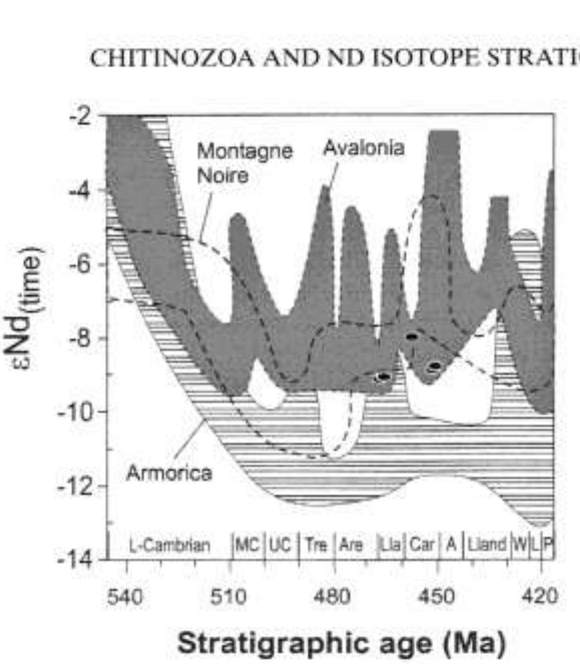

Fig 5. εNd(t) v. stratigraphic ages for sediments from the Ebbe Anticline (black circles) in comparison to well dated sediment successions from Perigondwanan terranes. Avalonia, sediments from Welsh basin, Welsh borderland, English Lake District, Stavelot Massif and Brabant Massif (*c.* 200 analyses); Armorica, sediments from Brittany, Cantabria and Central Iberia (*c.* 70 analyses); Montagne Noire, sediments from the Montagne Noire and the Pyrenees (*c.* 35 analyses). Nd isotopic evolution curves constructed from data in Michard *et al.* (1985); Thorogood (1990); Evans (1992) and references therein; McCaffrey (1994); Leng & Evans (1994); Stone & Evans (1997); Nagler *et al.* (1995); Beetsma (1995); Simien *et al.* (1999); André *et al.* (1986); André (1991); Gerdes *et al.* (unpublished data). Abbreviations: MC = Middle Cambrian, UC = Upper Cambrian, Tre = Tremadoc, Are = Arenig, Lla = Llanvirn, Car = Caradoc, A = Ashgill, Lland = Llandovery, W = Wenlock, L = Ludlow, P = Pridoli.

Brabant Massif, Wales and Lake District shales from upper Arenig to mid Llanvirn/late Darriwilian, which range from –8.7 to –9.4 (Thorogood 1990; Stone & Evans 1997; Gerdes *et al.* unpublished data). Comparable values are also the –8.0 εNd(t) of the (Rahlenberger) Grauwackenschiefer and those of lower Caradocian sediments from the Brabant Massif, which range from –8.0 to –8.2 (Gerdes *et al.* unpublished data). For the Oberer (Solingen) Tonschiefer no exact depositional age is previously known, however, an εNd(t) as low as –9.0 can be found in the Brabant Massif and the Welsh sediments above the lower Llanvirn Stage (middle Darriwilian) only in middle to upper Caradoc (Burrellian to Streffordian) and Upper Silurian strata.

Discussion

Stratigraphy

Apart from *Cyathochitina* sp. A and *Conochitina* sp. A, the chitinozoans recovered from the Ebbe Anticline are well-known from other localities, and their stratigraphic ranges have been established with high confidence, especially in North Gondwana (e.g. Paris 1981, 1990, 1996) and Baltoscandia (e.g. Nõlvak & Grahn 1993). With few exceptions, the observed chitinozoan taxa have broad stratigraphic ranges. Most of them, however, are confined to the Middle and Upper Ordovician.

Plettenberger Bänderschiefer The presence of *Belonechitina capitata* suggests a late Abereiddian (early Llanvirn/mid Darriwilian) to late Caradoc age (Paris 1981; Grahn 1982). The presence of *Cyathochitina calix* support that wide age assignment, as this taxon is known from upper Arenig to lower Caradoc strata elsewhere (Grahn 1982; Nõlvak & Grahn 1993). Some of the taxa kept in open nomenclature, i.e. especially *Euconochitina ?conulus*, *Pistillachitina ?pistillifrons* and *Lagenochitina ?ponceti* also support this time-range, provided they are conspecific with the original species.

Fig. 4. Selected chitinozoans from the Ordovician units of the Herscheider Schichten, Ebbe Anticline, W Germany. Number in parenthesis after field sample name refers to specimen on SEM preparate. Scale bar 50 µm in all illustrations except in (f), (k) and (m). (**a**) *Desmochitina* cf. *piriformis* (Laufeld 1967). EA99-4 (3). Unterer (Kiesberter) Tonschiefer/(Rahlenberger) Grauwackenschiefer. (**b**) *Pistillachitina ?pistillifrons* (Eisenack 1939). EA99-6 (7). (Rahlenberger) Grauwackenschiefer. (**c**) *Cyathochitina calix* (Eisenack 1931). EA99-7 (13). Plettenberger Bänderschiefer. (**d**) *?Rhabdochitina* sp. EA99-7 (28). Plettenberger Bänderschiefer. (**e**) *Pistillachitina ?pistillifrons* (Eisenack 1939). EA99-7 (30). Plettenberger Bänderschiefer. (**f**) *Cyathochitina calix* (Eisenack 1931). EA99-9 (26). Unterer (Kiesberter) Tonschiefer. Scale bar 100 µm. (**g**) *Lagenochitina* sp. EA99-14 (4). Unterer (Kiesberter) Tonschiefer. (**h**) *Laufeldochitina ?clavata* (Jenkins 1967). EA99-14 (13). Unterer (Kiesberter) Tonschiefer. (**i**) *Lagenochitina ?ponceti* (Rauscher 1973). EA99-20 (19). Plettenberger Bänderschiefer. (**j**) *Belonechitina capitata* (Eisenack 1962). EA99-1 (00-699: 2). Oberer (Solinger) Tonschiefer. (**k**) Detail of chamber surface at base of specimen in (**j**) showing small spines. Scale bar 10 µm. (**l**) *Belonechitina ?micracantha* (Eisenack 1931). EA99-1 (01-761: 8). Oberer (Solinger) Tonschiefer. (**m**) Detail of chamber surface at base of specimen as in (l), showing very small and probably worn spines. Scale bar 10 µm. (**n**) *Cyathochitina* sp. A. EA99-1 (01-761: 11). Oberer (Solinger) Tonschiefer.

The supply of volcanogenic detritus was probably the reason for a general increase of the εNd(t) values (–8 to –5) in middle Llanvirn/middle Darriwilian to lower Caradoc sediments from Brabant and Wales (Thorogood 1990; Evans 1992; Gerdes *et al.* unpublished data). Episodic magmatic activity in Ordovician time seems to have delivered juvenile detritus contemporaneously over a more than 700 km wide area, causing a specific Nd-isotope evolution trend for Avalonian sedimentation (Thorogood 1990; Gerdes *et al.* 2001; Fig. 5). However, Middle Cambrian to Upper Ordovician (Caradoc) sedimentation is usually dominated by detritus derived from the exposed Gondwanan/Avalonian crust. Its average composition is defined by the relatively uniform εNd(t) value (–8.9 ± 0.4; n = 41) of Avalonian sediments lacking juvenile detritus. Correlating the Plettenberger *Bänderschiefer* εNd(t) value with those obtained from other Avalonian areas suggests deposition not after mid Llanvirn/late Darriwilian or at late Caradoc times for this unit. Thus, the Abereiddian (early Llanvirn/mid Darriwilian) age given by graptolites is supported both by the recovered chitinozoans and the Nd-isotope data.

Unterer (Kiesberter) Tonschiefer As in the Plettenberger Bänderschiefer, the biostratigraphically most important species is *Belonechitina capitata* which indicates a late Abereiddian (early Llanvirn/mid Darriwilian) to late Caradoc age (Paris 1981; Grahn 1982). Specimens referred to *Laufeldochitina ?clavata* hint at a middle to late Llanvirn age for the Unterer (Kiesberter) Tonschiefer, as true *L. clavata* are known from upper Abereiddian to Llandeilian (upper Darriwilian) strata elsewhere (Paris 1990). The recovered graptolites are indicative of an Abereiddian age (Maletz & Servais 1993), and that assignment is thus confirmed by the sparse chitinozoan data.

Independently, the Nd isotopes also support this age attribution, as sediments with an εNd(t) value of about –9 are unknown from the ATA or from Avalonia between late Llanvirn/late Darriwilian to mid Caradoc times.

(Rahlenberger) Grauwackenschiefer No biostratigraphically unequivocal taxa were recovered, but the presence of *Pistillachitina ?pistillifrons* in EA99-6 gives a hint about the age of the (Rahlenberger) Grauwackenschiefer as true *P. pistillifrons* (Eisenack) are known from lower Caradoc to lower Ashgill strata (Elaouad-Debbaj 1986). The chitinozoans reported by Eisenack (1939) from siliceous concretions within the (Rahlenberger) Grauwackenschiefer include (taxonomy as currently understood) *Cyathochitina campanulaeformis* (Eisenack), possible *Cyathochitina calix* (Eisenack), *Laufeldochitina stentor* (Eisenack), *Euconochitina primitiva* (Eisenack), *Belonechitina micracantha* (Eisenack), *Desmochitina minor* Eisenack, *Eisenackitina rhenana* (Eisenack), *Rhabdochitina magna* Eisenack, *Pistillachitina pistillifrons* (Eisenack), *Conochitina minnesotensis* (Stauffer) and *Conochitina* aff. *claviformis* (Eisenack). Eisenack (1939) did not give precise information from where his siliceous concretion sample of the Grauwackenschiefer came from. However, Richter & Richter gave the material to him (Eisenack 1939), and these two authors mention the locality, 'Fundpunkt 04', in a later publication describing the trilobite '*Cyclopyge*' *illaenoides* (Richter & Richter 1954, p. 54; see also Koch 1999*a*, p. 385, 'Fundpunkt 8'). This locality has now been built over, and our locality close to that of Eisenack (1939), behind the Herscheid school (Turnhalle) was excavated much later. Unfortunately, our siliceous concretion (EA99–6) yielded only a few poor chitinozoans. Therefore, the chitinozoan assemblage reported by Eisenack (1939) still gives the most precise biostratigraphic age for the (Rahlenberger) Grauwackenschiefer, i.e. Aurelucian (earliest Caradoc).

The εNd(t) values in the Brabant Massif sediments seem to decrease continuously from about –8.0 to –8.8 in lower to upper Caradoc strata (Gerdes *et al.* 2001). Correlation of the (Rahlenberger) Grauwackenschiefer with the Brabant Massif sediments shows that the Nd-isotope data support the more precise biostratigraphic age.

The two samples belonging either to the Unterer (Kiesberter) Tonschiefer or the (Rahlenberger) Grauwackenschiefer might be of an early Caradoc age, as *Desmochitina* cf. *piriformis*, provided it is a true *D. piriformis,* indicates this age (Paris 1981). The samples therefore possibly derive from the (Rahlenberger) Grauwackenschiefer.

Oberer (Solinger) Tonschiefer The species *Belonechitina capitata* is known from strata of late Abereiddian (early Llanvirn/mid Darriwilian) to late Caradoc ages (Paris 1981; Grahn 1982). Because the Oberer (Solinger) Tonschiefer is observed to be overlying the (Rahlenberger) Grauwackenschiefer (Timm *et al.* 1981) and the latter unit has been assigned an earliest Caradoc age, the Oberer (Solinger) Tonschiefer must be of the same age, or younger, than the

(Rahlenberger) Grauwackenschiefer. We therefore suggest an early to late Caradoc age for the Oberer (Solinger) Tonschiefer based on chitinozoans only. If we also correlate the Nd-isotope data of the Oberer (Solinger) Tonschiefer with that of sediments from the Brabant Massif, the obtained εNd(t) values of –8.7 to –9 indicate a late Caradoc or late Silurian age (Fig. 5). Accordingly, based on the combined chitinozoan and Nd-isotope study, a late Caradoc age is suggested for the Oberer (Solinger) Tonschiefer.

Attribution of the Ebbe Anticline (Herscheider Schichten) to Avalonia

The Ebbe Anticline belongs to the Rheinisches Schiefergebirge which in turn forms part of the Rheno-Hercynian Zone of central Europe north of the so-called Rheic Suture and the Saxo-Thuringian Zone (e.g. Erdtmann 1991; Cocks *et al.* 1997; Pharaoh 1999). The Rheno-Hercynian nappes of Cornubia (SW England) and central Europe are interpreted as representing parts of Avalonia separated from the parent continent during the Variscan Orogeny (Dallmeyer *et al.* 1995). In addition, most of the autochthonous parts of the Rheinisches Schiefergebirge were also part of Avalonia, because fossil faunas in these areas are most closely comparable to other Avalonian faunas (e.g. Siegfried 1969; Anderle 1987; Koch 1999*a*).

Individual chitinozoan taxa typical for a higher latitude area (here identified as Avalonia or Perigondwana) were recovered neither by the present investigation nor by Eisenack (1939). A possible exception would be those specimens herein attributed to *Lagenochitina ?ponceti* from the Plettenberger Bänderschiefer, as this taxon was previously never described from low-latitude Baltoscandian sediments. However, the poor level of preservation and the uncertain taxonomic attribution of these specimens do not provide evidence for the inclusion of Ebbe Anticline in Avalonia. Instead, the total taxonomic composition of the chitinozoan assemblage itself appears to be of some palaeobiogeographic significance. Cluster analysis and coefficient of similarity calculations on the Eisenack (1939) chitinozoan assemblage from the chitinozoan *stentor* biozone (i.e. the (Rahlenberger) Grauwackenschiefer) together with other contemporary Avalonian assemblages from the Rügen 5/66 borehole (North Germany) and the Brabant Massif, Belgium, show that the thus postulated Avalonian fauna is different from contemporary faunas recovered from both North Gondwana and Baltoscandia (Samuelsson *et al.* 2002). This indirectly supports the inclusion of the Ebbe Anticline succession in Avalonia. In addition, acritarchs in the Ebbe Anticline are typical cold-water, high-latitude species, and thus provide additional evidence for that attribution (Maletz & Servais 1993).

Lower Palaeozoic sediments from the ATA show different εNd(t) trends compared to eastern Avalonian sediments (Fig. 5). The ATA is characterized by at least two distinct regions in terms of their sedimentary Nd-isotope composition, each with similar εNd(t) trends over a wide depositional area (Gerdes *et al.* 2001). Sediments from the Montagne Noire and the Pyrenees show less negative εNd(t) values in comparison to the Ebbe Anticline sediments, and sediments from Brittany, Cantabria and Central Iberia usually more negative εNd(t) values during Llanvirn and Caradoc times (Michard *et al.* 1985; Nagler *et al.* 1995; Beetsma 1995; Simien *et al.* 1999). Thus the Nd-isotope signatures support the idea that the Ordovician succession of the Ebbe Anticline belongs to the same palaeogeographic unit as the Lower Palaeozoic of the Brabant Massif and the Welsh Basin, i.e. Avalonia.

Stratigraphic correlations

A much clearer picture of the stratigraphic relationship between the rock successions interpreted as forming part of Eastern Avalonia has emerged over the last years (e.g. Verniers *et al.* 2002; Fig. 6).

To the west of the Ebbe Anticline, Ordovician rocks are known from Belgium, where Lower Palaeozoic sediments occur in three distinct tectonostratigraphical units, from north to south the Brabant Massif (which is underlying most of Belgium), the Condroz Inlier (also called 'Bande de Sambre-et-Meuse'), and the Ardenne inliers (Stavelot, Rocroi, Serpont, and Givonne inliers) in southern Belgium. The Ebbe succession is most similar to the succession of dark shale and sandstone of the Condroz Inlier. The Huy Formation of an early Llanvirn age in the Condroz Inlier has a lithology and a fossil content (acritarchs, graptolites, trilobites, and ichnofossils) similar to those of the Plettenberger Bänderschiefer and the Unterer (Kiesberter) Tonschiefer. The Huy Formation is overlain by the Sart-Bernard, Vitrival-Bruyère and Oxhe formations, of which only the latter is accurately dated by trilobites (Dean 1991) as Longvillian (latest Burrellian, mid Caradoc) in age. The two other formations, which only occur locally, are probably of an Abereiddian to Aurelucian age (Servais & Maletz 1992) and

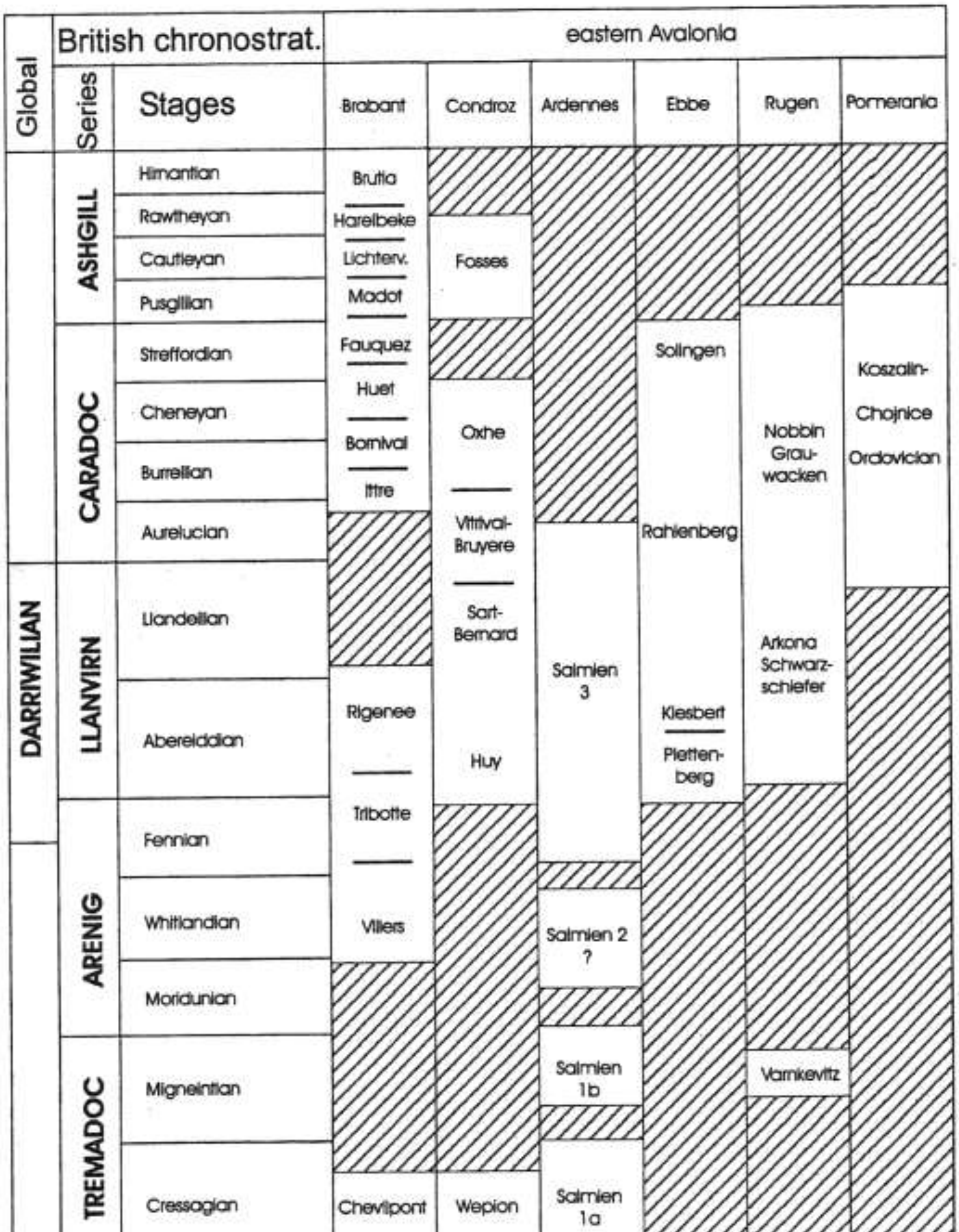

Fig. 6. Correlation between Ordovician units of the Brabant Massif (Samuelsson & Verniers 2000), the Condroz Inlier (Servais & Maletz 1992), the Stavelot Inlier (Verniers *et al.* in press.), the Ebbe Anticline, the Rügen successions (Servais *et al.* 2001), and Pomerania (Samuelsson *et al.* 2002). Chronostratigraphy after Fortey *et al.* (1995). Oblique lines indicate lack of evidence for deposition.

thus represent possible equivalents of the (Rahlenberger) Grauwackenschiefer. The other formations in the Condroz Inlier, the Wépion Formation of a Tremadoc age and the Fosses Formation of an Ashgill (pre-Hirnantian) age, have no equivalents in the Ebbe area.

Although the Plettenberger Bänderschiefer and the Unterer (Kiesberter) Tonschiefer may be correlated with the Rigenée Formation of the Brabant Massif, dated as Abereiddian (early Llanvirn/mid Darriwilian) in age (Maletz & Servais 1998; Samuelsson & Verniers 2000), the

(Rahlenberg) Grauwackenschiefer does not appear to have any time-equivalent counterparts in the Brabant Massif. However, the suggested late Caradoc age of the Oberer (Solinger) Tonschiefer may have its parallel in the late Caradoc or earliest Ashgill Huet and Fauquez formations of the Brabant Massif (Samuelsson & Verniers 2000). Unfortunately, no hitherto observed chitinozoan taxa are common between Oberer (Solinger) Tonschiefer and the Madot Formation.

In the Stavelot Inlier, a succession of shale and siltstone forming the so-called 'Salm 3' unit of the Salm Group were attributed to the Arenig–Llandeilo series by Vanguestaine (1986), i.e. Arenig to upper Llanvirn/upper Darriwilian strata (Verniers *et al.* 2001), and can thus be compared with the two lowermost Ebbe Anticline units. In the Rocroi Inlier, corresponding strata are attributed to the 'Revin 5' unit of the Revin Group (Roche *et al.* 1986). Correlations between the Ardenne inliers and the Ebbe Anticline therefore remain problematical.

Jaeger (1967), who first described the lithology and the palaeontology (graptolites and phyllocarids) of the Ordovician rocks underlying the island of Rügen (NE Germany), pointed out the close relationship of Rügen with the Ordovician of the Rheinisches Schiefergebirge. He suggested that both areas are related palaeogeographically, possibly belonging to the same sedimentation area, with Rügen being located at the margin and the Rheinisches Schiefergebirge in the central part of the Rheno-Hercynian Belt. This view, which is similar to the modern interpretation of the Rügen Ordovician rocks being part of Eastern Avalonia, is sustained by recent studies which indicate that the Ordovician succession of Rügen is of a Llanvirn to Caradoc (and possibly early Ashgill) age (Servais *et al.* 2001). Furthermore, both lithology, macrofossils (e.g. graptolites and phyllocarids), and microfossils (acritarchs and chitinozoans) of Rügen and the Ebbe anticline are very similar.

The Ordovician succession of the Koszalin–Chojnice area in western Pomerania (northwestern Poland) can be considered as an eastward extension of Eastern Avalonia, i.e. the Rügen succession. Samuelsson *et al.* (2002) evaluate the stratigraphy of this Polish succession, which in part can be correlated with the uppermost unit of the Rügen Ordovician. Therefore, it corresponds to the Upper Ordovician units of the Ebbe Anticline (Fig. 6).

This project was started during the postdoctoral studies of J. Samuelsson and A. Gerdes while recipients of research grants from the EU funded TMR program PACE (Palaeozoic Amalgamation of Central Europe) at the University of Ghent (Belgium) and the NERC Isotope Geoscience Laboratory (UK), respectively. The project was finished by J.S. at the University of Rennes I (France) with a postdoctoral fellowship from the Swedish government through STINT. F. Paris (Rennes) kindly hosted J.S. during his latter stay. S. Van Cauwenberghe (Ghent) processed the samples for microfossils. O. Paris (Rennes) drew the chitinozoan figure. K.-H. Eiserhardt (Hamburg) discussed Ebbe Anticline stratigraphy. J. Verniers was research director of the Fund for Scientific Research (Flanders), Belgium until 2000. Constructive reviews were made by S. Noble and J. Maletz. This paper is a contribution to IGCP 410 'The Great Ordovician Biodiversification Event'.

Appendix

Sample	Locality	Formation	Notes
EA99-1	Hohl	Oberer (Solinger) Tonschiefer	Road to Hohl, *c.* 75 m from road cross
EA99-2	Hohl	Oberer (Solinger) Tonschiefer	2.3 m S of EA99–1
EA99-3A	Herscheid, Neubaugebiet	Unterer (Kiesberter) Tonschiefer or (Rahlenberger) Grauwackenschiefer	1–1.5 m from NNW corner of Weissdornweg 13
EA99-4	Herscheid, Neubaugebiet	Unterer (Kiesberter) Tonschiefer or (Rahlenberger) Grauwackenschiefer	'Kieselgallen', Schlehenweg
EA99-5	Herscheid, Rahlenberg Schule	(Rahlenberger) Grauwackenschiefer	Behind sports hall (Turnhalle), 4 m from left corner of house, 3.6 m from wall, *c.* 1.1 m height

Appendix – *continued*

Sample	Locality	Formation	Notes
EA99-6	Herscheid, Rahlenberg Schule	(Rahlenberger) Grauwackenschiefer	'Kieselgallen' to the left of EA99-5, *c.* 1.5 m above base of sports hall
EA99-7	Herscheid Umgehungstrasse	Plettenberger Bänderschiefer	1.40 m above road, 4 m to the right of road sign
EA99-8	Herscheid Umgehungstrasse	Plettenberger Bänderschiefer	1.90 m above road, 19 m to the left of road sign
EA99-9	Brenscheider Fahrweg	Unterer (Kiesberter) Tonschiefer	200 m east of Waldminer Kreuz, in a 'sunken' dirt road, 0.70 m above road
EA99-10	Brenscheider Fahrweg	Unterer (Kiesberter) Tonschiefer	0.90 m above road, 5 m above EA99-9
EA99-12	Hangweg NE Kiesbert	Unterer (Kiesberter) Tonschiefer	Maletz & Servais (1993) loc. A, 2 m above road
EA99-13	Hangweg NE Kiesbert	Unterer (Kiesberter) Tonschiefer	Maletz & Servais (1993) loc. A
EA99-14	Hangweg NE Kiesbert	Unterer (Kiesberter) Tonschiefer	Maletz & Servais (1993) loc. C, 2.5 m above road
EA99-15	Hangweg NE Kiesbert	(Rahlenberger) Grauwackenschiefer	37 m west of oak, 1.7 m above road, base of outcrop
EA99-16	Frehlinghausen	(Rahlenberger) Grauwackenschiefer	'Kieselgallen', base of outcrop, not exactly positioned
EA99-17	Frehlinghausen	(Rahlenberger) Grauwackenschiefer	'Kieselgallen', 30 cm above ground
EA99-18	Plettenberg – Hechmecker Weg	Unterer (Kiesberter) Tonschiefer	*c.* 1 m above ground
EA99-19	Ziegelei Loos (Plettenberg)	Plettenberger Bänderschiefer	Behind supermarket, *c.* 1 m above ground
EA99-20	Ziegelei Loos (Plettenberg)	Plettenberger Bänderschiefer	1 m from previous sample, 1 m above ground

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