

Late Oligocene Warming Event in the southern North Sea Basin: benthic foraminifera as paleotemperature proxies

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Abstract

The investigation of foraminiferal assemblages from a series of Oligocene borehole sections allowed paleoenvironment and paleoclimate reconstructions for the Rupelian and Chattian (Lower and Upper Oligocene) Stages in their type region, the southern North Sea Basin. A striking feature coinciding with the Rupelian-Chattian (R-C) unconformity is the major change in paleotemperature and paleobathymetry. The shallow marine to restricted marine subtropical fauna at the base of the Chattian is in strong contrast with the deeper marine and cooler upper Rupelian assemblages. This study suggests that the early Chattian transgression is genetically related to a widespread major warming pulse, known as the Late Oligocene Warming Event.

Keywords: benthic foraminifera, global warming, Oligocene, paleotemperature, Rupelian-Chattian boundary

Introduction

As most of the Paleogene climatic and oceanographic studies focused on intervals of presumed rapid global change and biotic extinctions, such as those at the Cretaceous-Tertiary (K-T), Paleocene-Eocene or Eocene-Oligocene boundary, most researches did not further explore the remainder of the Paleogene geological archive. This has led to the generally accepted assumption that, since the Early Eocene Climatic Optimum (or 'EECO', e.g., Zachos et al., 2001), a long-termed, gradual and pervasive global deterioration of the earth's climate resulted in a unidirectional cooling and the development of a significant Arctic and Antarctic cryosphere, as known from the present earth conditions (Ivany et al., 2003). However, detailed deep-sea benthic $\delta^{18}\text{O}$ studies from continuous ODP holes show that the presumed gradual climatic trend is characterised by strong short-term fluctuations. A

series of warmer (e.g., the 'Middle Eocene Climatic Optimum', Bohaty & Zachos, 2003; the 'Late Oligocene Warming Event' and 'Mid Miocene Climatic Optimum', Zachos et al., 2001), and colder intervals (e.g., the Oi- and Mi-'events' or 'glaciations', Miller et al., 1987, 1991, 1998; Zachos et al., 1993, 1994, 1996, 1999, 2001) were recognised, and correlated around both hemispheres. While the impact and significance of these events now begins to be realised by the scientific community, clearly influencing our understanding of the nature of long- and short-term climate changes, only few speculations on possible underlying mechanisms have been put forward (Bohaty & Zachos, 2003).

We here report on a drastic climate change associated with the base of the Chattian unit-stratotype in the southern North Sea Basin, recognised by means of benthic foraminiferal assemblages, and further suggest possible correlation with the Late Oligocene Warming Event of Zachos et al. (2001).

Geological setting

Both the classic Lower- and Upper Oligocene unit-stratotypes (respectively the Rupelian and Chattian Stages) were defined on the basis of southern North Sea Basin successions, and have been the topic of many (micro)paleontological, sedimentological and geochemical studies (for an overview see Van Simaey et al., 2004). The R-C unconformity in the southern North Sea Basin is associated with major changes in benthic foraminiferal assemblages (De Man et al., 2004). The base of the Chattian sequence is characterised by the bloom of benthic foraminifer *Asterigerinoides guerichi guerichi* (>70%). This distinct and widespread 'Asterigerina Horizon' can be recognised throughout the North Sea Basin (e.g., Ellermann, 1958; Indans, 1958, 1965; Doppert & Neele, 1983; Ulleberg, 1987; King, 1983, 1989; De Man et al., 2004) and allows clear recognition of the R-C boundary in its type region (Van Simaey et al.,

2004). Other significant bio-events, coeval with the 'Asterigerina Horizon', are the first occurrences of *Elphidium subnodosum* and *Protelphidium roemeri* (De Man et al., 2004). Despite the fact that regional biostratigraphy achieves high resolution, chronostratigraphic calibration of these successions to the international time scale remains problematic, mainly due to the marginal to restricted marine nature of most deposits and the near absence of traditional, age-indicative calcareous microfossils. Recent dinoflagellate correlations, however, revealed that the R-C unconformity in the stratotype area is genetically related to the Oligocene Glacial Maximum (OGM, see Van Simaey et al., submitted) and further suggest that the oldest of the time-transgressive glauconitic fine Chattian sands in the southern North Sea Basin were deposited around 26.7 Ma (Van Simaey, 2004).

Material & Methods

The benthic foraminiferal investigation is based on approximately 80 samples from 4 cored boreholes in NE Belgium, covering the Rupelian Boom Clay and the Chattian Voort Sand Formation (Fig. 1, see also De Man et al., 2004). These data are furthermore completed with published results from the lower part of the Boom Clay Formation (Hooyberghs et al., 1992; Grimm & Steurbaut, 2001). A composite section (CS) for the R-C transition in the southern North Sea Basin is compiled on the basis of geophysical well log data and biostratigraphy. The 'Asterigerina Horizon' – defining the base of the Chattian Stage – is designated as reference level zero (see De Man et al., 2004).

Equally sized samples (~200g) were dried in an oven and then soaked in a dilute solution of a phosphate-containing detergent ('Sun'). All samples were washed on a 63 µm sieve, dried, and then split on a 120 µm sieve. Only the fraction >120 µm was examined quantitatively. Relative abundances were calculated from at least 200 benthic individuals, except when the faunas were very sparse (Table 1; for details and range charts see De Man et al., 2004). For the lower part of the section (up to level S50), counts are limited to 100 benthic foraminifera per sample (data by Hooyberghs et al., 1992 and Grimm & Steurbaut, 2001) and hence are statistically not representative. To recognise and evaluate post-mortem changes, i.e. dissolution and transport, the quality of preservation for the foraminiferal assemblages was evaluated (see e.g., Murray, 1984, p. 467). Only assemblages revealing minor post-mortem modifications are applied in the present paleo-environmental reconstructions.

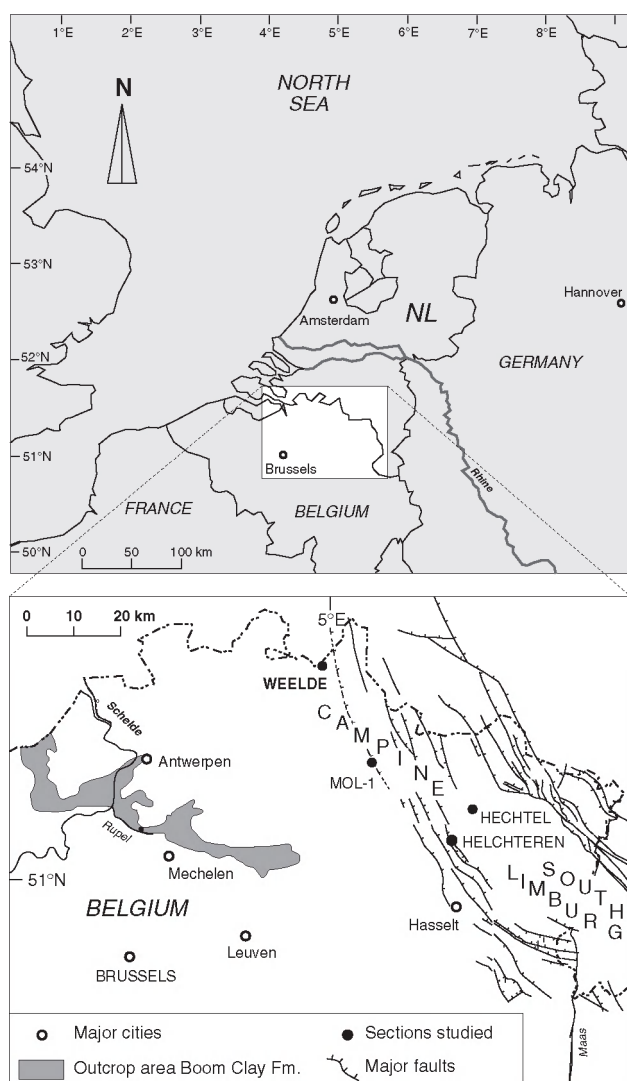


Fig. 1. Location of the sections studied (modified after Van Simaey et al., 2004).

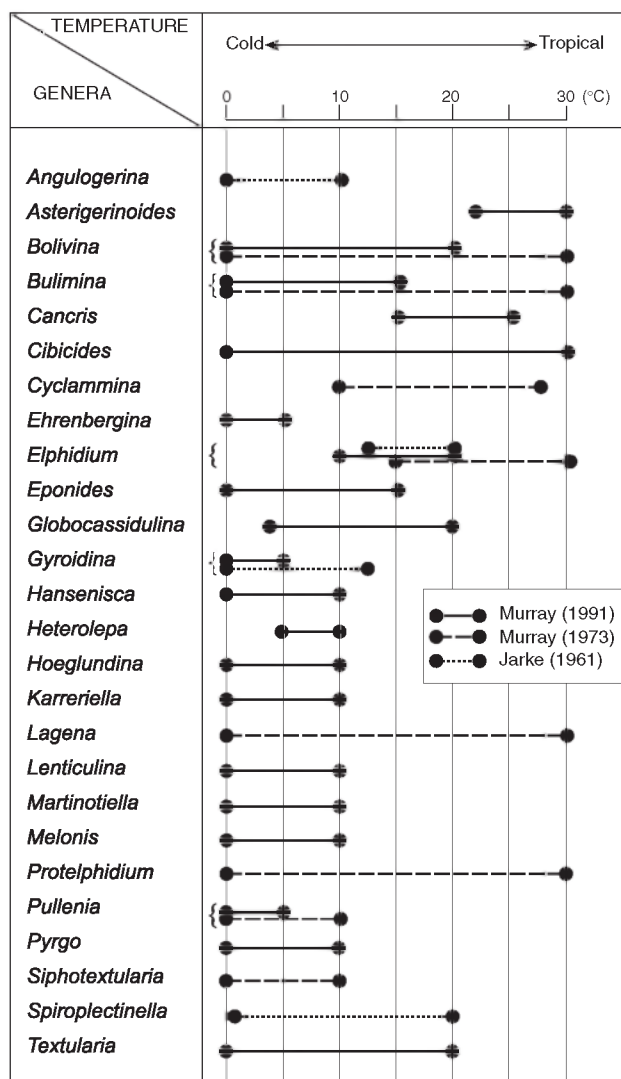


Fig. 2. Temperature ranges of selected, encountered taxa, as recorded in literature.

The planktonic foraminifera were not identified to species level, but only calculated as percentages ($P\% = [\text{number planktonic} / (\text{number benthic} + \text{planktonic foraminifera})] \times 100$). In a semi-enclosed basin, this value is not primarily related to depth but rather to the influx of oceanic water into the basin (Murray, 1976). The Fisher diversity index (α), allowing comparison with modern equivalent environments, is determined following standard procedures as described by Murray (1973). The three suborders (hyaline, porcellaneous and agglutinated forms) are taken into account for the triangular plot (Murray, 1973, p. 26), and additional differentiation is made for calcareous and non-calcareous agglutinants (according to King, 1989), allowing recognition of low oxygen levels.

Temperature delineation for each genus is based on the assumption that the environmental conditions for modern genera are essentially the same as for the fossil record. This assumption is fairly reliable for

Cenozoic times (Murray, 1984, p. 469). Additionally, this assumption is evaluated through comparison with Oligocene shallow marine faunas from different paleogeographic provinces (e.g., Beckmann, 1953; Corliss, 1981; Wong, 1976; Wood et al., 1985). These approaches led to the establishment of 4 different categories, each category grouping species with a clear affinity towards respectively 'cold', 'temperate', 'warm' or 'cold to warm' conditions (Table 1). Quantification of these temperature-restricted eco-groups is based on comprehensive lists of temperature preferences for modern benthic foraminifera (e.g., Jarke, 1961; Haake, 1962; Hofker, 1977; Murray, 1973, 1991; see Table 1 and Fig. 2).

These data allow the reconstruction of a paleo-temperature curve according to the equation of Lommerzheim (1991); a method successfully applied for late Oligocene samples (Kohnen, 1995):

$$T_{\text{trend}} = (1/n) \sum_{i=1}^n n_i * [(T_{\text{min},i} + T_{\text{max},i})/2]$$

With i representing a certain taxon, n the total amount of specimens counted within the assemblage, n_i the appropriate number of specimens of taxon i and $T_{\text{min},i}$, $T_{\text{max},i}$ its minimum and maximum temperature (see Fig. 2). It is here stressed that this method only provides a trend value for comparing the different assemblages, and should not be regarded as an absolute method for determining paleotemperatures.

Paleoenvironment: results and interpretation

Evaluation of the assemblage-quality

The majority of the assemblages yield specimens with shiny to dull hyaline tests, with juveniles and adults of the same species present, and broken tests being very rare. There is no significant loss of agglutinated tests, as indicated by the presence of both adult and juvenile *Karreriella siphonella*. Hence, these assemblages are regarded as reliable for paleoecological interpretations (field I of Murray, 1984, p. 467). Some upper Rupelian samples (around -74 m and -55 m in the CS) are anomalously enriched in pyritised agglutinants (medium to large agglutinated tests), suggesting dissolution of hyaline calcareous tests. The latter assemblages are assigned to field IIIIC (Murray, 1984, p. 467), and hence cannot be used in further paleo-environmental reconstructions.

Results

The Fisher diversity index (α index), representing the assemblage diversity, is high for the lower part of the

Table 1. Quantitative distribution of environmental important benthic foraminiferal taxa from the Weelde (W), Hechtel (He) and Helchteren (Hr) borehole. Grey zones indicate statistically not representative samples.

	Cold										Temperate			Warm			Cold to warm												
Sample depth (m)	<i>Angulogerina</i> spp.	<i>Ehrenbergina variabilis</i>	<i>Hansensica soldanii</i>	<i>Hoeglundina elegans</i>	<i>Karrerietta siphonella</i>	<i>Karrerietta chilotoma</i>	<i>Lenticulina</i> spp.	<i>Melonis affinis</i>	<i>Pullenia</i> spp.	<i>Pyrgo bulloides</i>	<i>Siphonotextularia labiata</i>	<i>Eponides</i> spp.	<i>Globocassidulina subglobosa</i>	<i>Heterolepa dutemplei</i>	<i>Spiroplectinella</i> spp.	<i>Asterigerinoides guerichi guerichi</i>	<i>Canceris auriculus</i>	<i>Elphidium subnodosum</i>	<i>Pararotalia canui</i>	<i>Alabamina</i> spp.	<i>Bolivina</i> spp.	<i>Bulimina elongata</i>	<i>Cibicides</i> spp.	<i>Lagena</i> spp.	<i>Protelphidium roemeri</i>	<i>Textularia</i> aff. <i>gramen</i>	Other taxa	Total benthics counted	
W229.79	41	12					3					2	2	2		2	2	2		2		8	13		6		4	65	
W231.16	24		4						3							20		12		2			9		9		17	105	
W239.28	7		1				1	0								70		4				11	1		1		4	324	
W240.00	3															86		1				9			0		1	256	
W241.81	(2)															(16)											(1)	19	
W243.20	39		1		1		1	3	1							2				3	1	25	4	3			16	399	
W244.27	27		2	2	1		9	3	1			0	0		3					2	19	0		1			30	975	
W248.30	(8)		(4)				(3)																(1)	(1)			(6)	23	
W254.85	11		2		3		30	2	1						6					5			7				33	195	
W255.92			(1)		(3)										(6)								(1)				(11)	22	
W264.24																											(18)	18	
W267.30	13		1	12		0	30		2						22												20	418	
W279.08	42		3		5	1	2	3	2					1	5					3	1		9	2			21	275	
W285.05	30		1	6	4	1	23	0	1						18						1	0	3	0			12	470	
W288.13	(20)		(1)		(1)	(2)	(12)																(2)				(15)	53	
W292.08	27		4	13	2	4	2	1	8						14								6	0			19	336	
W297.08	7		2	1	2	1	2	3	4					1	68								3				6	196	
W301.08	10		5	5					3					5	58								5				9	66	
W305.99	(4)														(5)												(12)	21	
W309.66	29			10				2	2				2		12					8			10				25	89	
W312.06	5			9	1										64					13			6				2	80	
W316.56			2	6	0	0	11		1			0			59						0		13	0			8	238	
W326.04			2						1					26	39								20				12	191	
W334.04				39					1	1				1	13	9				4			14				18	160	
W337.08			1	10	3	2	1	13	16				1	2					10			5					36	229	
W341.80				72										12													3	65	
He210	9		1								1		1			37		3		3	1	1	15		3		25	157	
He215	27													2		34		3				1	14	1	3		15	93	
He218	18						1		1					1		68						1	3				7	146	
He224	14		0		0		1	4	0	0		1	0			53		1		0		6	3	1	1		15	216	
He229	34							3						1		48						5	3		1		5	177	
He233	57		1					3								16			3				1	8			11	149	
He237	26		17				11	8	1						10	1					4	5	3				14	174	
He241	(14)						(3)					(2)											(1)					25	
He245	33		2		0		4	5	2				2	2					0				1				49	290	
Hr112	11	1				0	12	1		2							0	1					19	21	1	9	1	21	279
Hr113	44	1					3			0					2		1					15	18	1	8		7	277	
Hr114	15	4	0			0	11	3		5					2		2		1			14	8	3	14		18	244	
Hr115	13	9	0			3	4			11					2		1	1	2			11	13		11	2	17	209	
Hr116	16	3	1			3	4			9						2						7	18		19	4	14	159	
Hr117	22						5			10								2				6	14	3	26		12	155	
Hr118	28		1				4			2		1		2			1	4				6	11	2	22	2	14	122	
Hr119	10						10			18							2	1		2		2	15	2	9	2	27	130	
Hr121	33		1			1	4			1				1			2	4				2	20	1	13	2	15	136	
Hr122	36					0	3					1		5			1	2	2			1	20	2	9	2	16	384	
Hr123	41						8							2		0	2		1			1	14		4	6	21	98	
Hr124	(18)						(4)	(1)	(6)						(1)								(5)		(4)	(1)	(13)	53	
Hr126	(9)						(1)		(1)						(1)							(1)	(3)		(3)	(1)	(14)	34	
Hr128	(10)								(1)														(2)				(9)	22	
Hr130	(6)																						(1)	(1)	(4)		(2)	14	
Hr133	(7)														(3)							(3)	(4)			(4)	(15)	36	
Hr134	23		1				9									25		1					15	2		1	23	103	
Hr135	(4)					(1)										(4)							(5)		(2)	(1)	(17)	33	
Hr136	(6)					(1)	(4)									(2)			(1)			(1)	(3)	(2)			(5)	25	
Hr137	(4)						(2)									(6)	(3)	(1)					(1)	(4)			(6)	29	
Hr138	(3)		(3)			(1)	(3)					(3)		(3)	(12)							(2)	(2)	(1)			(7)	37	

Rupelian section (for the interval –130 to –90 m: α values vary between 7 and 16) and gradually declines for the upper Rupelian samples (for the interval –90 to 0 m: α values vary between 3 and 7; see Table 2 and Fig. 3). One upper Rupelian sample, i.e. –37 m in the CS, shows an unexpected high α index (see Table 2 and Fig. 3). The Fisher diversity index for the base of the Chattian succession is distinctly lower compared to the Rupelian assemblages (for the interval 0 to 10 m: α values vary between 1 and 4, Fig. 3). Higher up the Chattian, the Fisher diversity index increases again, reaching maximum values around 43 and 48 m in the CS (Fig. 3).

In general, planktonic foraminifera are rare throughout the Oligocene southern North Sea Basin successions. Only in the lower part of the Rupelian section, planktonic foraminifera are more common, and reach maximum values around –118 m in the CS ($P \sim 50\%$, Fig. 3, Table 2). In the upper part of the section, planktonic foraminifera are very rare ($<5\%$), except for 3 levels (–95, –74 and 43 m), showing values around $\sim 17\%$. The Oligocene southern North Sea Basin foraminiferal assemblages are furthermore dominated by hyaline taxa. The porcellaneous component shows slightly higher values in the Chattian as compared to the Rupelian assemblages, whereas non-calcareous agglutinants are more represented within the Rupelian (Fig. 3).

Interpretation

The foraminiferal assemblages from the lower part of the Rupelian successions suggest normal marine shelf conditions (~ 100 m water depth), based on a high Fisher diversity index ($\alpha > 7$) and the proportion of hyaline taxa on the triangular plot (Murray, 1991) (see Fig. 3). The common occurrence of planktonic foraminifera further suggests open marine connections to the oceanic realm (Grimm & Steurbaut, 2001); the maximum abundance of planktonic foraminifera in –118 m coincides with a maximum flooding surface (Vandenberghe et al., 2001). The upper Rupelian foraminiferal assemblages (–90 m to 0 m), showing a lower diversity index and rare planktonic foraminifera, suggest a gradual shallowing of a poorly ventilated and more isolated marine environment (Van Simaëys et al., 2004). The increased assemblage diversity around –37 m (α index = 10), coinciding with the recurrence of several dinocyst taxa and the first occurrence of some calcareous nannoplankton species (Van Simaëys et al., 2004), suggests a renewed opening of a marine pathway and the inflow of well-oxygenated water masses, re-installing normal marine conditions. The basal Chattian foraminiferal

assemblage suggests marginal marine to brackish-marine conditions, with water depths not exceeding 20 m. The glauconiferous sandy substrate points towards increased hydrodynamic energy compared to the upper Rupelian successions. Higher up the Chattian, conditions return to a normal marine environment.

Paleotemperature: results and interpretation

Evaluation of the encountered taxa

Temperature delineation for the different ecogroups and – if specified – for different taxa is based on values listed in literature (see Fig. 2). In case different temperature-ranges were listed for the same taxon, the maximum range was taken into account and used in the equation of Lommerzheim (1991) (see above). Extinct taxa (e.g. *Rotaliatina*) and taxa with no clear or unknown affinity towards specific climatic conditions (e.g. nodosariids) are grouped as ‘other taxa’ (see Table 1) and are not used in the present paleo-environmental analysis.

Asterigerinoides guerichi guerichi, originally described as *Asterigerina guerichi* Franke, 1912, is here considered to have the same paleoecological preferences as the genus *Asterigerina*. The latter genus is reported as an inner shelf species occurring in subtropical to tropical conditions (Murray, 1991, p. 288 & p. 323). *Asterigerinoides* is reported from late Eocene sections in northern Italy, with presumed water temperatures exceeding 22°C (Murray, 1991, p. 308). In the late Oligocene North Sea Basin successions, *Asterigerinoides guerichi guerichi* co-occurs with *Miogypsina* (Anderson et al., 1971), a larger foraminifera, clearly favouring warm subtropical conditions. The affinity of *Pararotalia* towards warm conditions is confirmed by Lauriat-Rage et al. (1993); this taxon is believed to have a temperature preference between 15 and 25°C. Also the keeled *Elphidium subnodosum* is regarded as a typical shelf species, favouring warm conditions (Murray, 1991, p. 129 & p. 324).

Globocassidulina subglobosa is listed as a cold temperate to temperate species in modern faunas, occurring in water masses between 4 and 20°C (Murray, 1991, p. 80 & p. 159). In Oligocene times, however, this species tends to prefer much warmer conditions (see e.g. Wood et al., 1985 and Corliss, 1981). The same holds true for both *Eponides* spp. and *Heterolepa dutemplei*. In modern faunas these species have affinity towards cold temperate to temperate conditions, while during the Oligocene, these species frequently occur in subtropical regions.

Table 2. Foraminiferal paleoenvironment parameters for the Oligocene southern North Sea Basin successions. Sample depth refers to the exact depth in the appropriate borehole or outcrop section (Hr: Helchteren borehole; He: Hechtel borehole; W: Weelde borehole; TW: Terhagen West; SN: Sint Niklaas). Counts not exceeding 100 specimens per sample are indicated in grey.

Sample depth (m)	CS (m)	Total benthics counted	Number of species	α - index	% hyaline	% porcellaneous	% calcareous agglutinants	% non calcareous agglutinants	P %
Hr112	50	279	26	7	92	5	2	1	0
Hr113	49	277	20	5	97	1	2	0	0
Hr114	48	244	31	10	91	2	7	0	0
Hr115	47	209	29	9	82	3	13	2	1
Hr116	47	159	20	6	84	3	9	4	3
W 229	46	65	19	7	98	0	2	0	12
Hr117	45	155	17	5	86	3	10	0	0
Hr118	44	122	22	8	92	3	3	2	2
Hr119	43	130	27	11	74	5	19	2	16
Hr121	41	136	23	9	90	4	3	2	4
Hr122	40	384	32	9	89	5	4	2	2
Hr123	39	98	20	7	87	5	2	6	6
Hr124	38	53							
Hr126	36	34							
W 231	30	105	18	6	100	0	0	0	4
Hr134	28	103							1
He210	26	157	23	7	95	4	1	0	6
Hr138	25	37							
He215	20	93	14	4	97	1	2	0	1
He218	18	146	13	3	98	1	1	0	0
He224	12	216	26	7	97	2	1	0	1
He229	7	177	11	3	100	0	0	0	1
W 239	3	324	15	3	100	0	0	0	0
He233	3	149	15	4	99	1	0	0	4
W 240	2	256	6	1	100	0	0	0	0
W 241	1	19							
W 242	0	0							
W 243	-1	399	26	6	97	1	1	1	1
He237	-1	174	20	6	90	0	10	0	1
W 244	-2	975	36	7	95	0	4	1	2
He241	-5	25			100				4
W 248	-6	23			100				
He245	-9	290	19	5	98	0	2	0	1
W 252	-10	0			100				0
W 254	-12	195	24	7	92	0	5	3	3
W 260	-18	0			100				
W 267	-25	418	14	3	77	0	22	0	0
W 272	-30	0			100				
W 276	-34	0			100				
W 279	-37	275	34	10	87	1	6	6	1
W 285	-43	470	23	5	77	0	17	6	0
W 288	-46	53			100				
W 292	-50	336	22	5	79	1	14	6	1
W 297	-55	196	20	5	27	1	69	3	2

Sample depth (m)	CS (m)	Total benthics counted	Number of species	α - index	% hyaline	% porcellaneous	% calcareous agglutinants	% non calcareous agglutinants	P %
W 301	-59	66			100				
W 305	-64	21			100				
W 309	-67	89	11	3	88	0	12	0	0
W 312	-70	80	8	3	34	1	65	0	0
W 316	-74	238	26	8	39	1	59	1	19
W 322	-80	3			100				
W 326	-84	191	13	3	61	0	39	0	0
W 334	-92	160	12	3	83	8	9	0	4
W 337	-95	229	22	6	92	2	0	6	21
TW 51	-103.5	100	24	11	100	0	0	0	21
W 341	-105	65			100				
TW 46	-108	100	14	4,5	100	0	0	0	1
TW 43	-110.5	100	21	8	98	0	1	1	13
TW 41	-112.5	100	16	5	99	0	0	1	9
TW 18	-118	100	25	11	92	0	8	0	87
TW 16	-118.2	100	26	11	86	1	12	1	43
TW 15	-118.4	100	23	10	95	0	5	0	26
TW 14	-118.7	100	26	11	93	0	7	0	7
TW 13	-119	100	22	8	95	0	5	0	60
TW 12	-120	100	28	13	66	0	31	3	23
TW 11	-120.5	100	20	7	93	0	6	1	34
TW 10	-121	100	24	10	90	0	7	3	44
TW 9	-121.5	100	28	13	88	1	11	0	21
TW 8	-122	100	29	14	93	0	5	2	29
TW 8b	-123	100	21	8	95	0	5	0	34
TW 7	-124	100	25	11	97	1	1	1	34
TW 6	-124.5	100	29	13	96	0	4	0	3
TW 5	-125.5	100	28	12	92	0	8	0	5
TW 4	-126	100	26	11	93	0	6	1	3
TW 3	-126.4	100	26	11	92	0	6	2	3
TW 2	-126.7	100	26	11	93	0	6	1	2
TW 1	-127	100	22	8	84	0	15	1	11
TW 35	-127.3	100	20	7	97	0	3	0	46
TW 34	-127.5	100	24	10	94	0	1	5	24
SN 11	-128	100	22	9	88	0	10	2	63
TW 33	-128.5	100	26	12	90	0	8	2	2
SN 10	-129	100	27	12	80	0	17	3	1
SN 9	-129.5	100	29	13	97	0	3	0	12
TW 31	-130	100	17	6	96	0	4	0	0
SN 8	-131	100	23	7	95	0	4	1	7
SN 7	-132	100	20	7	93	0	6	1	6
SN 5	-134	100	32	16	86	0	10	4	26
SN 3	-138	100	26	13	86	0	10	4	17

Angulogerina spp., often used in synonymy with *Trifarina* spp., nowadays occurs in water masses with temperatures between 4 and 11°C (Murray, 1991,

p. 251). From the Southern Ocean, this genus is even recorded in shelf deposits with water temperatures between -2 and 1°C (Murray, 1991, p. 274). Other

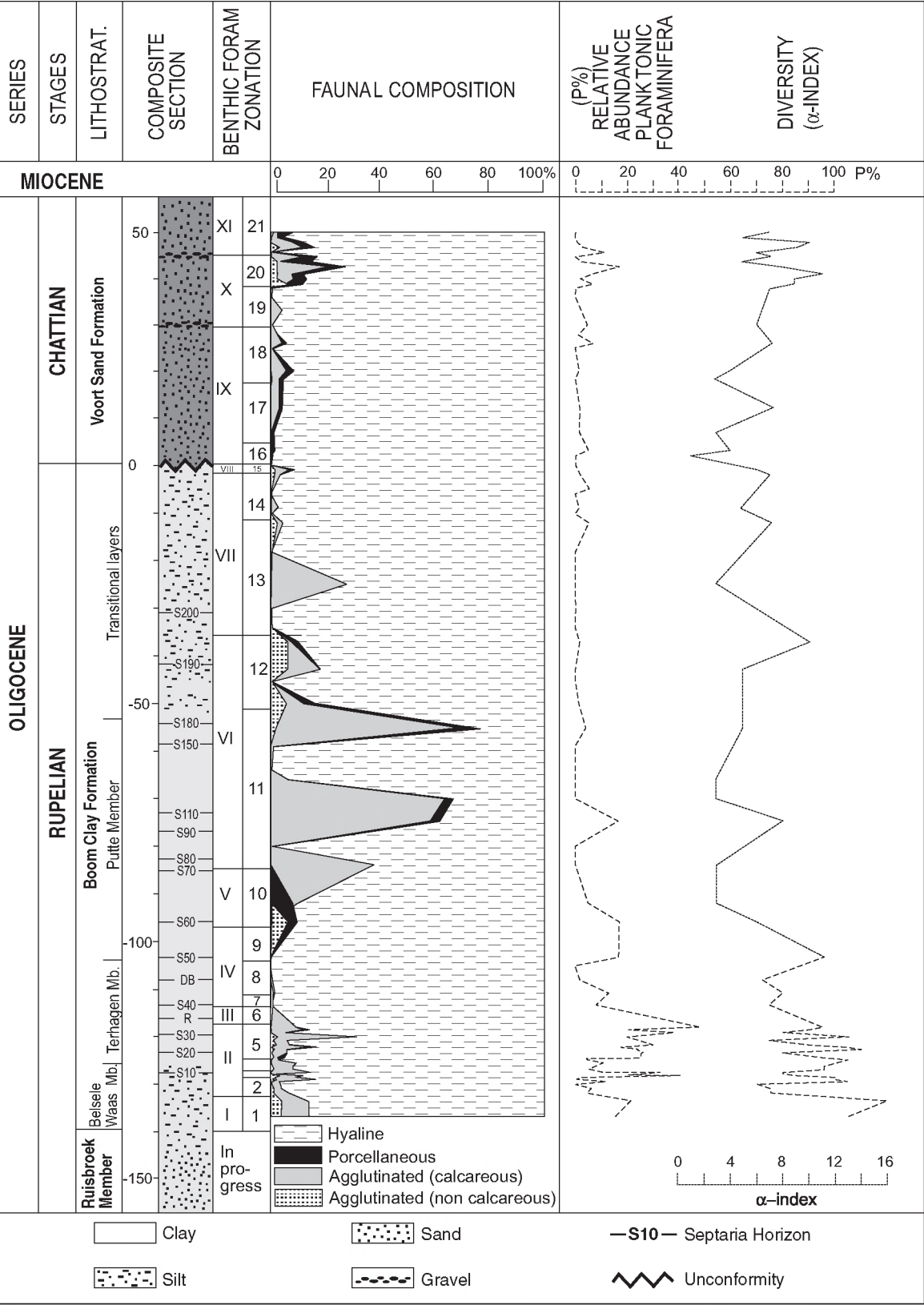


Fig. 3. Foraminiferal paleoenvironment parameters for the Oligocene southern North Sea Basin successions. Composite section and benthic foram zonation after De Man et al., 2004. Data from the outcrop section (up to S50) by Hooyberghs et al. (1992). Counts not exceeding 100 specimens per sample are indicated by dashed lines.

recent cold water taxa (e.g. *Karreriella*, *Lenticulina*, *Pullenia* and *Pyrgo*) generally occur in water masses with temperatures not exceeding 10°C.

The distribution of the genus *Protelphidium*, of which the modern representative is thought to be *Haynesina* (Murray, 1991, p. 136 & p. 309), is primarily related to salinity. However, optimum temperature conditions for this genus are between 15 and 20°C.

Results

A paleotemperature curve, based on the benthic foraminiferal assemblage for each sample and using the equation as explained above, has been constructed for the Oligocene southern North Sea Basin successions (Fig. 4). In general, the Rupelian assemblages are dominated by cold to cold-temperate taxa (i.e.

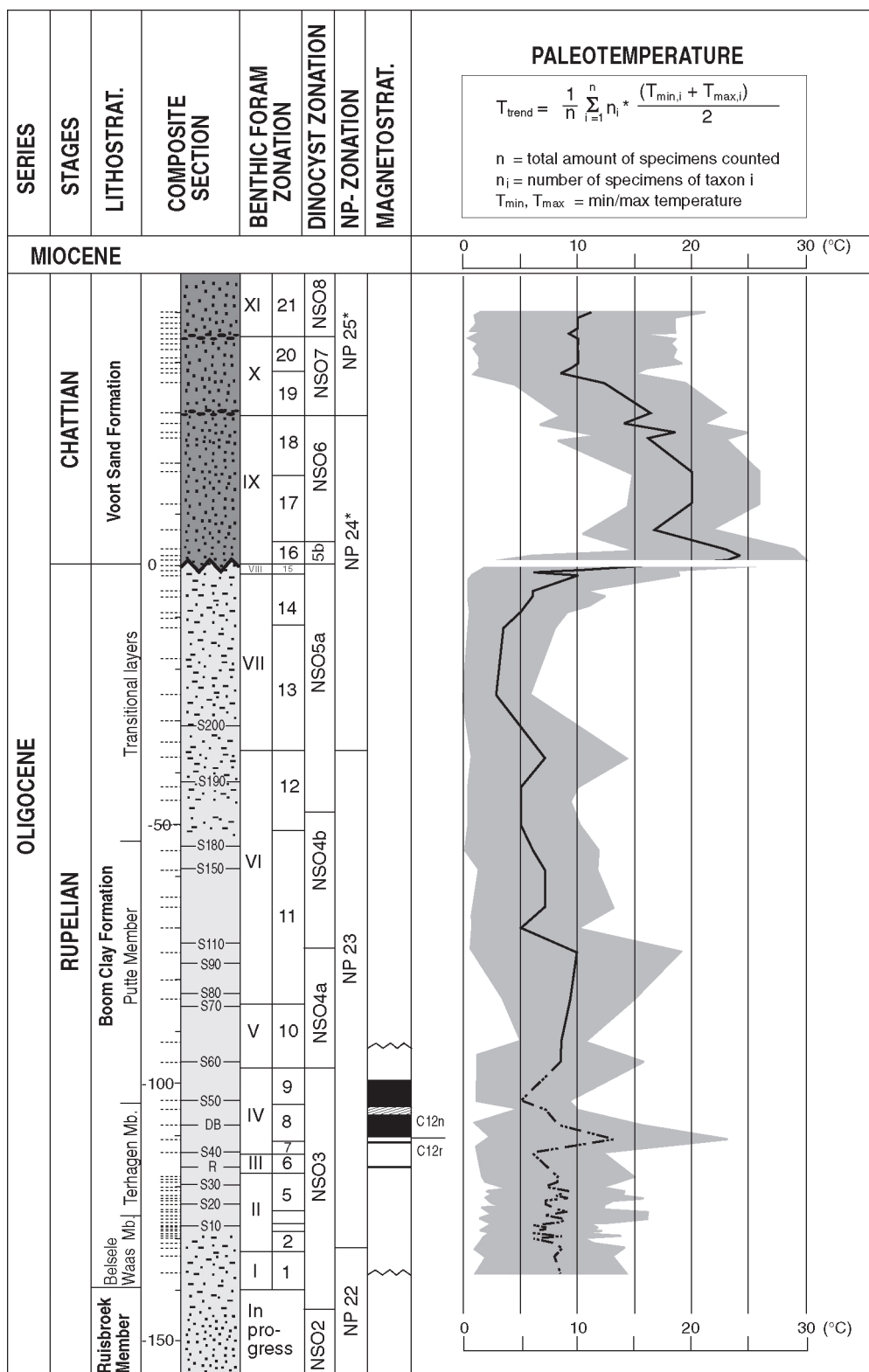


Fig. 4. Benthic foraminiferal paleotemperature curve for the Oligocene southern North Sea Basin successions. Grey zone indicates the reliability interval, as calculated from minimum and maximum values for the temperature range of taxa. Composite section and benthic foraminifer zonation after De Man et al., 2004; NP*-zonation after Van Simaey et al., 2004; dino-cyst zonation after Van Simaey et al., in press; magnetostratigraphy after Vandenberghe et al., 2001. Counts not exceeding 100 specimens per sample are indicated by a dashed line. Legend as in Fig. 3.

Lenticulina, *Pullenia*, *Hoeglundina*, *Spiroplectinella*, *Hansenisca*, *Angulogerina*, etc.), and the calculated bottom water paleotemperatures never exceed 10°C (Fig. 4). Some rare Rupelian samples (i.e., –110 m, –74 m and –37 m in the CS), however, are characterised by both cold- and warm temperate taxa (e.g., *Quinqueloculina* and *Bolivina*) and hence show slightly higher bottom water paleotemperatures. The base of the Chattian, on the contrary, is characterised by abundant warm temperate, tropical to subtropical taxa (i.e. *Asterigerinoides*, *Elphidium*, *Cancris*) and the calculated bottom water paleotemperatures exceed 20°C (Fig. 4). Higher up the Chattian, the warm temperate to subtropical species are less abundant, and cold-temperate taxa (i.e. *Angulogerina*, *Lenticulina*, *Melonis*, *Ehrenbergina*) become more frequent.

Interpretation

The most obvious climate change recognised in the Oligocene southern North Sea Basin successions is the major warming-event associated with the basal Chattian sediments. Although the attributed equation should not be used for determining absolute paleotemperatures, it is clear that the cold to cold-temperate Rupelian benthic foraminiferal assemblages are in strong contrast with the tropical to subtropical fauna as recorded from the basal Chattian sediments.

A Late Oligocene Warm Episode?

As the marked tropical to subtropical conditions for the basal Chattian sediments in the southern North Sea Basin clearly conflict with the general perception of a long-termed, pervasive global deterioration of the Paleogene climate, our findings need to be considered with caution. Do the tropical to subtropical Chattian deposits at Northern Hemisphere mid latitudes indicate temporal climate amelioration, or are these results biased by the simultaneous shallowing of the environment?

Other records of Late Oligocene warm temperate to subtropical conditions in the southern North Sea Basin have been documented in both the marine and continental realm. Estimated paleotemperatures, based on benthic foraminiferal assemblages from the Chattian unit-stratotype, i.e. the Doberg section in NW-Germany (Fig. 5), reveal annual average temperatures between 14°C and 19°C (Kohnen, 1995). Moreover, from the middle part of the Doberg section, Anderson et al. (1971) reports on the presence of

Miogypsina septentrionalis, a larger foraminifer, indicating tropical to subtropical conditions (Murray, 1973; Murray, 2002). Chattian *Hiatella arctica* molluscs from the well calibrated Kapellen and Rossenray profiles (Fig. 5; see also Ellermann, 1958; Indans, 1958) yield summer temperatures¹ between 26.5 and 27°C, while winter temperatures range between 20.5°C and 24.5°C (Strauch, 1968). The unexpected high paleotemperatures for the lower Chattian deposits, as calculated in our study, are within the range the previous paleotemperature reconstructions for the southern North Sea Basin.

Two localities from the southernmost margin of the Lower Rhine Embayment (Fig. 5) further yield substantial data on the Late Oligocene climatic conditions. The lake Rott sequence – consisting of lagoonal to lacustrine clay and brown coal deposits – belongs to the upper part of MP30 (Mörs, 2002) and hence has an approximate age of ~24 Ma (Utescher et al., 2000). The Enspel locality yields a rich and diversified flora containing fruits, seeds and leaves; a radiometric date of 25.8 Ma (or MP 28, Storch et al., 1996) indicates a Late Oligocene age. From these localities, Utescher et al. (2000) reconstruct the terrestrial paleoclimate, by using the coexistence approach on different paleobotanical records. The authors calculate Mean

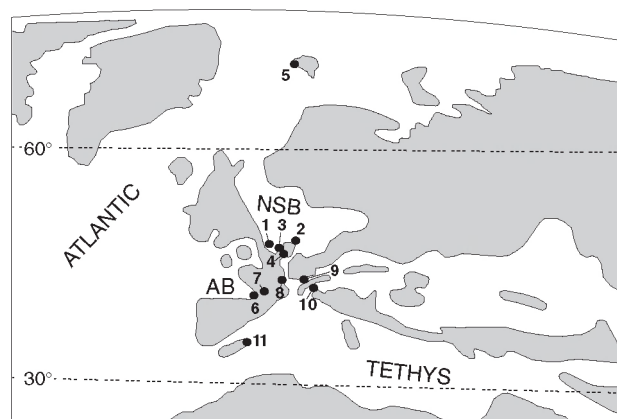


Fig. 5. Location of other Late Oligocene warm to subtropical records. 1. Rupelian unit stratotype (this study); 2. Chattian unit stratotype (Anderson et al., 1971; Kohnen, 1995); 3. Lower Rhine Embayment, i.e. Kapellen and Rossenray sections (Strauch, 1968); 4. Southernmost part of Lower Rhine Embayment, i.e. Lake Rott and Enspel (Schwarzbach, 1952; Utescher et al., 2000; Mörs, 2002); 5. Spitsbergen (Feyling-Hanssen & Ulleberg, 1984); 6. Aquitaine Basin (Lauriat-Rage et al., 1993; Antunes & Cahuzac, 1999); 7. Aquitaine molasse basin (Astruc et al., 2003); 8. Swiss Molasse (Berger, 1998); 9. Bavarian folded molasse (Uhlir et al., 2000); 10. Slovenian Sava Basin (Bruch & Mosbrugger, 2002); 11. Mallorca (Ramos et al., 2001). Paleogeographic map modified from Ziegler (1990), Scotese & Golanka (1992) and Sissingh (2003).

¹ By investigating the numerical distribution, shell form and growth of recent *Hiatella arctica*, Strauch (1968) deduced quantitative temperature data from size measurements of adult fossil populations.

Annual Temperatures (MAT) of 15.7–16.8°C for Enspel and 16.5–20.8°C for lake Rott; while the Warm Month Mean (WMM) for both localities respectively lies around 25°C and between 26–28°C. The authors (Utescher et al., *ibid.*) interpret both the Enspel and lake Rott flora as to be deposited during very warm conditions. The warm nature of the lake Rott flora is furthermore supported by the remains of tropical palms (Schwarzbach, 1952) and the rich vertebrate fauna, containing crocodiles, snakes, Rhinocerotidae and Marsupialia (von Koeningswald & Mosbrugger, 1989; Mörs, 1995, 1996, 2002). Feyling-Hanssen & Ulleberg (1984) report on a peculiar benthic foraminiferal assemblage from Sarsbukta, Spitsbergen (Fig. 5): up to ~10–20% of the benthic foraminifera consist of *Asterigerinoides* cf. *guerichi*; hence this association can tentatively be attributed to the early Chattian ‘*Asterigerina*-Horizon’. Recent representatives of this genus, however, show clear affinity to shallow, warm temperate to subtropical conditions (Fig. 2). This observation suggests much warmer conditions on Spitsbergen during the Late Oligocene as compared to the present Arctic climate.

Several other studies report on Late Oligocene warm temperate to subtropical conditions in NW Europe: in the Aquitaine Basin (SW France, see Fig. 5), the Escornebeou sections have been ascribed to the Chattian based on the reported P22 (planktonic foraminifera), the NP25 (nannoplankton) calcareous microfossil assemblages (Antunes & Cahuzac, 1999) and based on Sr-dating (foraminiferal tests are dated as 25.8 Ma $\pm$ 0.31 Ma, Cahuzac et al., 1997). The warm, at least subtropical climate during the deposition of these Chattian successions is inferred from the presence of Tomistomine crocodilians, which cannot live at temperatures lower than 10°C as a minimum during the coldest season (Antunes & Cahuzac, 1999). Other climate indicators, pointing towards warm, tropical conditions, are the presence of numerous larger foraminifera (i.e. *Nummulites bouillei*² and *Miogyopsinoides*), the abundance of hermatypic corals (>120 species), echinoids, molluscs and sharks³; for an overview see Lauriat-Rage et al. (1993). Also the vertebrate fauna from the Aquitaine molasse basin (Fig. 5) reveals several taxa with affinities to warm conditions: Astruc et al. (2003) reports on vertebrate bearing localities with Rhinocerotidae in MP25/26 (early Chattian) and crocodile-, lizard-, snake- and Marsupialia remains assigned to MP26 (Chattian).

From the Swiss Molasse (Fig. 5), Berger (1998) reports on the ‘Rochette’ fossil assemblage, of which the ‘warm character’ is clearly indicated by the abundance of *Lygodium*⁴ and by the large size of the turtles and crocodiles. These Lower Freshwater Molasse localities are dated by mammals (MP29, ~25.5 Ma according to Berger, 1992) and charophytes (*notata* zone, Late Oligocene). Uhlig et al. (2000) report on tropical, estuarine environments with mangrove vegetation from the Lower Cyrena Beds in the Bavarian folded molasse (Fig. 5). These beds correspond to the upper part of mammal zone MP24 and hence can be attributed to the lower Chattian. Bruch & Mosbrugger (2002) reconstruct the Late Oligocene paleoclimate in the Slovenian Sava Basin (Fig. 5) and document warm temperate, humid climate conditions with low annual variation. Ramos et al. (2001) report on the presence of crocodile and turtle remains (mean monthly temperature ~20°C) and elements of rain forest vegetation⁵ from the Late Oligocene lacustrine Cala Blanca Formation, Mallorca (Fig. 5). Stratigraphic age control is based on charophytes, palynomorphs and rodent fossil remains (Ramos et al., 2001).

From this, and previous studies – using independent tools of paleoclimate reconstruction – it becomes clear that warm to tropical conditions emerged during the Late Oligocene in NW-Europe. This widespread major warming pulse suggests correlation with the global Late Oligocene Warming Event (LOWE, Zachos et al., 2001); this assumption is supported by dinoflagellate cyst correlations (Van Simaey, 2004). The LOWE – calibrated against magnetochron C8 – induced a major sea level rise, which seems to be genetically related to the early Chattian transgression in the southern North Sea Basin (Van Simaey, 2004).

Quantitative data from Northern Hemisphere mid latitude Oligocene deposits is limited, poorly calibrated (Buchardt, 1978), or altered by diagenesis (Attendorn, 1995). Detailed oxygen isotope analysis on benthic foraminifera and incrementally sampled otoliths and bivalves from Belgian Oligocene deposits should enable recognition of the Late Oligocene Warming Event in the stratotype regions (De Man et al., *in prep.*).

² Recent *Nummulitidae* occur in tropical conditions with sea surface temperatures between 24–34°C (Langer & Hottinger, 2000).

³ i.e. Carcharhiniforms, suggesting at least moderately warm waters (Antunes & Cahuzac, 1999).

⁴ Leaves of a lower vascular plant of which the recent *Lygodium palmatum* is found in Florida (Berger, 1998).

⁵ i.e. *Sabal*, *Sapindus*, *Ficus*.

Conclusions

Quantitative analysis of benthic foraminifera from several boreholes throughout the Oligocene southern North Sea Basin successions enables the reconstruction of both paleoenvironment and paleoclimate changes associated with the Rupelian-Chattian transition in their type region.

By determining the Fisher α diversity index, the proportion of hyaline, porcellaneous and agglutinated taxa, and the relative abundance of planktonic foraminifera (P%), it is shown that the lower part of the Rupelian is characterised by normal marine shelf conditions with temporal open connections towards the ocean realm and water depths around 100 m. The upper Rupelian successions show a gradual shallowing and the realisation of a poorly ventilated and more isolated marine environment. The base of the Chattian sequence, on the contrary, is characterised by marginal marine to brackish-marine conditions, with water depths not exceeding 20 m. Higher up the Chattian successions, conditions return to a normal marine environment.

A major climate change coincides with the Rupelian-Chattian unconformity in the southern North Sea Basin: the unexpected tropical to subtropical benthic foraminiferal assemblages from the basal Chattian sediments in the southern North Sea Basin are in strong contrast with the cold to cold-temperate Rupelian fauna. Previous studies – using independent tools of paleoclimate reconstruction – confirm that warm to tropical conditions emerged during the Late Oligocene in NW-Europe. This widespread major warming pulse suggests correlation with the global Late Oligocene Warming Event (LOWE, Zachos et al., 2001); an assumption supported by dinoflagellate cyst correlations (Van Simaëys, 2004).

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References

- Anderson, A.J., Hinch, W., Martini, E., Müller, C. & Ritzkowski, S., 1971. Chattian. *Giornale di Geologia* 37(2): 69-79.
- Antunes, M. & Cahuzac, B., 1999. Crocodilian faunal renewal in the Upper Oligocene of Western Europe. *Comptes rendus de l'académie des sciences serie II Fascicule A-Sciences de la terre et des planètes* 328(1): 67-72.
- Astruc, J.-G., Hugueney, M., Escarguel, G., Legendre, S., Rage, J.-C., Simon-Coinçon, R., Sudre, J. & Sigé, B., 2003. Puycelci, a new vertebrate-bearing locality in the Aquitaine molassic basin. Density and continuity of the Paleogene biochronologic record in the Quercy and peripheral basins area. *Geobios* 36(6): 629-648.
- Attendorn, 1995. $\delta^{13}\text{C}$ und $\delta^{18}\text{O}$ -Isotopenverhältnisse von Pectiniden des Chatt der Niederrheinischen Bucht, NW-Deutschland. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen* 198(1/2): 223-232.
- Beckmann, J.P., 1953. Die Foraminiferen der Oceanic Formation (Eocaen-Oligocaen) von Barbados, Kl. Antillen. *Eclogae Geologicae Helveticae* 46(2): 301-412.
- Berger, J.-P., 1992. Correlative chart of the European Oligocene and Miocene: Application to the Swiss Molasse Basin. *Eclogae Geologicae Helveticae* 85(3): 573-609.
- Berger, J.-P., 1998. 'Rochette' (Upper Oligocene, Swiss Molasse): a strange example of a fossil assemblage. *Review of Palaeobotany and Palynology* 101: 95-110.
- Bohaty, S. & Zachos, J.C., 2003. Significant Southern Ocean warming event in the late middle Eocene. *Geology*, 31(11): 1017-1020.
- Bruch, A.A. & Mosbrugger, V., 2002. Palaeoclimate versus vegetation reconstruction – palynological investigations on the Oligocene sequence of the Sava Basin, Slovenia. *Review of Palaeobotany and Palynology* 122: 117-141.
- Buchardt, B., 1978. Oxygen isotope palaeotemperatures from the Tertiary period in the North Sea area. *Nature* 275: 121-123.
- Cahuzac, B., Turpin, L. & Bonhomme, P., 1997. Sr isotope record in the area of the Lower Miocene historical stratotypes of the Aquitaine Basin (France). In: Montanari, A., Odin, G.S., Coccioni, R. (eds), *Miocene stratigraphy: an integrated approach. Developments in Paleontology and Stratigraphy*. Elsevier (Amsterdam): 33-56.
- Corliss, B.H., 1981. Deep-sea benthonic foraminiferal faunal turnover near the Eocene/Oligocene boundary. *Marine Micro-paleontology* 6: 367-384.
- De Man, E., Van Simaëys, S., De Meuter, F., King, C. & Steurbaut, E., 2004. Oligocene benthic foraminiferal zonation for the southern North Sea Basin. *Bulletin van het Koninklijk Belgisch Instituut voor Natuurwetenschappen – Aardwetenschappen* 74 supplement: 177-195.
- De Man, E., Vandenberghe, N., Van Simaëys, S. & Ivany, L., in preparation. $\delta^{18}\text{O}$ record of the Rupelian-Chattian boundary in NE Belgium.
- Doppert, J.W.C. & Neele, N.G., 1983. Biostratigraphy of marine Paleogene deposits in the Netherlands and adjacent areas. *Mededelingen Rijks Geologische Dienst* 37(2): 4-79.
- Ellermann, C., 1958. Die mikrofaunistische Gliederung des Oligozäns im Schacht Kapellen bei Moers (Niederrhein). *Fortschritte Geologie von Rheinland und Westfalen* 1: 205-214.
- Feyling-Hanssen, R.W. & Ulleberg, K., 1984. A Tertiary-Quaternary section at Sarsbukta, Spitsbergen, Svalbard, and its foraminifera. *Polar Research* 2 n.s.: 77-106.

- Grimm, K.I. & Steurbaut, E., 2001. Foraminiferal biofacies analysis of the Boom Clay in the Rupel area (Oligocene, Belgium) and correlation with the Mainz Basin (Germany). *In*: N. Vandenberghe (ed), Contributions to the Paleogene and Neogene Stratigraphy of the North Sea Basin. Aardkundige Mededelingen 11. Leuven University Press, Leuven: 9-20.
- Haake, F.-W., 1962. Untersuchungen an der Foraminiferen-Fauna im Wattengebiet zwischen Langeoog und dem Festland. *Meyniana* 12: 25-64.
- Hofker, J., 1977. The foraminifera of dutch tidal flat and salt marches. *Netherlands Journal of Sea Research* 11(3/4): 223-296.
- Hooyberghs, H., Vercauteren, T., De Meuter, F. & Symons, F., 1992. Foraminiferal studies in the Boom Formation. Ministerie van Economische Zaken, Belgische Geologische Dienst, Professional paper 8(258): 1-46.
- Indans, J., 1958. Mikrofaunistische Korrelationen im marinen Tertiär der Niederrheinischen Bucht. *Fortschritte Geologie von Rheinland und Westfalen* 1: 223-238.
- Indans, J., 1965. Nachweis des Asterigerinen-Horizontes im Oberoligozän des Dobergs bei Bünde/Westfalen. *Neues Jahrbuch Geologie und Paläontologie, Abhandlungen* 123(1): 20-24.
- Ivany, L.C., Nesbitt, E.A. & Prothero, D.R., 2003. The marine Eocene-Oligocene transition: a synthesis. *In*: Prothero, D.R., Ivany, L.C. & Nesbitt, E.A. (eds), From Greenhouse to Icehouse. The marine Eocene-Oligocene transition. Columbia University Press, New York: 522-534.
- Jarke, J., 1961. Die Beziehungen zwischen hydrographischen Verhältnissen, Faziesentwicklung und Foraminiferenverbreitung in der heutigen Nordsee als Vorbild für die Verhältnisse während der Miocän-Zeit. *Meyniana* 10: 21-36.
- King, C., 1983. Cainozoic micropalaeontological biostratigraphy of the North Sea. Report Institute of Geological Sciences 82(7): 1-40.
- King, C., 1989. Cenozoic of the North Sea. *In*: D.G. Jenkins & J.W. Murray (eds), Stratigraphical atlas of fossil foraminifera. British micropalaeontological society series. Ellis Horwood Limited (Chichester): 418-489.
- Kohnen, O., 1995. Paläotemperaturen aus dem Oberoligozän des Norddeutschen Beckens. *Neues Jahrbuch für geologie und paläontologie – Abhandlungen* 198(1/2): 233-241.
- Langer, M. & Hottinger, L., 2000. Biogeography of selected larger foraminifera. *Micropaleontology* 46(1): 105-126.
- Lauriat-Rage, A., Brébion, Ph., Cahuzac, B., Chaix, Ch., Ducasse, O., Ginsburg, L., Janin, M.-C., Lozouet, P., Margerel, J.-P., Nascimento, A., Pais, J., Poignant, A., Pouyet, S. & Roman, J., 1993. Palaeontological data about the climatic trends from Chattian to present along the Northeastern Atlantic frontage. *Ciencias da Terra, Universidade Nova Lisboa* (1st Congress R.C.A.N.S., Lisboa, 1992) 12: 167-179.
- Lommerzhim, A., 1991. Mikropaläontologische Indikatoren für Paläoklima und Paläobathymetrie in der borealen Oberkreide: Bohrung Metelen 1001. *Facies* 24: 183-254.
- Miller, K.G., Fairbanks, R.G. & Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion. *Paleoceanography* 2(1): 1-19.
- Miller, K.G., Feigenson, M.D., Wright, J.D. & Clement, B.M., 1991. Miocene isotope reference section, Deep Sea Drilling Project site 608: an evaluation of isotope and biostratigraphic resolution. *Paleoceanography* 6(1): 33-52.
- Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sogerman, P.J., Christie-Blick, N., Katz, M.E. & Wright, J.D., 1998. Cenozoic global sea level, sequences, and the New Jersey transect: results from coastal plain and continental slope drilling. *Reviews of Geophysics* 36(4): 569-601.
- Mörs, T., 1995. Die Sedimentationsgeschichte der Fossilagerstätte Rott und ihre Alterseinstufung anhand neuer Säugetierfunde (Oberoligozän, Rheinland). *Courier des Forschungs-Instituts Senckenberg* 187: 101-115.
- Mörs, T., 1996. Die Säugetiere der oberoligozänen Fossilagerstätte Rott bei Bonn (Rheinland). *Decheniana* 149: 205-232.
- Mörs, T., 2002. Biostratigraphy and paleoecology of continental Tertiary vertebrate faunas in the Lower Rhine Embayment (NW-Germany). *Netherlands Journal of Geosciences* 81(2): 177-183.
- Murray, J.W., 1973. Distribution and ecology of living benthic foraminifera. Heinemann, London, 274 pp.
- Murray, J.W., 1976. A method of determining proximity of marginal seas to an ocean. *Marine Micropaleontology*, 22: 103-119.
- Murray, J.W., 1984. Benthic Foraminifera: some relationships between ecological observations and palaeoecological interpretations, Benthos '83; 2nd Int. Symp. Benthic Foraminifera, Pau, April 1983: 465-469.
- Murray, J.W., 1991. Ecology and Palaeoecology of benthic foraminifera. Longman Scientific and Technical, New York, 341 pp.
- Murray, J.W., 2002. Introduction to benthic foraminifera. *In*: Haslett, S.K. (ed) Quaternary environmental micropalaeontology. Arnold, London: 5-13.
- Ramos, E., Cabrera, L., Hagemann, H.W., Pickel, W. & Zamarreño, I., 2001. Palaeogene lacustrine record in Mallorca (NW Mediterranean, Spain): depositional, palaeogeographic and palaeoclimatic implications for the ancient southeastern Iberian margin. *Palaeogeography, Palaeoclimatology, Palaeoecology* 172: 1-37.
- Schwarzbach, M., 1952. Aus der Klimageschichte des Rheinlandes. *Geologische Rundschau* 40: 128-136.
- Scotese, C.P. & Golanka, J., 1992. Paleogeographic atlas, PALEOMAP progress report 20-0692. Arlington, University of Texas: 34 pp.
- Sissingh, W., 2003. Tertiary paleogeographic and tectonostratigraphic evolution of the Rhenish Triple Junction. *Palaeogeography, Palaeoclimatology, Palaeoecology* 196: 229-263.
- Storch, G., Engesser, B. & Wuttke, M., 1996. Oldest fossil record of gliding in rodents. *Nature* 379: 439-441.
- Strauch, F., 1968. Determination of Cenozoic sea-temperatures using *Hiatella arctica* (Linné). *Palaeogeography, Palaeoclimatology, Palaeoecology* 5: 213-233.
- Uhlig, U., Reichenbacher, B. & Bassler, B., 2000. Mammals, fish otoliths and charophytes from the Lower Cyrena Beds (Oligocene) of the folded molasse of Bavaria (Murnau syncline). *Eclogae Geologicae Helvetiae* 93(3): 503-516.
- Ulleberg, K., 1987. Foraminiferal zonation of the Danish Oligocene sediments. *Bulletin geological Society Denmark* 36: 191-202.
- Utescher, T., Mosbrugger, V. & Ashraf, A.R., 2000. Terrestrial Climate Evolution in Northwest Germany Over the Last 25 Million years. *Palaios* 15: 430-449.
- Vandenberghe, N., Hager, H., Van Den Bosch, M., Verstraelen, A., Leroi, S., Steurbaut, E., Prüfert, J. & Laga, P., 2001. Stratigraphic Correlation by calibrated well logs in the Rupel Group between North Belgium, the Lower-Rhine area in Germany and Southern Limburg and the Achterhoek in The Netherlands with list of figures and in annex correlation plates. *In*: N. Vandenberghe (ed), Contributions to the Paleogene and Neogene Stratigraphy of the North Sea Basin. Aardkundige Mededelingen 11. Leuven University Press, Leuven: 69-84.
- Van Simaey, S., 2004. The Rupelian-Chattian boundary in the North Sea Basin and its calibration to the international time-scale. *Netherlands Journal of Geosciences / Geologie en Mijnbouw* 83(3): 241-248.

- Van Simaey, S., De Man, E., Vandenberghe, N., Brinkhuis, H. & Steurbaut, E., 2004. Stratigraphic and palaeoenvironmental analysis of the Rupelian-Chattian transition in the type region: evidence from dinoflagellate cysts, foraminifera and calcareous nannofossils. *Palaeogeography, Palaeoclimatology, Palaeoecology* 208: 31-58.
- Van Simaey, S., Brinkhuis, H., Pross, J., Williams, G. & Zachos, J., submitted. Arctic dinoflagellate migration marks the Mid Oligocene Climatic Minimum. *Geology*.
- Van Simaey, S., Munsterman, D. & Brinkhuis, H., in press. Oligocene dinoflagellate cyst biostratigraphy of the southern North Sea Basin. *Review Palaeobotany and Palynology*.
- Von Koeningswald, W. & Mosbrugger, V., 1989. Rott im Überblick. In: W. Von Koeningswald (ed), *Die Fossilagerstätte Rott bei Hennef im Siebengebirge*. Rheinlandia, Siegburg: 81-82.
- Wong, T.E., 1976. Tertiary stratigraphy and micropaleontology of the Guiana Basin. *Geologie en Mijnbouw Dienst Suriname, Mededeling* 25: 13-107.
- Wood, K.C., Miller, K.G. & Lohmann, G.P., 1985. Middle Eocene to Oligocene benthic foraminifera from the Oceanic Formation, Barbados. *Micropaleontology* 31(2): 181-197.
- Zachos, J.C., Lohmann, K.C., Walker, J.D.G. & Wise, S.W., 1993. Abrupt climate change and transient climates during the Paleogene: a marine perspective. *Journal of Geology* 101: 191-213.
- Zachos, J.C., Opdyke, B.N., Quinn, T.M., Jones, C.E. & Halliday, A.N., 1999. Early Cenozoic glaciation, Antarctic weathering, and seawater $87\text{Sr}/86\text{Sr}$: is there a link? *Chemical Geology* 161: 165-180.
- Zachos, J.C., Pagani, M., Sloan, L., Thomas, E. & Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292: 686-693.
- Zachos, J.C., Quinn, T.M. & Salamy, S., 1996. High-resolution (104 years) deep-sea foraminiferal stable isotope records of the Eocene-Oligocene climate transition. *Paleoceanography* 11(3): 251-266.
- Zachos, J.C., Stott, L.D. & Lohmann, K.C., 1994. Evolution of early Cenozoic marine temperatures. *Paleoceanography* 9: 353-387.
- Ziegler, P.A., 1990. Geological atlas of western and central Europe. Shell Internationale Petroleum Maatschappij B.V. (Den Haag), 239 pp.