Early Miocene foraminifers from the Upper Marine Molasse of the North Alpine Foreland Basin – Proxies for biostratigraphy and palaeoenvironmental change

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Ehrenwörtliche Versicherung

Ich versichere hiermit ehrenwörtlich, dass die Dissertation von mir selbstständig, ohne Beihilfe angefertigt worden ist.

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Erklärung

Hiermit erkläre ich, dass die Dissertation noch nicht in einem anderen Prüfungsverfahren vorgelegt und bewertet wurde.
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Contents

1. Introduction

The German segment of the North Alpine Foreland Basin (Molasse Basin) forms part of the Central and Western Paratethys. The deposits that fill this basin include marine, brackish and terrestrial sediments that range in age from late Eocene/early Oligocene to late Miocene. The clastic input predominantly comes from the Alps, but partially also from the Bohemian Massif and other sources in the north. This study focuses on the Upper Marine Molasse sediments which were deposited during the lower Miocene, i.e. the Eggenburgian and Ottnangian of the Central Paratethys (Fig. 1). During the Eggenburgian and Ottnangian major sea level fluctuations in the Paratethys realm resulted in significant environmental changes. Thus, the Eggenburgian-Ottnangian boundary is distinctive because of a regressive phase at the end of the Eggenburgian. The Ottnangian sediments are indicative of a normal marine development in the lower part, and display restricted marine to freshwater environments in the upper part (e.g. Lemcke 1988; Piller et al. 2007).

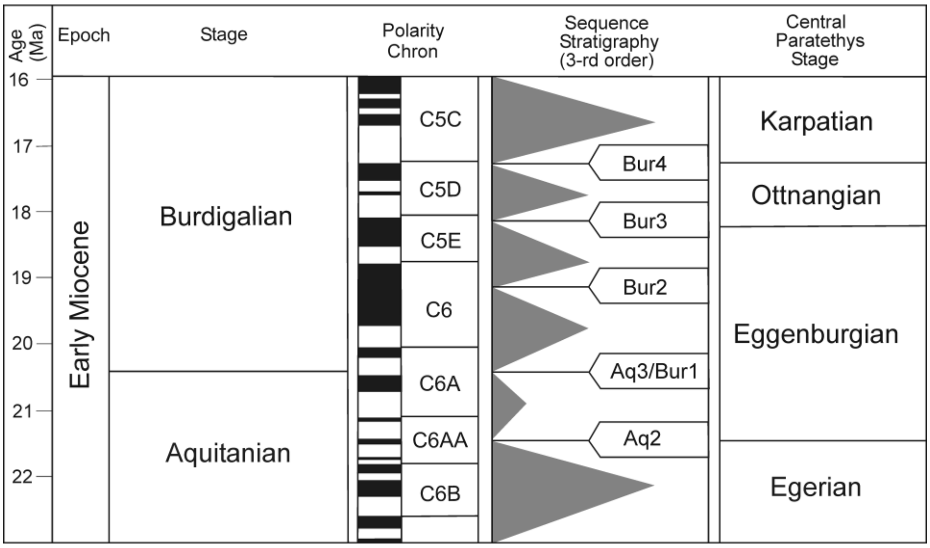

Fig. 1. Chronostratigraphic correlation of the Eggenburgian and Ottnangian stage (after Piller et al. 2007).

In the German part of the Molasse Basin, the sediments of the Upper Marine Molasse show considerable regional facies changes, mainly from west to east, but also from south to north. As a result, a ”Western Molasse” and ”Eastern Molasse" are separated, each containing specific lithostratigraphic units. In the Western Molasse, the Ottnangian segment of the Upper Marine Molasse is traditionally subdivided into two sedimentation cycles (according to Lemcke et al. 1953, see also Frieling et al. 2009a), whereas a single transgressive-regressive trend is evident in the Eastern Molasse (Wenger 1987a; Zweigel et al. 1998; Austria: e.g. Kovác et al. 2004; Harzhauser & Piller 2007; Piller et al. 2007). Moreover, the Ottnangian sediments of the Eastern and Western Molasse contain clearly different foraminiferal assemblages. Foraminifers from the Eastern Molasse are well comparable with those from Austria (see Cicha et al. 1998), but the assemblages from the Western Molasse do not show clear relations to the east (see Hagn 1961). To date, the reasons for these differences are largely unexplored, and it remains unclear whether syn-sedimentary tectonics, eustatic sea level rise and fall, or climatic changes are responsible for the sedimentary and environmental evolution of the Basin.

The objectives of this study are (1) to expose the palaeoecological and palaeoclimatic conditions during the deposition of the Upper Marine Molasse, (2) to reveal the effects of sea level fluctuations on the palaeoenvironmental development, (3) to point out the palaeobiogeographic and palaeoenvironmental differences within the North Alpine Foreland Basin and suggest their causes. However, the prerequisite for this purpose is a detailed stratigraphical subdivision of the Upper Marine Molasse and a precise correlation of the different lithostratigraphic units. The study is based on quantitative analysis of benthic foraminiferal assemblages from outcrops and boreholes in the Eastern and Western Molasse (see Fig. 2). Benthic foraminifers are useful in biostratigraphic studies especially within single depositional basins (e.g. Murray 2006). Furthermore, due to different ecological requirements, they are facies dependent and therefore valuable indicators to reconstruct palaeoecological conditions (e.g. Leckie and Olson 2003; Murray 2006). Additional studies on the planktonic foraminiferal assemblages that are used as proxies for palaeoecological condition of the water column were conducted as well.

It is shown that benthic foraminifers are significant biostratigraphical markers that can be used for a subdivision of the Upper Marine Molasse deposits and the stratigraphic correlation of the lithostratigraphic units. Based on various foraminiferal biofacies, which may be linked to shifts in water depth, organic flux, oxygenation of bottom waters and salinity, the environmental development of the Upper Marine Molasse Sea can be pointed out. In addition, the foraminiferal assemblages reveal that different time equivalent palaeoenvironmental zones existed during the deposition of the Upper Marine Molasse.

2. Geological setting

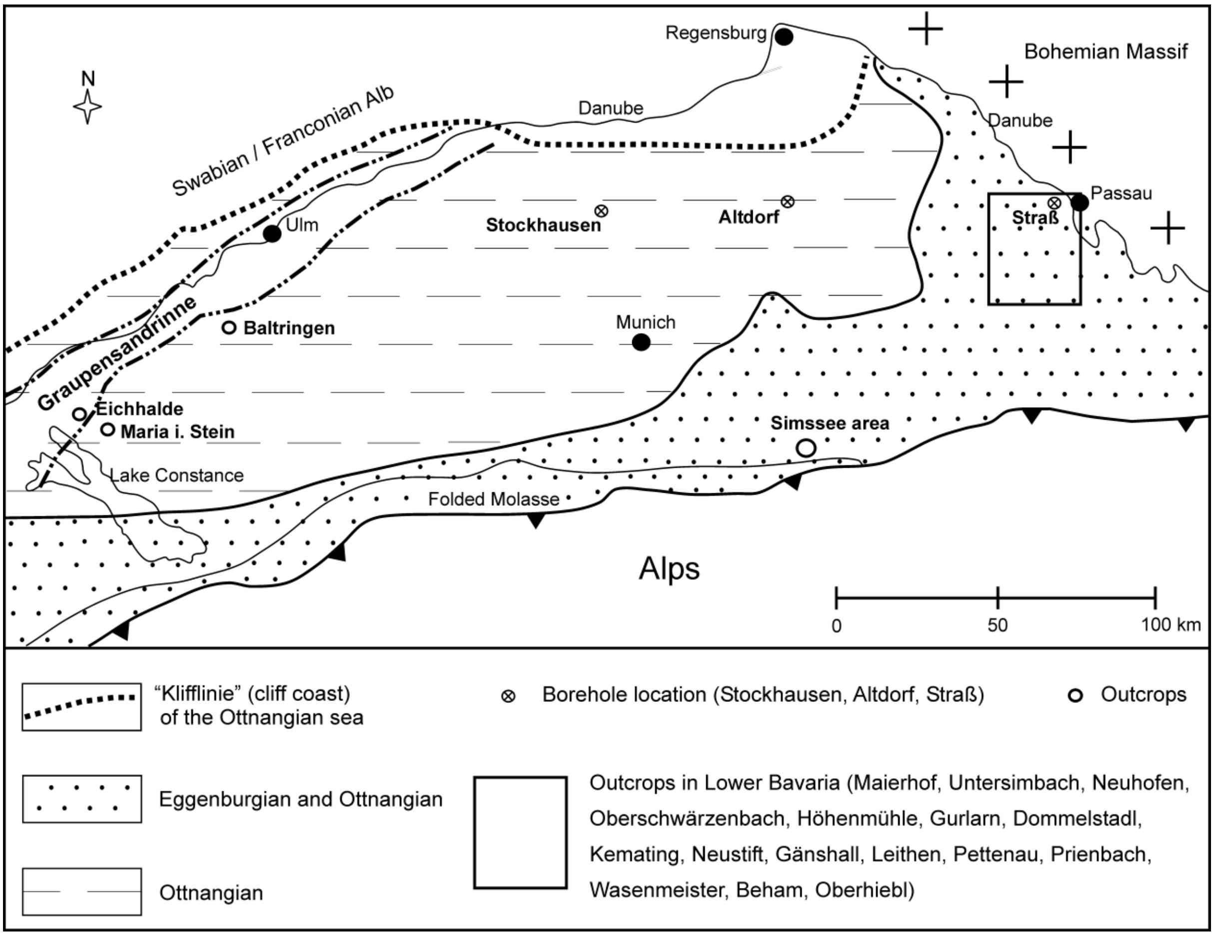

Fig. 2. Palaeogeography of the Eggenburgian and Ottnangian in the South German and westernmost part of the Austrian Molasse Basin (after Haus 1951, Lemcke 1988, Doppler & Schwerd 1996). Locations of the studied outcrops and boreholes are indicated.

The North Alpine Foreland Basin (Molasse Basin), which extends from the Lake Geneva area in the west via Switzerland and South Germany to Lower Austria in the east, belongs to the Paratethys realm (e.g. Kuhlemann & Kempf 2002). The geodynamic evolution of the Paratethys area, extending from the Rhone Basin in France to Inner Asia, lasted from the Eocene/Oligocene until the Miocene/Pliocene, and is characterized by the uplift of the Alpine-Carpathian, Dinarid and Balcan mountain chains (Popov et al. 2004). The Paratethys region was periodically connected with the Mediterranean Tethys, the Indo-Pacific and the Atlantic Ocean. The primary factors affecting the marine and non-marine phases were global and regional sea level fluctuations and regional geotectonic events (e.g. Rögl & Steininger 1983; Rögl 1999; Popov et al. 2004). The Western Paratethys includes the Rhone Basin and the North Alpine Foreland Basin of Switzerland and SW Germany, the Central Paratethys extends from SE Germany (Bavaria) in the West to the Carpathian Mountains in the East, and the Eastern Paratethys comprises the Black Sea, Caspian and Aral Sea areas (Steininger et al. 1976; Steininger & Wessely 2000; Harzhauser & Piller 2007). The fauna and flora of the Paratethys include many endemic elements, and thus stratigraphic correlation with the

Tethys realm is difficult. As a result, regional stratigraphic stages were introduced for the Olicocene-Miocene interval of the Central and Eastern Paratethys (Papp et al. 1971; Steininger et al. 1976; Cicha et al. 1998; Steininger & Wessely 2000). In the Central Paratethys, the late early Miocene stage Burdigalian is subdivided into the Eggenburgian, Ottnangian, and Karpatian (see Fig. 1).

In the German segment of the North Alpine Foreland Basin, the Molasse succession as a whole is traditionally divided into two transgressive-regressive megacycles, which are separated by an extensive unconformity (e.g. Lemcke 1988; Bachmann & Müller 1992; Schwerd et al. 1996). The first megacycle, starting in the late Eocene, comprises the Lower Marine Molasse, the Lower Brackish Water Molasse, and the Lower Freshwater Molasse. However, east of Munich marine sedimentation also prevailed during the deposition of the Lower Freshwater Molasse. The second megacycle includes the Upper Marine Molasse (Eggenburgian – middle Ottnangian), the Upper Brackish Water Molasse (upper Ottnangian), and Upper Freshwater Molasse (Karpatian – Pannonium) deposits (e.g. Doppler et al. 2005).

This study focuses on Eggenburgian and Ottnangian Upper Marine Molasse deposits in the German part of the Molasse Basin (see Fig. 2). The Eggenburgian and Ottnangian biostratigraphy is based largely on molluscs and benthic foraminifers (Papp et al. 1971; Steininger et al. 1976; Wenger 1987a; Cicha et al. 1973, 1998; Piller et al. 2007). Eggenburgian deposits are widespread in the Austrian Molasse Basin and in the easternmost part of the German Molasse Basin, whereas they are limited to a narrow zone proximal to the Alps in the area westwards (Lemcke 1973; Wenger 1987b; Kuhlemann & Kempf 2002; see here Fig. 2). Conversely, Ottnangian sediments are widespread throughout the North Alpine Foreland Basin and indicate the existence of seaways to the West and East, as well as a progradation to the North (Lemcke 1973; Wenger 1987a; Kuhlemann & Kempf 2002). In the German part of the North Alpine Foreland Basin, due to the existence of regional differences in facies composition, different informal and formal names have been given for the Upper Marine Molasse sediments of the ”Western Molasse” (west of river Lech) and ”Eastern Molasse" (east of river Lech) (see Table 1).

3. Lithostratigraphy of the Upper Marine Molasse

The informal and formal lithostratigraphic units of the Upper Marine Molasse, which were investigated in this study, are summarized in Table 1. The partially time equivalent successions are characterized by different sediments and macrofossils.

Lithostratigraphic unit	Abbreviation	Occurrence
Ortenburger Meeressande	no abbreviation	Eggenburgian/Eastern Molasse
Obere Meeresmolasse-Basisschichten	OMM-Basisschichten	Ottnangian/Eastern-Western Molasse
Untersimbacher Schichten	US-Beds	Ottnangian/Eastern Molasse
Neuhofener Schichten	NH-Beds	Ottnangian/Eastern Molasse
Marginal marine or nearshore facies	Marginal marine facies	Ottnangian/Eastern Molasse
Glaukonitsande und Blättermergel	GS-BM	Ottnangian/Eastern Molasse
Achen Formation (Auwiesholz Subformation, Hirnsberg Subformation)	Achen Fm. (Auwiesholz Sfm., Hirnsberg Sfm.)	Ottnangian/Eastern Molasse
Ulperting Formation	Ulperting Fm.	Ottnangian/Eastern Molasse
Heidenlöcher Schichten	HL-Beds	Ottnangian/Western Molasse
Kalkofen Formation (Sandschiefer, Sandmergelserie)	Kalkofen Fm.	Ottnangian/Western Molasse
Baltringen Formation (Bodmansande, Baltringer Schichten)	Baltringen Fm.	Ottnangian/Western Molasse
Steinhöfe Formation (Feinsandserie, Deckschichten)	Steinhöfe Fm.	Ottnangian/Western Molasse

Table 1. Eggenburgian and Ottnangian lithostratigraphic units of the Upper Marine Molasse in Germany and abbreviations used in the text (see also Table 3, chapter 7).

Ortenburger Meeressande – The Ortenburger Meeressande deposits reach a thickness of up to > 10 m and are primarily composed of fine- to coarse-grained sands. Typically, the marine sands contain a rich and diverse bivalve assemblage recently described by Schneider (2008). However, in the borehole Straß (see Pippèrr & Reichenbacher 2009), the fossiliferous sands are overlain by marls and fine-grained sands poor in macrofossils.

Obere Meeresmolasse-Basisschichten (**OMM-Basisschichten**) – In the borehole Altdorf, the 10.7 m thick basis layer of the Upper Marine Molasse consists of glauconitic coarse-grained sands and gravels, in the upper part alternating with marls (Pippèrr & Reichenbacher 2010). The sediments contain poorly preserved shell fragments, fish teeth and bones.

Untersimbacher Schichten (**US-Beds**) – According to Wenger (1987a) the Ottnangian US-Beds include the series of “Grobsande”/coarse sands and “Sandmergel”/sandy marls sensu Hagn (1953) and “Robulus-Schlier s. str.” sensu Knipscheer (1952). The type locality for the US-Beds is an outcrop near the village of Untersimbach. There, the mainly laminated fine-sandy marls of the US-Beds reached a thickness of about 10 m.

Neuhofener Schichten (**NH-Beds**) – In the Eastern Molasse the NH-Beds overlie the US-Beds/OMM-Basisschichten. The deposits are up to 220 m thick (the thickness decrease to the north) and are composed of clayey to fine sandy marls (Doppler et al. 2005). The type locality is an outcrop near the village of Neuhofen; there the NH-Beds consist of massively bedded, homogeneous, medium-grey, sand-poor marls. Occasionally indistinct stratification and lamination occur. In the upper part of the NH-Beds (e.g. Oberschwärzenbach, Lower Bavaria), the sediments contain upwards an increasing proportion of fine-grained sand (layers of fine-grained sand or small sand lenses, both up to millimetre-thin). Generally, a few beds contain shells of bivalves, scaphopods, brachiopods, and few bryozoans.

Marginal marine facies – Several outcrops, situated at the northeastern margin of the Molasse basin, expose the marginal marine (nearshore) facies of the Ottnangian Upper Marine Molasse. In Gurlarn, the fossiliferous basal layer, deposited above a highly structured granitic relief, contains bryozoans, bivalves, brachiopods, balanids, and else (see Frieling et al. 2009b; Schneider et al. 2009). Section upwards follow marls and sands, predominately poor in microfossils. In the granite quarry Neustift, the transgression conglomerate (~ 0.5 m) and the following medium- to coarse-grained sands (~ 0.5 to 1.2 m) directly overlay the granite and contain a macrofauna with abundant bivalves and gastropods, brachiopods, bryozoans, shark and ray teeth (communicated by S. Schneider, Munich; see also Heller 1954). Above follow the GS-BM facies (about 5-7 m) with pebble-bearing coarse-grained sands (partly cross-bedded) and finely layered sandy marls. In Kemating, about 2 m thick coarse sands contain some marly layers as well as pebbles and abundant shell-fragments. The sands are placed directly above Eggenburgian strata (see Wenger 1987a), but today the Eggenburgian sediments are not exposed. In Dommelstadl, the Upper Marine Molasse is developed in an exceptional facies, i.e. “Bryozoenkalk”/bryozoan-limestone (e.g. Ammon 1888; Bauberger & Unger 1984). It contains abundant fossils and fragments of bryozoans as well as bivalves, brachiopods, balanids, fish teeth, and corals.

Glaukonitsande und Blättermergel (**GS-BM**) – In the Eastern Molasse, the GS-BM facies overlie the NH-Beds (or the marginal marine facies in some outcrops). The up to 70 m thick succession (Doppler et al. 2005) is composed of glauconitic sands and finely layered to laminated sandy marls (“Blättermergel”/BM). The glauconitic sand facies/GS consists of fine- to medium-grained sands, in places with abundant mud clasts or thin marly layers. The sands are structureless or exhibit various kinds of sedimentary structures such as horizontal lamination, wavy-bedding, or cross-bedding (e.g. Salvermoser 1999).

Achen Fm. – In the Simssee area (Upper Bavaria) the Achen Fm. (Pippèrr et al. 2007) overlies the NH-Beds and reaches a thickness of > 60 m. In the lower part, the succession is composed of medium-grained glauconitic sands with pelitic layers and clasts as well as sandy marls (Auwiesholz Sfm.). Sediments are fining upward and gradually change into silty marls in the upper part of the Achen Fm. (Hirnsberg Sfm.). The lowermost part of the Auwiesholz Sfm. includes a coarse-grained sand layer with abundant bioclasts and well-rounded gravel, and the sands exhibit various kinds of sedimentary structures such as wavy-bedding, or cross-bedding. The homogeneous marls of the Hirnsberg Sfm. are mainly unbedded, but in some sections also with well-developed parallel stratification (lamination).

Ulperting Fm. – The Ulperting Fm. overlies the Achen Fm. with a sharp unconformity and its thickness reaches up to ~ 25 m (Pippèrr et al. 2007). The sediments are characterised by glauconitic, fine- to medium-grained sands. In the lower part, cross bedding and shell-beds may occur; upwards, the sands are predominantly structureless. The typical and abundant fossils are large sized oyster shells.

Heidenlöcher Schichten (**HL-Beds**) – In the Western Molasse, the up to ~ 50 m thick glauconitic sands of the HL-Beds form the base of the Upper Marine Molasse deposits of the Lake Constance area (e.g. Schreiner 1958; Doppler et al. 2005).

Kalkofen Fm. – The approximately 20-70 m thick sandy-marly sediments of the Kalkofen Fm. (Heckeberg et al. 2010; Sandschiefer or Sandmergelserie in earlier studies) overlie or replace the HL-Beds in the Western Molasse. At the type section Eichhalde, the lower part of the succession consists of grey marls interbedded with glauconitic sands, while a mud-dominated facies of grey marls with glauconitic sand lenses and flasers occur in the upper part (for details see e.g. Schreiner 1958, 1966; Doppler et al. 2005; Heckeberg et al. 2010).

Baltringen Fm. – The about 10-50 m thick Baltringen Fm. (Heckeberg et al. 2010; Bodmansande or Baltringer Schichten in earlier studies) overlies the Kalkofen Fm. with a sharp unconformity. The basal layer of the Baltringen Fm. (Baltringer Horizont) consists of coarse- to medium-grained sands with bioclasts and pebbles up to ~ 20 cm. Above follow largely medium-grained glauconitic sands, at places with clayey-silty intercalations, cross-bedding and other sedimentary structures (Heimann et al. 2009; Heckeberg et al. 2010).

Steinhöfe Fm. – The Steinhöfe Fm. (Heckeberg et al. 2010; Feinsandserie, Deckschichten in earlier studies) overlies the Baltringen Fm. and reaches a thickness of up to ~ 15 m in the Lake Constance area. The succession is dominated by finely layered fine-grained sands and silts without macrofossils (for details see Heimann et al. 2009; Heckeberg et al. 2010).

4. Material

More than 160 samples from different outcrops (see Fig. 2) and boreholes (Straß, Altdorf, and Stockhausen) located in the West and East German parts of the Molasse Basin were sampled for micropalaeontological analyses, the most important are indicated in Table 2. In all, the samples include ~ 22.180 benthic and ~ 3.411 planktonic foraminifers.

Location (number of samples)	R/H	Lithofacies	Benthic Foraminifers	Planktonic Foraminifers	References
Outcrops					
Maierhof (3)	4589570/5382420	Ortenburger Meeressande	1436	2	**D**
Untersimbach (5)	4600920/5373580	US-Beds	635	184	**G**
Neuhofen (3)	4594570/5370020	NH-Beds	889	9	**F**+**G**
Oberschwärzenbach (4)	4595238/5367633	NH-Beds	657	67	**F**+**G**
Höhenmühle (2)	4593981/5371718	NH-Beds	119	33	**G**
Gurlarn (10)	4598740/5376940	Marginal marine facies	1163	249	**B**
Dommelstadl (2)	4505800/5377300	Marginal marine facies	466	19	**G**
Kemating (3)	4593800/5382200	Marginal marine facies	530	3	**G**
Neustift (1)	4588260/5383670	Marginal marine facies	269	45	**G**
Höhenmühle (4)	4593981/5371718	GS-BM	126	34	**F**+**G**
Gänshall (2)	4592800/5373450	GS-BM	427	102	**F**+**G**
Leithen (1)	4579515/5366420	GS-BM	140	4	**F**+**G**
Pettenau (3)	4582770/5351440	GS-BM	37	5	**F**+**G**
Prienbach “Hohlweg” (2)	4579195/5350660	GS-BM+OBM	~45	7	**F**+**G**
Prienbach (1)	4579640/5351150	GS-BM	8	1	**F**+**G**
Wasenmeister (1)	4586280/5353213	GS-BM	56	2	**F**+**G**
Beham (1)	4586894/5353425	GS-BM	21	3	**F**+**G**
Oberhiebel (1)	4587379/5353787	GS-BM	91	4	**F**+**G**
Simssee area (36)	different outcrops	Achen Fm.+Ulperting Fm.	1086	~37	**A**
Eichhalde (5)	3508750/5203100	Kalkofen Fm.	722	74	**E**
Eichhalde (3)	3508750/5203100	Baltringen Fm.	145	10	**E**
Baltringen (7)	different outcrops	Baltringen Fm.+Steinhöfe Fm.	442	4	**C**
Maria i. Stein (5)	3516900/5297925	Baltringen Fm.+Steinhöfe Fm.	20	0	**E**
Boreholes					
Straß (3)	4594800/5383017	Ortenburger Meeressande	4074	30	**D**
Altdorf (36)	4508025/5380715	OMM-Basisschichten, NH-Beds, GS-BM	4315	1146	**F**
Stockhausen (15)	4451612/5374371	NH-Beds, GS-BM	4261	1337	**G**

References within the framework of this cumulative dissertation: (**A**) Pippèrr et al. (2007); (**B**) Frieling et al. (2009b); (**C**) Heimann et al. (2009); (**D**) Pippèrr & Reichenbacher (2009); (**E**) Heckeberg et al. (2010); (**F**) Pippèrr & Reichenbacher (2010); (**G**) Pippèrr (submitted).

Table 2. Samples from different outcrops and boreholes in the Eastern and Western Molasse (German part of the Molasse Basin) and the number of benthic and planktonic foraminifers. (For abbreviations see Table 1; OBM = Upper Brackish Water Molasse).

5. Methods

The samples were processed by soaking in hydrogen peroxide solution for several hours. Then, the samples were washed under running water through > 63 µm mesh sieves. All faunal groups were picked from representative splits of the dried residues. The benthic foraminifers were identified to species level (as far as possible), sorted, and counted. The identification of genera and species largely follows Wenger (1987a), Cicha et al. (1998), and Rupp & Haunold-Jenke (2003). Planktonic foraminifers were specified as one group and counted in order to obtain P/B ratios, i.e. the percentages of planktonic foraminifers in the total foraminiferal assemblages (%P = P/(P+B)*100). Planktonic species were identified and their abundance was noted.

For the majority of samples, the following quantitative data for the benthic foraminiferal communities were calculated using the computer program PAST of Hammer et al. (2001), and Microsoft Excel:

- Relative abundance (%) of benthic foraminiferal species and genera.
- Number of species (S) and total number of individuals (n).
- The Fisher's α diversity index, defined implicitly by the formula $S = \alpha \ln(1+n/\alpha)$, where S is the number of taxa, n the number of individuals, and α is the Fisher's diversity index (Hammer & Harper 2006). The index remains constant regardless of the number of individuals. High values indicate high species diversity.
- The Simson index of dominance and Equitability index (for the Altdorf samples, see Pippèrr & Reichenbacher 2010).
- Percentage dominance, i.e. the highest percentage occurrence of a species in a sample.
- The relative abundance (%) of agglutinated taxa.
- The relative abundance (%) of epifaunal and infaunal taxa.
- In order to determine the quantity of oxygen in the bottom water, dysoxic, suboxic and oxic indicators (%) were calculated.

Palaeodepth was estimated using bathymetric ranges of benthic foraminifers and the relative abundance of planktonic foraminifers (P/B ratios). Benthic foraminiferal depth zonations are based on Leckie & Olson (2003), Rögl & Spezzaferri (2003), and Murray (1991, 2006). However, the taxa are not necessarily restricted to these zones. Generally, benthic foraminiferal occur in low abundance in a wide range of environmental conditions, but in higher abundance towards (near-) optimum conditions (Altenbach et al. 2003; Murray 2006). As a result, the suggestions with regard to the palaeoenvironmental conditions are primarily based on the dominant and abundant genera and species, while the subsidiary taxa are less regarded. The P/B ratios increase with increasing water-depth and distance to the shore (e.g. Van der Zwaan et al. 1990; Van Hinsbergen et al. 2005); ratios of < 20% are suggestive of inner shelf (inner neritic) environments, 10-60% of middle shelf (middle neritic), and 40-70% of outer shelf (outer neritic) environments (Murray 1991).

The proportional abundances of infaunal and epifaunal benthic foraminiferal species were used for estimating bottom water oxygen content and organic flux. For the reconstruction of the bottom water conditions, oxic, suboxic and dysoxic indicators were determined. The oxygen levels were described according to Kaiho (1994) as high oxic (3.0-6.0 mL/L), low oxic (1.5-3.0 mL/L), suboxic (0.3-1.5 mL/L), dysoxic (0.1-0.3 mL/L), and anoxic (0-0.1 mL/L). Oxic indicators are epifaunal under high-oxygen bottom water conditions and absent in low-oxygen environments; suboxic indicators are epifaunal and infaunal in high-oxygen bottom waters, but may also commonly occur as epifaunal dwellers in low oxygen conditions; dysoxic indicators are infaunal taxa that are tolerant with regard to low oxygen habitats (Kaiho 1994). The classification of the benthic foraminifers as either epifaunal or infaunal, and as either oxic, suboxic or dysoxic indicators is based on literature data and the morphology of the test (for details see Pippèrr & Reichenbacher 2010, Table 1 and 4.2)

According to Kaiho (1994), suboxic indicators can include small specimens (< 350 µm) of oxic species. However, the test sizes of foraminifers from the shallow epicontinental Paratethys Sea cannot be compared directly with foraminifers from open ocean sediments. Generally, the foraminiferal tests from the Upper Marine Molasse are relatively small in comparison with specimens from open marine condition. As a result, test sizes can only in a limited sense be used in our analyses.

6. Results

6.1. References within the framework of this cumulative dissertation

The majority of the results gathered during the work on the PhD thesis at the Ludwig-Maximilians-University Munich correspond to manuscripts published in international journals (manuscripts 2-7); one article has just been submitted (manuscript 1).

Manuscript 1 (Appendix 1)

Pippèrr, M. (submitted): Characterisation of Ottnangian palaeoenvironments in the North Alpine Foreland Basin using benthic foraminifera - a review on the Upper Marine Molasse of Southern Germany. Marine Micropaleontology.

Manuscript 2 (Appendix 2)

Heckeberg, N., **Pippèrr, M.**, Läuchli, B., Heimann, F.U.M. & Reichenbacher, B. (2010): The Upper Marine Molasse (Burdigalian, Ottnangian) in southwestern Germany – Facies interpretation and a new lithostratigraphic terminology. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 161, 285-302.

Manuscript 3 (Appendix 3)

Pippèrr, M. & Reichenbacher, B. (2010): Foraminifera from the borehole Altdorf (SE Germany): proxies for Ottnangian (early Miocene) palaeoenvironments of the Central Paratethys. Palaeogeography, Palaeoclimatology, Palaeoecology 289, 62-80.

Manuscript 4 (Appendix 4)

Frieling, D., **Pippèrr, M.**, Schneider, S. & Reichenbacher, B. (2009): Sedimentology and stratigraphy at the rocky coast of the upper Burdigalian Molasse Sea: a case study from Gurlarn near Passau (SE Germany). Facies 55, 47–62.

Manuscript 5 (Appendix 5)

Heimann, F.U.M., Schmid, D.U., **Pippèrr, M.** & Reichenbacher, B. (2009): Re-interpreting the Baltringer Horizont as a subtidal channel facies: Implications for a new understanding of the Upper Marine Molasse "Cycles" (Early Miocene). Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 254, 135-149.

Manuscript 6 (Appendix 6)

Pippèrr, M. & Reichenbacher, B. (2009): Biostratigraphy and paleoecology of benthic foraminifera from the Eggenburgian "Ortenburger Meeressande" of southeastern Germany (Early Miocene, Paratethys). Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 254, 41-61.

Manuscript 7 (Appendix 7)

Pippèrr, M., Reichenbacher, B., Witt, W. & Rocholl, A. (2007): The Middle and Upper Ottnangian of the Simssee area (SE Germany): Micropalaeontology, biostratigraphy and chronostratigraphy. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 245, 353-378.

6. 2. Microfossil assemblages with focus on benthic foraminifers

Ortenburger Meeressande – In addition to predominantly large and well preserved benthic foraminifers, the samples contain few planktonic foraminifers (P/B ratios < 1.5%), *Globigerina praebulloides* and *G. ottnangiensis* representing the most abundant taxa. Moreover, the samples include rich and large-sized ostracod faunas, numerous echinoid spines, balanid plates, several shark and sparid fish teeth, and a few otoliths. One sample from the upper part from Straß also includes abundant and well preserved radiolarians.

The benthic foraminiferal assemblages gathered from samples of the borehole Straß and the Maierhof outcrop are rich in species and specimens. A total of 5510 individuals assignable to 77 different species have been identified. Almost all species belong to the hyaline group, whereas agglutinated taxa are represented by two species (*Textularia gramen*, *Spiroplectammina pectinata*).

Fisher’s α index ranges between 8 and 12 in the Straß samples and between 6 and 8 in Maierhof. The most abundant genera in the Straß samples are *Lenticulina* (*L. calcar*, *L. cultrata*, *L. limbosa*, *L. buergli*, and less frequent *L. inornata*, *L. paupercula*), *Elphidium* (e.g. *E. crispum*, *E. felsense*, *E.* cf. *flexuosum*, *E. subtypicum*, *E. ortenburgense*, *E. reussi*), *Elphidiella* (*E. cryptostoma*, *E. dollfusi*, *E. heteropora*, *E. minuta*, *E. subcarinata*), and *Ammonia* (*A. beccarii* s.l.). Besides, *Porosononion granosum* is abundant in the lower part (9-12%) but absent in the upper part. In general, the foraminiferal assemblage of the upper part is distinctly different from the assemblages below. *Nonion commune* (suboxic indicator, 31%), *Ammonia beccarii* s.l. (13%), and *Lenticulina buergli* (10%) are the most abundant species and the proportion of *Bulimina elongata* is distinctly higher (dysoxic indicator, 6%), whereas the proportional abundance of *Elphidium* is noticeably lower (9%). The benthic foraminiferal assemblages from Maierhof are comparable to those from Straß: *Elphidium* is abundant (15-35%) and *Elphidiella* is common (5-18%). In Maierhof, however, *Lenticulina*, *Nonion* and *Ammonia* are scarce in all samples, whereas *Asterigerinata planorbis* is abundant (10-41%). For details see Appendix 6.

OMM-Basisschichten / US-Beds – In the coarse grained OMM-Basisschichten of Altdorf benthic foraminifers are rather poorly preserved and only a small number of specimens (84) were recovered. In addition, the samples contain echinoid spines, shark and ray teeth, and fragments of bones and molluscs shells which are also poorly preserved and show signs of transport and erosion. In the samples of the outcrop Untersimbach (US-Beds) moderate to well preserved benthic and planktonic foraminifers are rare to abundant (26 to 331 specimens per sample). The proportions of planktonic foraminifers (P/B ratios) range from 3.9 to 36.4% and the assemblages are generally low in diversity (most abundant species: *Globigerina praebulloides*). In addition, fragments of bryozoans, ostracods, radiolarians, and diatoms (*Coscinodiscus*) occur. The co-occurring nannoplankton assemblage (determinations by Erlend Martini) is low diverse; most common are *Coccolithus pelagicus* (Wallich) and *Reticulofenestra* spp.

In Altdorf, the abundance and diversity of benthic foraminifers slightly increase upwards, the Fisher’s α index attains 6.7 in the upper part. The most abundant taxa are *Cibicidoides* (32%) and *Elphidium* (18%). In the upper part occur *Spiroplectammina* and *Lenticulina*. Additionally, in the fine sandy marls of Untersimbach (US-Beds), the benthic foraminiferal abundance and diversity increase upwards as well. In the upper part, the Fisher’s α diversity index varies between 6.2 and 8.1. The majority of species and specimens belong to the hyaline group. The assemblages are dominated by *Lenticulina inornata*/*L. melvilli* (up to 66%); *Fursenkoina acuta* (2-13%), *Nonion commune* (3-30%), and *Cibicidoides lopjanicus*/*C. tenellus* (5-16%) are partly abundant. In the uppermost part of the US-Beds, species such as *Sigmoilopsis ottnangensis* (3%) and *Amphicoryna ottnangensis* (8%) appear, which are typical taxa of the NH-Beds. For details see Appendix 1 (US-Beds) and 3 (OMM-Basisschichten).

NH-Beds – The samples from the outcrops Neuhofen, Oberschwärzenbach, and Höhenmühle (located in Lower Bavaria) contain rich and largely well preserved benthic foraminiferal assemblages and also large numbers of ostracods, otoliths (myctophid fishes), and diatoms (*Coscinodiscus*). In contrast, in the boreholes Altdorf and Stockhausen, most samples include only a few ostracods. The NH-Beds are characterised by the frequent occurrence of benthic foraminifers (253 to 1272 specimens per sample). In the lower part of the NH-Beds, planktonic foraminifers are partially very rare (e.g. Neuhofen: P/B ratios 0.5 to 1.5%), whereas they occur in higher abundance in the upper part (e.g. Altdorf, between 12 and 24%). The most frequent species are *Globigerina ottnangiensis* and *G. praebulloides* associated with *G. dubia*, *G. lentiana*, and *Tenuitellinata angustiumbilicata*, whereas *Globoturborotalia woodi*, *Globigerinoides trilobus*, *Paragloborotalia*? *acrostoma* are rare. Moreover, the samples contain low diverse and moderately preserved nannoplankton assemblages (determinations by Erlend Martini); *Coccolithus pelagicus* is the most common species. In addition, all nannoplankton assemblages include reworked Jurassic, Cretaceous and Paleogene forms.

In the Lower Bavaria sections, the diversity of benthic foraminiferal assemblages is moderate in the lower part of the NH-Beds (Neuhofen, Fisher’s α index between 5.5 and 6.6) and relative high in the upper part (Oberschwärzenbach, α = 9.0 to 9.5; Höhenmühle α = 7.9). This development is similar to that observed in Altdorf, where the Fisher’s α index varies between 3.9 and 14.4 and the lower part of the NH-Beds is characterized by α < 8 and the overlying part by α > 8. In the Stockhausen samples, the diversity index varies between 4.5 and 6.2. Hyaline taxa are most abundant. The agglutinated group is represented by only two species in the outcrop samples (*Textularia gramen* and *Spiroplectammina pectinata*), but by four species in Stockhausen, and by seven species in Altdorf (*Reticulophragmium* spp., *Textularia* spp., *Siphotextularia concava*, *Spiroplectammina* spp.). Miliolids are represented by *Sigmoilopsis ottnangensis* which is abundant and *Sigmoilinita* which occurs only sparsely in a few samples. In all, the highest proportional abundances of agglutinated taxa (up to 50% in Altdorf) and *Sigmoilopsis* (up to 15% in Neuhofen) occur in the lower part of the NH-Beds. The benthic foraminiferal assemblages of the samples from Neuhofen, Oberschwärzenbach, and Höhenmühle are generally dominated by *Lenticulina inornata*/*L. melvilli* (up to 54%). In contrast, in the Altdorf (A) and Stockhausen (S) assemblages the dominant species are *Reticulophragmium* (A), *Lenticulina inornata*/*L. melvilli* (A), *Heterolepa dutemplei* (A, S), or *Ammonia beccarii* s.l. (A, S). Other common species include *Textularia gramen* (Neuhofen, up to 28%), *Spiroplectammina pectinata* (up to 20%), and *Amphicoryna ottnangensis* (up to 4%). *Elphidium* is common in the upper part of the NH-Beds (up to 16%), but the genus is generally absent or scarce in the lower part. Furthermore, in the upper part of the NH-Beds, oxyphylic species are comparatively abundant and relatively large-sized (e.g. *Cibicides lobatulus*), while they rarely occur in most samples of the lower part. On the other hand, low oxygen tolerant taxa such as *Bolivina scitula*, *B. dilatata*, and *Fursenkoina* spp. are most frequent in the lower part of the NH-Beds. For details see Appendix 1 and 3.

Marginal marine facies – The samples from Gurlarn (basal layers), Neustift (basal layers), Kemating, and Dommelstadl contain predominantly rich and well preserved benthic foraminiferal assemblages (Gurlarn: 256 to 295 specimens per sample; Neustift: 269 specimens; Kemating: 21 to 263 specimens per sample; Dommelstadl: 169 and 297 specimens). Planktonic foraminifers are absent or relatively rare in Kemating and Dommelstadl (P/B ratios < 8%), whereas they occur in higher abundance in Gurlarn and Neustift (P/B ratios between 13 and 27%). The assemblages contain the dominant species *Globigerina ottnangiensis*, associated with *G. praebulloides*, *G. dubia*, *G. lentiana*, *Globoturborotalia woodi*, *Globigerinoides trilobus*, and *Paragloborotalia*? *acrostoma*. Echinoid spines, fragments of bryozoans, balanides and molluscs are abundant; ostracods and fish remains also occur. In the upper part of the Gurlarn succession, foraminifers (9 to 134 specimens per sample) and other fossils are less frequent. In Neustift all samples from the upper part of the section are decalcified.

The basal layers of the Upper Marine Molasse succession of Gurlarn contain diverse benthic foraminiferal assemblages (Fisher's α index > 11). The most abundant taxa are *Lenticulina inornata*/*L. melvilli* (up to 22%), *Elphidium* spp. (up to 20%), *Ammonia beccarii* s.l. (up to 17%), and *Cibicides lobatulus*/*Cibicidoides* spp. (up to 32%). Moreover, *Spiroplectammina pectinata* is relatively common while *Sigmoilopsis ottnangensis* only rarely occurs. The marls section upwards contain less diverse foraminiferal assemblages (Fisher's α index between 4.8 and 7.5), but the composition of these assemblages is similar to the foraminiferal fauna of the basal layers. The overlying sands and marls contain only few foraminifers; the predominant taxa are *Ammonia* and *Elphidium*. The benthic foraminiferal assemblages of Neustift, Kemating, and Dommelstadl are largely moderately diverse (Fisher's α index between 4.4 and 8.6). In all, the benthic foraminiferal assemblages are characterized by rich and diverse associations of elphidiids and abundant *Ammonia beccarii* s.l. In some samples *Textularia* and *Cibicidoides* are common. In most cases, *Elphidium* is highly dominant (up to 61%). The proportional abundance of oxyphylic taxa is generally high and dysoxic taxa are mainly absent. For details see Appendix 1 and 4.

GS-BM – The samples from various outcrops in Lower Bavaria (see Table 2) contain partially rich foraminiferal assemblages (e.g. Gänshall, 462 specimens). However, in most cases foraminifers occur relatively infrequent in the GS-BM (e.g. Höhenmühle, 11 to 55 specimens per sample). Furthermore, some samples contain few ostracods and abundant, but poorly preserved diatoms (*Coscinodicus*). In the borehole Altdorf, the lower part of the GS-BM is still characterized by the frequent occurrence of benthic and planktonic foraminifers (> 250 specimens per sample). In addition, mainly well preserved tests of ostracods are relatively abundant. However, a distinct change is recognizable section upwards where foraminifers scarcely occur. In the uppermost part of the GS-BM foraminifers and other fossils are completely absent. In the borehole Stockhausen, benthic and planktonic foraminifers show high variations in abundance throughout the marine succession of the GS-BM; in some segments foraminifers are absent. In all, the benthic foraminiferal assemblages are moderately well to well preserved and predominantly small-sized. Furthermore, the P/B ratios vary considerable with values up to 60% in Altdorf. The planktonic foraminiferal assemblage is similar to that of the NH-Beds (see above).

Benthic foraminiferal assemblages are partially diverse (e.g. Gänshall, $\alpha = 8$). However, the Fisher's α index varies strongly and in many cases the diversity is very low and foraminifers are scarce. In Altdorf, the Fisher's α index varies between 4.4 and 11.5 in the lower part of the GS-BM. In Stockhausen, the values range from 5.2 to 12.6 and in some cases foraminifers are absent (e.g. lowermost part of the GS-BM) or very rare (2 to 8 specimens per sample). Thus, these samples are not included in the statistical analyses. In all, *Ammonia beccarii* s.l. is the most abundant taxon and partially highly dominant (e.g. Altdorf, up to 78%) and agglutinated and miliolide species are absent or extremely rare. Other frequent taxa include *Elphidium* spp., *Elphidiella heteropora*, *E. minuta*, *Nonion commune*, *Cibicidoides lopjanicus*/*C. tenellus*, and *Hanzawaia boueana*. *Pappina primiformis* occurs in numerous samples, but is only relatively common in Gänshall (6.5%). Additionally, the GS-BM deposits are characterized by variable ratios of oxyphylic/suboxic/dysoxic taxa. Suboxic taxa appear frequently in several samples, and dysoxic indicators are partially abundant (e.g. *Bolivina dilatata* and *B. scitula* in Höhenmühle up to 20%). For details see Appendix 1 and 3.

Achen Fm. and Ulperting Fm. – Benthic foraminifers are rare to relatively common (1 to 195 specimens per sample) and the assemblages are usually dominated by small-sized and moderately well preserved individuals. Planktonic foraminifers are generally scarce and small-sized. Moreover, ostracods occur sporadically in the Auwiesholz Sfm. (lower part of the Achen Fm.) and are most diverse and abundant in the Hirnsberg Sfm. (upper part of the Achen Fm., 17 species). On the other hand, only a single ostracod species has been recorded in the overlying Ulperting Fm. The lowermost part of the Auwiesholz Sfm. includes bryozoans, balanids, fish otoliths, shark and ray teeth, and, more rarely, bones and teeth of marine and terrestrial mammals. Furthermore, in the Auwiesholz Sfm. (upper part) and Hirnsberg Sfm. (lower part), well preserved sponge spicules occur in abundance, and diatoms are common, most of which belong to the genus *Coscinodiscus*, whereas *Actinoptychus* is less frequent.

Benthic foraminifers show clear variations in abundance and species-diversity throughout the marine succession. In the Auwiesholz Sfm. the species diversity increases upwards, with the highest overall species diversity present in the uppermost part (Fischer's α diversity index up to 5). In the overlying sediments of the Hirnsberg Sfm. species diversity and abundance of benthic foraminifers decrease rapidly and also the Ulperting Fm. (top of the marine succession) is characterized by extremely low diverse benthic foraminiferal assemblages (up to 5 species). The most abundant species in the Auwiesholz Sfm. and in the Ulperting Fm. are *Elphidium glabratum* and *Ammonia beccarii* s.l. In the lower part of the Hirnsberg Sfm. the suboxic species *Nonion commune* is highly dominant (> 50% in all samples). Section upwards, *Ammonia* is abundant whereas other taxa rarely occur and partially foraminifers are completely absent. In all, other common taxa include *Elphidiella* *heteropora*, *Elphidiella minuta*, and *Hanzawaia boueana*. Miliolide species are absent and the single agglutinated species (*Spiroplectammina pectinata*) is extremely rare. For details see Appendix 7.

Kalkofen Fm. – The samples from the Eichhalde section contain moderately well preserved microfaunas, including foraminifers (44 to 192 specimens per sample), ostracods, and echinoid spines. Planktonic foraminifers are predominantly rare with P/B ratios ranging from 0 to 9% (in one sample 39%) and benthic foraminifers which occur more frequent are often characterized by small-sized tests.

The most diverse benthic foraminiferal assemblage appears in the lower part of the Kalkofen Fm. (α = 8.4), whereas the Fisher's α diversity index varies between 4.0 and 6.4 % in the upper part. Almost all species belong to the hyaline group; miliolids are absent and specimens of agglutinated taxa (*Textularia* cf. *gramen*, *Spiroplectammina pectinata*) are infrequent. The most abundant taxa include *Cibicidoides lopjanicus*/*C. tenellus* (up to 51%), *Ammonia beccarii* s.l. (up to 39 %), *Hanzawaia boueana* (up to 18%), *Elphidiella minuta* (up to 23%), *Elphidium* spp. (up to 15%), and *Nonion commune* (up to 20%). Less frequent species are represented by *Bolivina concinna*, *Melonis pompilioides*, and *Cassidulina laevigata*; very rare are *Lenticulina* cf. *inornata* and *Amphicoryna ottnangensis*. For details see Appendix 1 and 2.

Baltringen Fm. and Steinhöfe Fm. – The samples from the lower part of the Baltringen Fm. contain largely well preserved and relatively large sized benthic foraminifers (34 to 208 specimens per sample). Planktonic foraminifers are usually rare (P/B ratios < 5%, in one sample 10%). In addition, ostracods, balanids, bryozoans, echinoid spines, and fish teeth occur. However, section upwards, in the upper part of the Baltringen Fm. and in the Steinhöfe Fm., foraminiferal specimens and other fossils are generally scarce and the tests are often poorly preserved.

The samples from the lower part of the Baltringen Fm. include rich but low diverse benthic foraminiferal assemblages. The Fisher's α indices varies between 2.9 and 5.1. The predominant taxa are *Elphidium* spp. (up to 41%), *Elphidiella minuta* (up to 40%), and *Ammonia beccarii* s.l. (up to 28%). Moreover, *Cibicidoides lopjanicus*/*C. tenellus* and *Hanzawaia boueana* occur frequently, whereas other taxa are rare. For details see Appendix 1, 2, and 5.

7. Biostratigraphy

Stratigraphic considerations based on **planktonic foraminifers** are limited in the Paratethys because most of the tropical and Mediterranean zonal markers are very rare or absent (Cicha et al. 1998; Bicchi et al. 2003). As a result, other planktonic foraminifers have been used in the Miocene biostratigraphy of the Central Paratethys (Rögl 1985; Cicha et al. 1998). However, the stratigraphic classification of the Central Paratethys stages Eggenburgian and Ottnangian based on planktonic foraminifers is impossible. For instance, the most abundant Ottnangian species *Globigerina ottnangiensis* occurs also in older Eggenburgian sediments and in younger Karpatian strata.

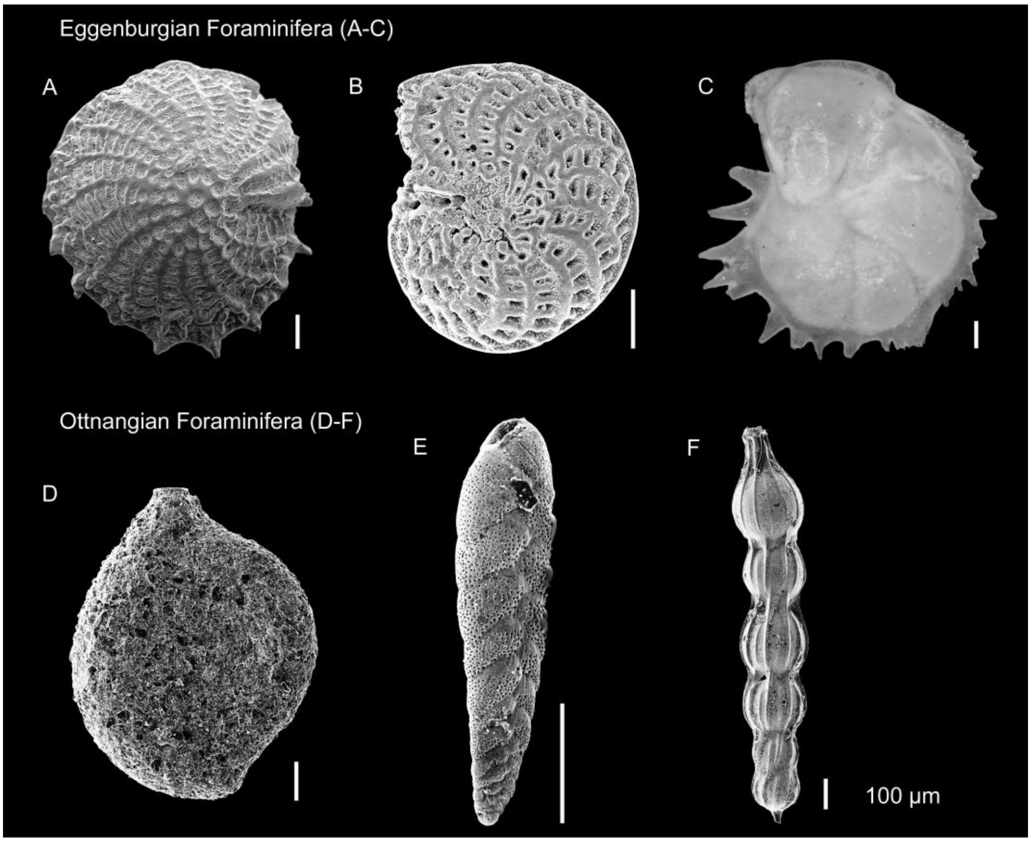

Fig. 3. Biostratigraphic marker species, (A) *Elphidium felsense*, Straß; (B) *Elphidium ortenburgense*, Maierhof; (C) *Lenticulina buergli*, Straß; (D) *Sigmoilopsis ottnangensis,* Neuhofen; (E) *Bolivina scitula*, Neuhofen; (F) *Amphicoryna ottnangensis*, Neuhofen.

However, a subdivision based on **benthic foraminifers** is possible (Fig.3). The Egerian-Eggenburgian boundary in the South German Molasse Basin and the Central Paratethys coincides with a marked change in the composition of benthic foraminiferal assemblages (see Wenger 1987a; Holcová 2008). Additionally, Eggenburgian and Ottnangian Upper Marine Molasse strata differ significantly from each other with regard to species composition (for Eggenburgian foraminifers see Pippèrr & Reichenbacher 2009; for Ottnangian foraminifers see Pippèrr et al. 2007; Frieling et al. 2009b; Pippèrr & Reichenbacher 2010; Pippèrr submitted). Index fossils of the Eggenburgian include *Lenticulina buergli* (Fig. 3C), *Elphidium felsense* (Fig. 3A), *Pararotalia batavensis*, and with restrictions also *Elphidium ortenburgense* (occurs very rarely in the Ottnangian; Fig. 3B), whereas *Sigmoilopsis ottnangensis* (Fig. 3D), *Amphicoryna ottnangensis* (Fig. 3F), *Bolivina scitula* (Fig. 3E), and *B. matejkai* are typical Ottnangian species. Moreover, some benthic foraminiferal species became extinct in the upper Eggenburgian (e.g. *Elphidiella cryptostoma*, *E. subcarinata*). In addition, the Eggenburgian benthic foraminiferal assemblages of the Ortenburger Meeressande and the Ottnangian strata of the German part of the Molasse Basin are clearly different with respect to abundances of certain species. Specimens of *Lenticulina calcar*, *L. cultrata*, *L. limbosa*, *Virgulopsis tuberculatus*, *Reussella spinulosa*, and *Elphidiella dollfusi* are partly very abundant in the Eggenburgian, whereas these species are absent or occur sparsely in a few samples in the Ottnangian. On the other hand, *Spiroplectammina pectinata* and *Elphidium glabratum* are widespread and abundant only in Ottnangian sediments.

Lithostratigraphy of unfolded Foreland Molasse in Germany				
Western Molasse (Lake Constance – Lech)			Eastern Molasse Upper Bavaria + Lower Bavaria	
Ottnangian	middle	Steinhöfe Formation (Deckschichten, Feinsandserie)	Ulperting Formation	Glaukonitsande und Blättermergel (GS-BM)
		Baltringen Formation (Bodmansande, Baltringer Schichten)	Achen Formation (Hirnsberg Sfm. Auwiesholz Sfm.)	
	lower	Kalkofen Formation (Sandschiefer, Sandmergelserie)	Neuhofener Schichten (NH-Beds)	
		Heidenlöcher Schichten (HL-Beds) / OMM-Basisschichten	Untersimbacher Schichten (US-Beds)	
Eggen-burgian		Hiatus	Eggenburg-Sand-Mergel-Folge	Ortenburger Meeressande

Table 3. Lithostratigraphic units of the Upper Marine Molasse (OMM) in the German part of the North Alpine Foreland Basin and their stratigraphic correlation (compiled after Hagn 1961; Wenger 1987a, b; Pippèrr et al. 2007; Heckeberg et al. 2010; Pippèrr submitted.).

A subdivision of the Eggenburgian into a lower, middle, and upper segment was proposed by Wenger (1987a), based on foraminiferal assemblages from Eggenburgian successions in Upper Bavaria (Eggenburg-Sand-Mergel-Folge, see Table 3). Furthermore, Wenger (1987a) correlated the Ortenburger Meeressande (Lower Bavaria) with the middle Eggenburgian. The new data support this assignment; however, the borehole Straß includes also sediments, which are most probably upper Eggenburgian in age (Pippèrr & Reichenbacher 2009). These upper Eggenburgian sediments of the borehole Straß are recorded for the first time for the German part of the Molasse Basin and are characterized by abundant specimens of *Lenticulina buergli*. This species is regarded as an index fossil for the Eggenburgian stage in Austria and occurs abundantly in the Hall Formation (e.g. Cicha et al. 1998; Rupp & Haunold-Jenke 2003). Furthermore, it can also be used as an Eggenburgian index fossil in the German part of the Molasse Basin (Pippèrr & Reichenbacher 2009).

Both in the Western and Eastern German part of the Molasse Basin, a subdivision of the Ottnangian into a lower and middle segment (upper segment: brackish Molasse) was proposed based on benthic foraminiferal assemblages (Knipscheer 1952; Hagn 1953, 1961; Wenger 1987a; Pippèrr et al. 2007; Frieling et al. 2009b; Pippèrr & Reichenbacher 2010; Pippèrr submitted). In the Eastern Molasse, the US-Beds and NH-Beds can be correlated with the lower Ottnangian, whereas the GS-BM (Lower Bavaria), Achen Fm. and Ulperting Fm. (Upper Bavaria) are middle Ottnangian in age (see Table 3). Characteristic lower Ottnangian taxa are *Sigmoilopsis ottnangensis*, *Spiroplectammina pectinata, Lenticulina inornata*/*L. melvilli*, and *Amphicoryna ottnangensis*. These species are widespread and abundant in the lower Ottnangian but are absent or occur sparsely in a few samples in middle Ottnangian strata. In Lower Bavaria (borehole Altdorf and outcrops), the middle Ottnangian cannot clearly be separated from the lower Ottnangian. Nevertheless, after a transition zone, a clear change of benthic foraminiferal assemblages is apparent (see Pippèrr & Reichenbacher 2010; Pippèrr submitted). However, the situation is clearly different to the west. In the borehole Stockhausen, the lower to middle Ottnangian transition is not gradual, but sharp, and the succession is comparable with the general situation in the Western Molasse (Pippèrr submitted). There, the lower Ottnangian equivalents of US-Beds and NH-Beds, i.e. HL-Beds and Kalkofen Fm., are separated from the middle Ottnangian succession (Baltringen Fm., Steinhöfe Fm., see Table 3) by an unconformity. The abrupt shift between the mud-dominated Kalkofen Fm. and the sand-dominated middle Ottnangian Baltringen Fm. is also accompanied by a change of foraminiferal assemblages (see Heckeberg et al. 2010; Pippèrr submitted).

In earlier studies, the marginal marine sediments of the outcrops Neustift, Kemating, and Dommelstadl were correlated with the middle Ottnangian (Hagn et al. 1981; Wenger 1987a). However, foraminifers provide support for an early Ottnangian age (see Pippèrr submitted). The foraminiferal assemblages altogether, like the entire fossil content from Neustift, Kemating, and Dommelstadl, are similar to the assemblages from the basal layers of Gurlarn. These basal layers of the Gurlarn succession can be correlated with the lower Ottnangian and contain benthic foraminiferal assemblages that show similarities with those from the lower Ottnangian NH-Beds; distinctions occur because of different water depths (for details see Frieling et al. 2009b; Pippèrr submitted). *Spiroplectammina pectinata* occurs in all samples (Gurlarn, Neustift, Kemating, and Dommelstadl) whereas *Lenticulina inornata*/*L. melvilli* is abundant in Gurlarn and Neustift, and *Sigmoilopsis ottnangensis* and *Amphicoryna ottnangensis* are present in Gurlarn. All these species are characteristic for lower Ottnangian strata.

8. Discussion

8.1. Benthic foraminifers as proxies for palaeoenvironmental conditions

8.1.1. State of the art

Studies on modern benthic foraminiferal assemblages have shown that certain associations of species characterize different environments (e.g. Murray 2006). Ecological factors which may influence the distribution of benthic foraminifers include, among others, water temperature, salinity, substrate type, bottom-water oxygenation, and organic flux to the seafloor. In addition, several taxa display characteristic depth ranges (e.g. Leckie & Olson 2003; Murray 1991, 2006); therefore, benthic foraminifers are often used to estimate palaeo-water depths. The depth zoning is probably not controlled by bathymetry itself, since various environmental variables co-vary with water depth, including substrate, sedimentation rate, turbulence, light, organic flux, and dissolved oxygen (e.g. Jorissen 1987, 1988; Altenbach et al. 2003; Leckie & Olson 2003). However, several taxa rather consistently occur in deep waters, whereas other are confined to shallow areas and a major faunal break occurs at about 100 m water depth (Jorissen 1987, 1988; Van der Zwaan et al. 1999).

Many authors have pointed out that organic flux and oxygenation of bottom waters are major factors describing benthic foraminiferal distribution patterns (e.g. Jorissen 1987, 1988; Sen Gupta & Machain-Castillo 1993; Schmiedl et al. 1997; Altenbach et al. 1999; Jian et al. 1999; Van der Zwaan et al. 1999; Den Dulk et al. 1998, 2000; Abu-Zied et al. 2008). Besides, an increasing organic carbon flux (and thus food supply) to the sea floor may lead to an increase in benthic foraminiferal abundance (see Loubere & Fariduddin 1999; Holbourn et al. 2001). However, high organic flux causes eutrophicated conditions and increased consumption of oxygen (e.g. Jorissen et al. 1995; Jorissen 1999). According to the model of Jorissen (1999), oligotrophic environments are regulated mainly by food supply, but do not display oxygen limitation and their benthic foraminiferal assemblages are rich in epifaunal species, whereas eutrophic habitats are regulated by critical oxygen levels and infaunal species tend to dominate. In oxygen depleted environments, benthic foraminifers are partly very abundant; however, in some cases the abundance is also extremely low (e.g. Bernhard & Sen Gupta 1999; Holbourn et al. 2001). In addition, a reduction of the oxygen content of bottom water can cause a marked decrease in species diversity and produces assemblages with few species showing high dominance (e.g. Sen Gupta & Machain-Castillo 1993; Den Dulk et al. 1898; Bernhard & Sen Gupta 1999).

8.1.2. Palaeoecology of the Molasse Sea based on benthic foraminifers

Eggenburgian – The diverse benthic foraminiferal assemblages of the Ortenburger Meeressande from Straß and Maierhof suggest a marine environment. Typical shallow marine taxa with preferred depth ranges of 0-50 m (e.g. *Elphidium*) or 0-100 m (e.g. *Asterigerinata*) are most frequent, whereas typical outer neritic to bathyal genera with a preferred water depth of > 100 m occur only sparsely in both sections (for details see Pippèrr & Reichenbacher 2009). Therefore, the Eggenburgian sediments were most probably deposited in a shallow marine environment with a water depth less than 50 m.

Moreover, the middle Eggenburgian assemblages are characterized by a high amount of epifaunal and oxic taxa as well as relatively high species diversities (Pippèrr & Reichenbacher 2009). Such assemblages are characteristic for a well oxygenated environment. However, the conditions change in the upper part of the Ortenburger Meeressande at Straß (upper Eggenburgian). Diversity and proportional abundances of epifaunal and oxic indicators decrease, whereas proportions of infaunal and low oxygen tolerant taxa (*Nonion commune*, *Bulimina elongata*) increase strongly. The composition of dysoxic, suboxic, and low ratios of oxic indicators is typical for an environment with slightly reduced oxygen content of bottom waters (low oxic, 1.5-3.0 mL/L, according to Kaiho 1994).

Possible reasons for the slight oxygen depletion may have been the intensified organic flux caused by increased fluviatile input and primary productivity, or the appearance of a stratified water column (seasonal thermocline or halocline). The former explanation is supported by the fact that the high abundance of benthic foraminifers (and other microfossils) in all samples of the Ortenburger Meeressande indicates a high productivity environment.

Early Ottnangian – In the Eastern Molasse the transgressive deposits of the US-Beds (or OMM-Basisschichten at Altdorf) are overlain by the deep neritic basinal facies of the NH-Beds. The benthic foraminiferal assemblages of the NH-Beds are indicative of marine, middle to outer neritic environments. A relative sea level highstand with water depth of up to > 100 m can be assumed for the lower part of the NH-Beds. In the upper part of the NH-Beds, upward increasing proportions of characteristic shallow water foraminifers (*Elphidium* and *Ammonia*) are indicative of a shallowing-upward trend.

During the relative sea level highstand, the benthic foraminiferal assemblages of the NH-Beds are predominantly indicative of high organic flux and moderate oxygen depletion of bottom water (suboxic, 0.3-1.5 ml/l according to Kaiho 1994). The assemblages are characterized by high foraminiferal abundances, relatively low species diversities, scarcity and small size of oxyphylic foraminifers, and high proportions of low oxygen tolerant taxa (e.g. *Fursenkoina* spp., *Bolivina scitula*, *B. dilatata*). In the upper part of the NH-Beds, a more oxygenated benthic environment is indicated by higher diversity indices and occurrence of oxic indicators (e.g. *Cibicides lobatulus*, *Heterolepa dutemplei*; for details see Pippèrr & Reichenbacher 2010; Pippèrr submitted).

In the nearshore settings of the early Ottnangian Molasse Sea, macro- and microfossil rich sediments were deposited. The faunas from the marginal marine equivalents of the NH-Beds (Gurlarn, Neustift, Dommelstadl, Kemating) contain benthic foraminifers typical of well oxygenated, shallow marine environments with marine character (see Pippèrr submitted). At Gurlarn, the macro- and microfossil assemblages suggest a water depth of approximately 20 m (see Frieling et al. 2009b).

In contrast to the Eastern Molasse sections (NH-Beds), benthic foraminifers in the early Ottnangian sediments (Kalkofen Fm.) of the Western Molasse are comparatively infrequent and small-sized. In addition, the respective foraminiferal assemblages are relatively distinct (Hagn 1961; Pippèrr submitted). The differences most probably depend on different water depths (and co-varying environmental variables) of these areas because the environment in the western part of the German Molasse Basin was distinctly shallower. The foraminifers of the Kalkofen Fm. indicate an inner to middle neritic environment, probably with a water depth predominantly below 50 m. Environmental stress, like intermittent salinity fluctuations or high sedimentations rates, has affected the development of foraminifers (for details see Heckeberg et al. 2010; Pippèrr submitted).

Middle Ottnangian – In the Eastern Molasse, middle Ottnangian lithostratigraphic units include the GS-BM in Lower Bavaria, and the Achen Fm. and Ulperting Fm. in Upper Bavaria (Simssee area). The most common and partly highly dominant benthic foraminifer of these sediments is *Ammonia beccarii* s.l. (Pippèrr et al. 2007, Pippèrr & Reichenbacher 2009, 2010; Pippèrr submitted), which is a well known euryhaline taxon in marginal marine and inner neritc environments (e.g. Sen Gupta 1999; Murray 2006). In addition, the middle Ottnangian GS-BM foraminiferal assemblages are characterised by variable values of abundances and diversities, in some segments foraminifers (and other macro- and microfossils) are scarce or absent. This points to unstable conditions and, in some sections, to salinity fluctuations and strong oxygen depletion of bottom water (more details in Pippèrr & Reichenbacher 2010; Pippèrr submitted). Nevertheless, the partly relatively diverse benthic foraminiferal assemblages in some sections indicate also certain periods with better living conditions. Moreover, the lowermost part of the Upper Brackish Water Molasse (“Mehlsande”, upper Ottnangian) still contains microfaunas composed of extremely small benthic and planktonic foraminifers (see also Reichenbacher 1993).

In all, benthic foraminifers from the middle Ottnangian Achen Fm. and Ulperting Fm. (Eastern Molasse, Upper Bavaria, Simssee area) are similar to the assemblages from the GS-BM and suggest variable conditions as well (see Pippèrr et al. 2007). Conversely, in the Western Molasse, benthic foraminifers (and other marine micro- and macrofossils) are only common in the lowermost part of the middle Ottnangian sediments (lower part of the Baltringen Fm.). The assemblages are characterised by very low P/B ratios and diversities of benthic foraminifers, as well as elphidiid-*Ammonia* associations; such assemblages are characteristic of marginal marine to inner neritic environments. In the upper part of the Baltringen Fm. and in the Steinhöfe Fm. the abundance and diversity of foraminifers (and other fossils) are generally extremely low and indicate a period during which marine life conditions declined.

8.2. Planktonic foraminifers as proxies for palaeoenvironmental conditions

8.2.1. State of the art

The ratio between planktonic and benthic foraminifers (P/B ratios) can be used to determine water depths since the proportional abundances of planktonic specimens usually increase with distance to the shore and increasing water depth (e.g. Van der Zwaan et al. 1990; Van Hinsbergen et al. 2005). Ratios of < 20% are suggestive of inner shelf (inner neritic) environments, 10-60% of middle shelf (middle neritic), and 40-70% of outer shelf (outer neritic) environments (Murray 1991). However, the proportional abundances of planktonic forms found in sediments depend also on a number of other factors affecting the abundance of life and dead planktonic foraminifers (see Bé & Hutson 1977). Prior to deposition on the sea floor, dead individuals may be transported by currents over a long distance, depending on water depth, current velocity, and differential settling velocity of tests (Bé & Hutson 1977; Murray 1991; Schmuker 2000; Schmuker & Schiebel 2002). Moreover, dissolution of calcite can influence the abundance of tests in the sediment (Hemleben et al. 1989; Schmuker 2000; Schmuker & Schiebel 2002). Carbonate dissolution is usually found in the deep sea; however, it is also known to occur in shallow water environments (e.g. shelf seas, lagoons, estuaries) because of water masses depleted in calcium carbonate or enhanced organic carbon fluxes (Alexandersson 1978; Schrader et al. 1983; Jorissen 1987; Murray 1991; Peebles & Lewis 1991; Steinsund & Hald 1994; Den Dulk et al. 2000; Schmuker & Schiebel 2002). Furthermore, planktonic foraminifers are generally much more susceptible to dissolution than benthic forms, leading to depressed P/B ratios (e.g. Steinsund & Hald 1994; Den Dulk et al. 2000; Petrizzo et al. 2008; Nguyen et al. 2009).

Studies in modern oceans have shown that the most conspicuous planktonic foraminiferal distribution patterns are latitudinal, and different biogeographic zones can be distinguished throughout the world based on species composition (see e.g. Lipps 1979; Arnold & Parker 1999). This implies that temperature is an important factor in controlling species distributions. On the other hand, the influence of temperature correlated phenomena like productivity may also play an important role (see Arnold & Parker 1999).

8.2.2. Palaeoecology of the Molasse Sea based on planktonic foraminifers

Eggenburgian – The proportional abundance of planktonic foraminifers in the samples from the Ortenburger Meeressande is generally extremely low (P/B ratios < 1.5%). In accordance with the benthic foraminiferal assemblages, the low abundance of planktonic forms suggests a shallow marine (inner neritic) environment.

Ottnangian – The P/B ratios of the Ottnangian Upper Marine Molasse sediments strongly indicate that the values cannot confidently be used for determining palaeodepths (Pippèrr & Reichenbacher 2010; Pippèrr submitted). Planktonic foraminiferal assemblages of the lower Ottnangian NH-Beds are partially depleted although benthic foraminifers suggest middle to outer neritic environments (see Fig. 4). This is shown for example in Neuhofen, where benthic foraminiferal assemblages are indicative of an outer neritic environment, but P/B ratios are constantly low (< 2%). Moreover, in the middle Ottnangian GS-BM the P/B ratios vary considerably (see Fig. 4) and planktonic foraminifers may be abundant (P/B ratios up to 68%), although benthic foraminifers indicate an inner neritic environment. It can be assumed that the P/B ratios are affected by taphonomic processes, including current-dependent transport of dead individuals before deposition on the sea floor and selective carbonate dissolution. Moreover, also a restricted connection to the open ocean or brackish water influx could have affected the living assemblages. The North Alpine Foreland Basin was efficiently connected with the Mediterranean Tethys in the early Ottnangian, but high river discharge could locally have produced a salinity decrease in surface water, associated with a reduction of planktonic foraminiferal abundances. In all, the partly very low planktonic foraminiferal proportions of the lower Ottnangian NH-Beds are probably the result of several factors which have affected living as well as dead assemblages.

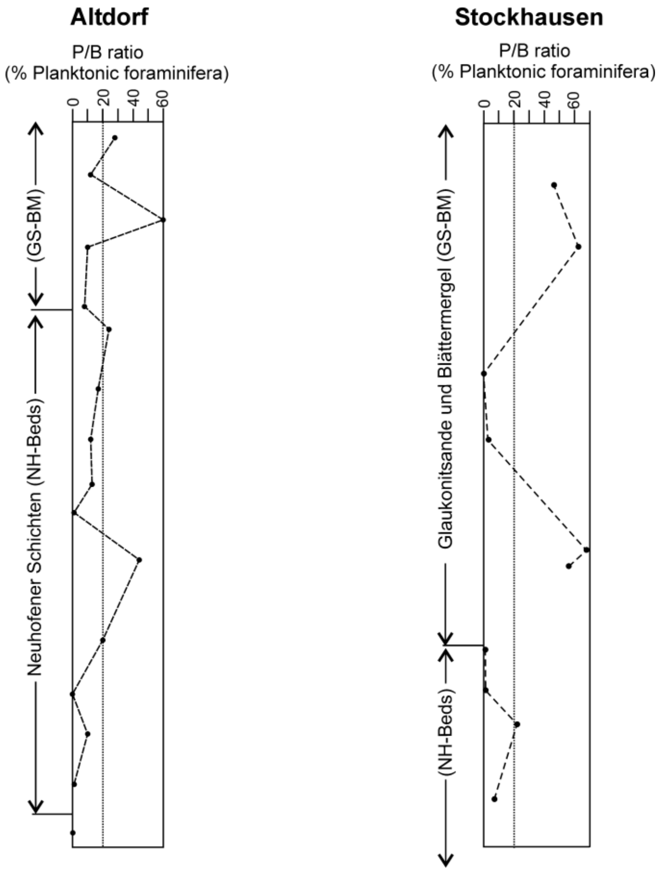

Fig. 4. The P/B ratios of samples in the boreholes Altdorf and Stockhausen.

Generally, the planktonic foraminiferal assemblages of the Ottnangian Upper Marine Molasse deposits are indicative of nutrient-rich waters; the most abundant species *Globigerina ottnangiensis* and *G. praebulloides* prefer high productivity environments (see Pippèrr & Reichenbacher 2010; Pippèrr submitted). Furthermore, the Ottnangian Upper Marine Molasse deposits (in the Central Paratethys in general) contain a planktonic foraminiferal assemblage that is typical for cold-temperate surface waters (see Grunert et al. 2009; Pippèrr & Reichenbacher 2010). However, high nutrient availability and selective dissolution could have affected the assemblages (see chapter 8.2.3). Planktonic foraminifers are generally much more vulnerable to dissolution than benthic foraminifers. Moreover, differences in morphology, test size, wall structure and thickness of their shells make some planktonic species more prone to dissolution than others (e.g. Petrizzo et al. 2008; Nguyen et al. 2009). Above all, typical warm water taxa tend to be easily dissolved, whereas most cold water species are more resistant (e.g. Spezzaferri & Premoli Silva 1991; Petrizzo et al. 2008). However, not only planktonic foraminiferal assemblages, but also other fossil groups (e.g. echinoderms, diatoms) suggest a brief temperature drop in the Ottnangian Central Paratethys Sea (see Kroh 2007; Grunert et al. 2009).

8.2.3. Dissolution textures

Shell textures of foraminifers resulting from dissolution can be used as taphonomic indicators. Dissolution textures studied on foraminiferal tests by Peebles & Lewis (1991) and Volbers & Henrich (2002) demonstrated that dissolution proceeds preferentially around the borders of the crystallites and around the pores leaving a coarsened surface relief. “As dissolution proceeds, pores get widened, the interpore areas is etched, ridges and spines become denuded until the specimen is finally broken down” (Volbers & Henrich 2002). In contrast to dissolution, abrasion of foraminiferal tests results in minute scratches and pits with flattened ornamentation and tests are noticeably polished in some cases (Peebles & Lewis 1991). A comparison of the planktonic foraminiferal surface textures of Ottnangian specimens from the Upper Marine Molasse with those of *Globigerina bulloides* studied by Volbers & Henrich (2002: increasing stages of dissolution are shown in fig. 4) reveals that some shells are affected by dissolution processes and also by abrasion (see also Fig. 5). This suggests a certain loss of planktonic foraminifers in some cases.

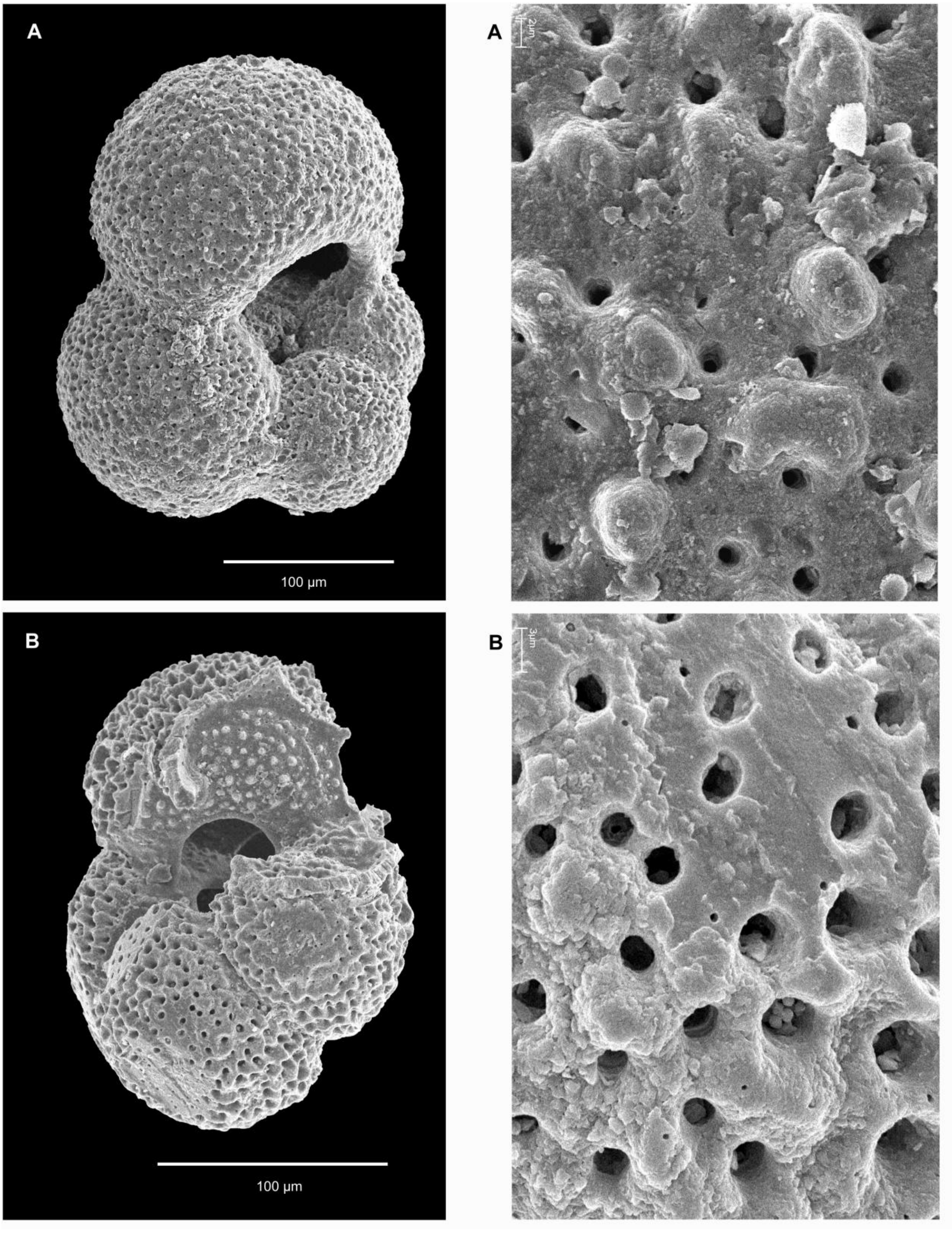

Fig. 5. *Globigerina praebulloides* from Gurlarn (A) and Stockhausen (B) and details of shells (right side). (A) Test with minor dissolution and abrasion textures. (B) Shell showing rough (uneven) texture and widened pores typical of dissolution (polished surface: abrasion).

8.3. Facies zones and environmental development

Eggenburgian – In the Eggenburgian, only a part of the North Alpine Foreland Basin was flooded (see Fig. 2). The frequent occurrence of *Lenticulina buergli* in the Ortenburger Meeressande of Straß indicates that a significant marine connection existed between the eastern part of the German Molasse Basin and Austria ("Haller Schlier"). Moreover, the assemblages of Maierhof and Straß correspond well with those from the shallow water deposits of the Eggenburg Group in Austria (see Pippèrr & Reichenbacher 2009). Altogether, the foraminiferal assemblages suggest that a uniform foraminiferal bioprovince existed in the Eggenburgian. Additionally, the benthic foraminiferal assemblages are indicative of different water depths, e.g. shallow water areas in Straß and Maierhof (this study) and partially outer neritic to upper bathyal environments in the Traun and Sur sections (Upper Bavaria, Wenger 1987a).

Ottnangian – In the Central Paratethys (including the Eastern Molasse Basin in Germany) the Ottnangian stage is differentiated because of a regression at the end of the Eggenburgian, which probably correlates with the Bur 3 lowstand (see Piller et al. 2007; Pippèrr & Reichenbacher 2009). In the easternmost area of the German Molasse Basin (Lower Bavaria, outcrops and borehole Altdorf), the benthic foraminiferal assemblages indicate a single transgressive-regressive cycle for the Ottnangian succession, which corresponds well with previous data from the Central Paratethys (e.g. Kovác et al. 2004; Harzhauser & Piller 2007; Piller et al 2007). The gradual lithofacies change from lower to middle Ottnangian Upper Marine Molasse sediments is accompanied by gradual changes of foraminiferal assemblages. Above follows the Upper Brackish Water Molasse, which was deposited during the upper Ottnangian.

To the west, in Stockhausen and in the Western Molasse, the transgressive-regressive succession of the Ottnangian Upper Marine Molasse is subdivided into two sedimentation cycles; the lower and middle Ottnangian sediments are separated by an unconformity and show an abrupt change of lithofacies and biofacies. Probably, the two sedimentation cycles can be regarded as a result of regional tectonics and basin development (see Lemcke et al. 1953; Pippèrr submitted) and the areas of the Eastern and Western Molasse may have been governed by different subsidence and sedimentations rates. However, due to the comparatively shallow marine environment in the Western Molasse, this area was much more sensitive to minor sea level fluctuations than the area of the Eastern Molasse. Stockhausen obviously was located in a transition zone because it shows the lithofacies and foraminiferal assemblages typical of the Eastern Molasse, but also the two sedimentations cycles found in the Western Molasse.

Furthermore, benthic foraminifers reveal that the relative sea level highstand and maximum extension of the Upper Marine Molasse Sea took place during the early Ottnangian. In the early Ottnangian of the Eastern Molasse, the fossiliferous marginal marine facies show characteristics of well oxygenated environments, whereas the foraminiferal assemblages of the deep neritic basin facies suggest high organic flux (eutrophic condition) and some oxygen depletion of bottom water during relative sea level highstand (lower part of the NH-Beds). However, in the upper part of the NH-Beds a regressive tendency and a shift to lower oxygen stress can be observed. The facies development as seen in the NH-Beds is similar to that of the early Ottnangian "Ottnanger Schlier" in Upper Austria (Ottnang-Schanze), for which an upward shallowing trend (outer neritic to middle neritic) coinciding with an increase in bottom water oxygenation has been described (Grunert et al. 2010). Conversely, in the Western Molasse, the early Ottnangian benthic foraminiferal assemblages suggest an inner to shallow middle neritic environment with increasing environmental stress in the upper sections.

In the middle Ottnangian, during a period of relative sea level lowstand, foraminiferal assemblages of the Eastern Molasse sections suggest a very shallow marine environment with unstable conditions. Most probably because of the combined effect of oxygen depletion of bottom water and reduced salinity, benthic foraminifers (and other fossils) are very rare or absent in some segments. The occurrence of laminated sediments and pyrite grains in some sections of the middle Ottnangian strata (Achen Fm.: Pippèrr et al. 2007; GS-BM: Pippèrr & Reichenbacher 2010) provide additional support for strong oxygen depletion of bottom waters. The conditions were comparable to the area of the Western Molasse, and most probably indicate a reduced water exchange to the open ocean and the occurrence of a temporarily stable halocline.

8.4. Environmental model for the Ottnangian Molasse Sea

In the North Alpine Foreland Basin, the Ottnangian environmental development can be compared with the model of Spaak et al. (1992) for enclosed (silled) basins. Accordingly, during periods of sea level lowstand, deep water renewal is limited and a stratified water column causes strong oxygen depletion of bottom waters. On the other hand, sea level highstands are periods of improved circulation. However, in basins with a positive water balance (fresh water input > evaporation) situated in humid areas, organic matter is provided by fluviatile discharge and high nutrient input may stimulate high primary productivity. Consequently, nutrient-rich bottom waters with some oxygen depletion may occur even during periods of sea level highstand. Conversely, in a silled basin with a negative water balance (evaporation > freshwater input), oligothrophic and oxygenated bottom waters occur during sea level highstand.

As a result, a model of a silled basin with a positive water balance can be proposed for the Ottnangian Molasse Sea (Pippèrr & Reichenbacher 2010; see here Fig. 6). High nutrient and organic matter input by rivers produced nutrient-rich environments, which is supported by planktonic foraminiferal and nannoplankton assemblages (*Coccolithus pelagicus*) indicative of nutrient-rich eutrophic environments (see 8.2.2 and Pippèrr & Reichenbacher 2010). Moreover, high freshwater input by rivers could have created an outflow (runoff) of comparatively less saline surface waters (see Fig. 6). In all, fluviatile input and estuarine circulation may have affected the relative abundances of planktonic foraminifers, besides other marine currents.

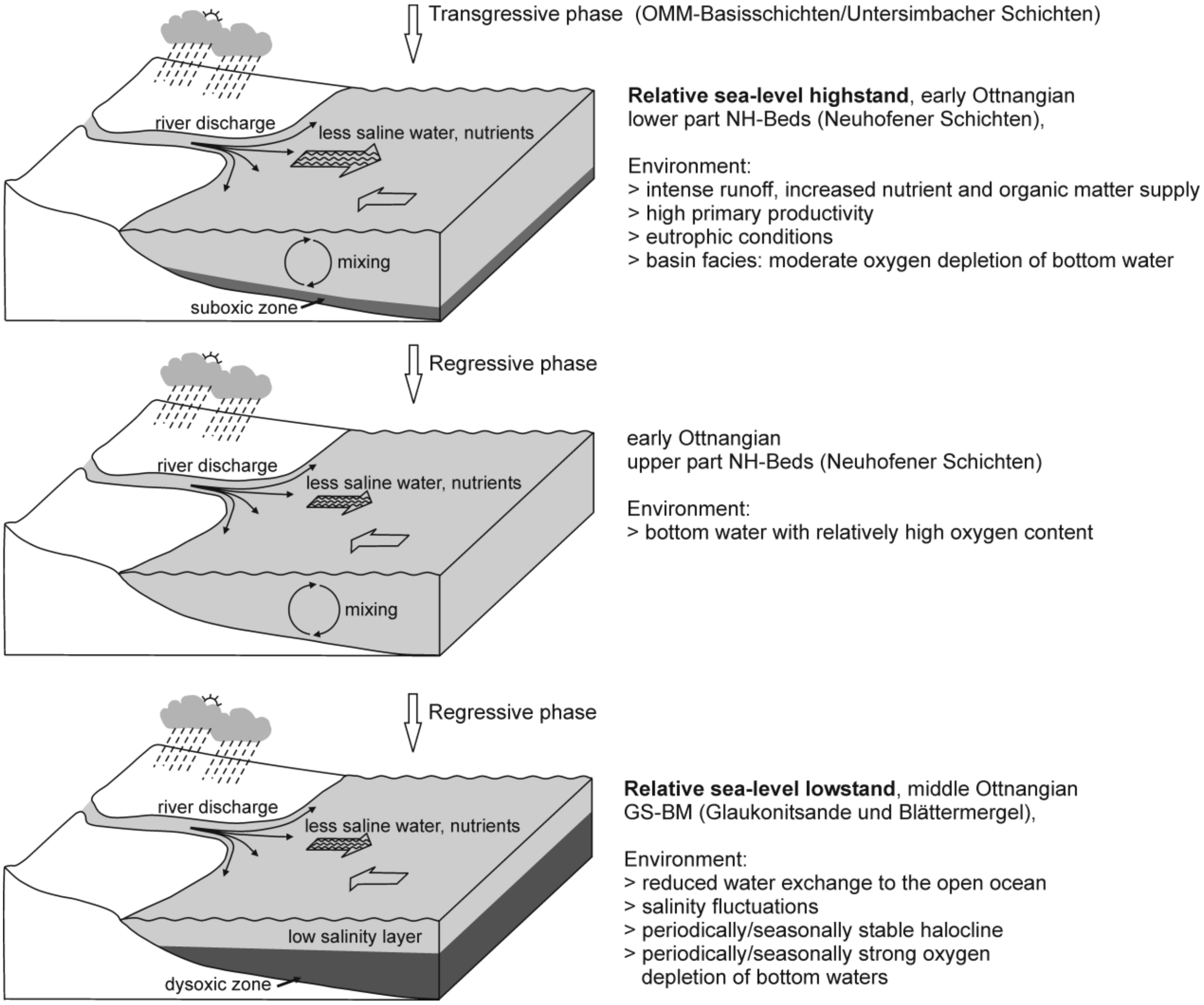

Fig. 6. Proposed environmental model for the Ottnangian Molasse Sea in the western Central Paratethys (according to Pippèrr & Reichenbacher 2010).

9. Summary

Benthic foraminifers are useful in biostratigraphic studies in the Western and Central Paratethys. Eggenburgian and Ottnangian assemblages can be differentiated based on several index fossils, and due to species composition and proportional abundances. Furthermore, a subdivision of the Ottnangian into a lower and middle segment (lower and middle Ottnangian) is possible on the basis of benthic foraminifers. In the easternmost sections of the German Molasse basin (borehole Altdorf and outcrops), benthic foraminiferal assemblages of the lower and middle Ottnangian are clearly different, but the change is gradual and a transition zone between the lower and middle Ottnangian assemblages appears. In contrast, the lower to middle Ottnangian transition is sharp and shows an abrupt change of benthic foraminiferal assemblages in the borehole Stockhausen and the Western Molasse.

In the Eastern Molasse (except Stockhausen and Simssee area) lithofacies and biofacies provide evidence for a single transgressive-regressive Ottnangian sequence, which is in accordance with other data from the Central Paratethys. There, the Ottnangian corresponds to a single third-order sea level cycle (Kovác et al. 2004; Piller et al. 2007). However, in Stockhausen and the Western Molasse Basin, the transgressive-regressive Upper Marine Molasse succession is subdivided into two sedimentations cycles and the data support the considerations of Lemcke et al. (1953) and Frieling et al. (2009a). Furthermore, the benthic foraminiferal assemblages reveal that the relative sea level highstand and maximum extension of the Upper Marine Molasse Sea took place during the early Ottnangian and not – as previously suggested – during the middle Ottnangian. In the early Ottnangian, the marginal marine (nearshore) facies is characterised by highly productive environments.

Moreover, benthic foraminiferal assemblages have been shown to serve as valuable proxies for palaeoecological and palaeoenvironmental reconstruction. In the Eastern Molasse (western Central Paratethys), the following environmental development can be suggested: (1) Eggenburgian: highly productive shallow water areas in Lower Bavaria (Ortenburger Meeressande) and partially outer neritic to upper bathyal environments to the south, i.e. in Upper Bavaria; (2) Eggenburgian-Ottnangian boundary: relative sea level drop and erosion period in Lower Bavaria; (3) lowermost Ottnangian (US-Beds/OMM-Basisschichten): transgressive phase with a distinct increase of foraminiferal abundance and diversity; (4) lower Ottnangian (lower NH-Beds): period of relative sea level highstand with outer neritic (Neuhofen), middle neritic (Altdorf) to marginal marine or nearshore (Gurlarn, Dommelstadl, Kemating, Neustift) environments; high organic flux and moderate oxygen depletion of bottom water in the basin facies; (5) lower Ottnangian (upper NH-Beds): a regressive phase with lower oxygen stress than before; (6) middle Ottnangian (GS-BM, Achen and Ulperting Fms): period of relative sea level lowstand; a shallow marine environment with unstable conditions, i.e. salinity fluctuations (temporarily decreased salinity) and periodically/seasonally strong oxygen depletion of bottom waters as a result of salinity stratification of water masses; (7) upper Ottnangian (Upper Brackish Water Molasse): brackish conditions and gradually decreasing salinity in Lower Bavaria and freshwater to brackish conditions in Upper Bavaria (Simssee area).

The Ottnangian benthic foraminiferal assemblages of the Western Molasse (Western Paratethys) differ significantly from those of the Eastern Molasse and the Central Paratethys, most probably due to different water depths (shallower in the Western Molasse) and co-varying environmental variables like substrate, sedimentation rate, turbulence, light, organic flux, and dissolved oxygen. In the Western Molasse, biofacies and lithofacies characterise again changing environmental conditions: (1) lowermost Ottnangian (HL-Beds): transgressive phase with a shallow marine environment; (2) lower Ottnangian (Kalkofen Fm.): inner to shallow middle neritic environment with increasing environmental stress; (3) middle Ottnangian (lower part of the Baltringen Fm.): marginal marine to inner neritic environment with well oxygenated water and more or less marine salinity; (4) middle Ottnangian (upper part of the Baltringen Fm. and Steinhöfe Fm.): shallowing and decreasing salinities, a period during which marine life conditions declined; (5) upper Ottnangian (Upper Brackish Water Molasse): brackish and freshwater conditions.

A model of a shallow epicontinental sea (silled basin), which was characterised by a positive water balance in a humide climate, can be proposed for the Ottnangian. Fluviatile input and marine currents most probably affected the P/B ratios, therefore the P/B ratios cannot confidently be used for determining paleodepths in the marine sediments of the study area. In addition, enhanced organic carbon fluxes could have produced carbonate dissolution and may be responsible for rare proportions of planktonic forms in sections where planktonic foraminifers could be expected (e.g. lower part of the NH-Beds). Moreover, the Ottnangian Upper Marine Molasse deposits in the Central Paratethys contain a planktonic foraminiferal assemblage that is typical for cold-temperate surface waters.

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Appendix

Appendix 1

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Appendix 2

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Appendix 3

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Appendix 5

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Appendix 7

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