The middle Burdigalian in the North Alpine Foreland Basin (Bavaria, SE Germany) – a lithostratigraphic, biostratigraphic and magnetostratigraphic re-evaluation

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With 8 figures and 3 tables

Abstract. For Oligocene and Miocene sediments of the Central Paratethys realm, regional chronostratigraphic stages have been defined on the basis of characteristic faunal assemblages, often containing abundant endemic elements. Although considerable progress has been made in correlating Paratethyan stages with the Global Time Scale (GTS), the task remains incomplete, especially for the Early Miocene period. The present study focuses on Lower Miocene deposits of the Central Paratethys in southeastern Germany, i.e. the Upper Marine Molasse (OMM) and Upper Brackish Molasse (OBM) of the North Alpine Foreland Basin (NAFB, Molasse Basin). The sediments concerned are assigned to the regional Ottnangian stage of the Central Paratethys, which corresponds to the middle Burdigalian in the GTS. We present a formal lithostratigraphic definition of the Untersimbach and Neuhofen Formations (both OMM), combined with litho-, bio- and magnetostratigraphic investigations, which together provide an improved chronology for the middle Burdigalian interval in the NAFB. The base of the Ottnangian stage is shown to correlate with polarity chron C5En, and we consider an absolute age of around 18.2 Ma to be most plausible. As the OMM in the southeast German part of the NAFB represents a single transgressive-regressive sequence, our new data suggest that the Ottnangian transgression began during chron C5En (~18.2 Ma), whereas the onset of the regressive phase lies within chron C5Dr.2r (~18 Ma). The uppermost marine deposits (top OMM/"Glaukonitsande & Blättermergel") and the lowermost brackish sediments (OBM/Oncophora Formation) are correlated with polarity chron C5Dn (~17.4 Ma). Moreover, our results clearly demonstrate that the lower Oncophora Formation (normal polarity) is not time-equivalent to the OBM/Kirchberg Formation in the southwest German sector of the NAFB (largely reverse polarity) as has hitherto been assumed. The lower Oncophora Formation is most probably contemporaneous with the lowermost OBM sediments (Grimmelfingen Formation) in the southwest German Molasse Basin.

Key words. Ottnangian, Upper Marine Molasse, Upper Brackish Molasse, Lithostratigraphy, Biostratigraphy, Magnetostratigraphy

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1. Introduction

The North Alpine Foreland Basin (NAFB), also referred to as the Molasse Basin, served as an important sedimentary basin from the Late Eocene/Early Oligocene until the Late Miocene. It formed part of the Central and Western Paratethys realm, and was filled with marine, brackish and terrestrial sediments that reflect the influence of global and regional sea-level fluctuations, climate change, and alpine tectonics (e.g. Lemcke 1988, Zweigel et al. 1998, Kuhlemann and Kempf 2002, Harzhauser and Piller 2007). The NAFB (Molasse Basin) of Switzerland and southwestern Germany largely relates to the Western Paratethys, while its counterpart in southeast Germany and Austria represents the westernmost Central Paratethys (e.g. Steininger et al. 1976, Harzhauser and Piller 2007).

The realm of the Western and Central Paratethys extended from the Rhône Basin in France across Central and Eastern Europe (Rögl and Steininger 1983, Popov et al. 2004). The rise of the Alpine–Carpathian, Dinaride and Balkan mountain ranges ultimately isolated this area from the Tethys, but intermittent connections were repeatedly established with the Mediterranean Sea, the Indo-Pacific and the Atlantic (e.g. Allen et al. 1985, Kuhlemann and Kempf 2002, Pippèrr et al. 2016). Regional chronostratigraphic stages have been defined for the Central Paratethys on the basis of characteristic faunal assemblages (especially molluscs and foraminifers) often containing abundant endemic elements (e.g. Piller et al. 2007, Hilgen et al. 2012). Although considerable progress has been made with the correlation of the Central Paratethys stages to the Global Time Scale (GTS) (e.g. Paulissen et al. 2011, de Leeuw et al. 2013, Palcu et al. 2015, Kirschcr et al. 2016), assignments of Lower Miocene stages remain controversial (e.g. Grunert et al. 2010, 2015, Reichenbacher et al. 2013, Sant et al. 2017, Teschner and Reichenbacher 2017).

This study provides new data relating to the chronology of the Early Miocene in the Central Paratethys, based on combined litho-, bio- and magnetostrati- graphic investigations in the SE German sector of the NAFB. The sections investigated here expose sediments that correspond to the middle Burdigalian of the GTS and can be assigned to the (regional) Ottnangian stage of the Central Paratethys (Fig. 1). The Ottnangian stage (Papp et al. 1973) was defined in a clay pit near the village of Ottnang in Upper Austria (outcrop Ottnang-Schanze, OMM, Ottnang Formation; Fig. 2). Index fossils used to recognize and further subdivide Ottnangian sediments mainly consist of molluscs and benthic foraminifers (Papp et al. 1973, Wenger 1987, Cicha et al. 1998, Piller et al. 2007). However, absolute age constraints are rare and/or ambiguous (Krijgsman and Piller 2012, Pippèrr and Reichenbacher 2017, Sant et al. 2017).

2. Geological setting

The marine sediments form part of the Upper Marine Molasse (Obere Meeremolasse, OMM), while the brackish deposits comprise a major segment of the Upper Brackish Molasse (Obere Brackwassermolasse, OBM) (Fig. 1). We use the German abbreviations ‘OMM’ and ‘OBM’ here in order to avoid confusion with the older Lower (‘Untere’) Brackish and Lower (‘Untere’) Marine Molasse terminology, abbreviated in German as ‘UBM’ and ‘UMM’.

2.1 The Upper Marine Molasse (OMM)

During the early to middle Burdigalian, a basin-wide transgression flooded the NAFB, and the area of the Western and Central Paratethys was connected to the western Mediterranean Sea by an open, but narrow seaway (e.g. Allen et al. 1985, Kuhlemann and Kempf 2002, Pippèrr et al. 2016). The Upper Marine Molasse represents the sediments that accumulated during this time span which corresponds to the Eggenburgian and Ottnangian in terms of Central Paratethys stages (Fig. 1).

The study area represents the SE German part of the NAFB. There the Ottnangian segment of the OMM is characterised by a single transgressive-regressive sequence, with fully marine conditions developing in the early Ottnangian and a more restricted marine environment characterizing the middle Ottnangian (Wenger 1987, Rupp et al. 2008, Pippèrr and Reichenbacher 2010, Pippèrr 2011, Grunert et al. 2012, Pippèrr et al. 2016). Lithostratigraphically, the OMM of the study area consists (from bottom to top) of the lower Ottnangian Untersimbach Beds (sensu Wenger 1987), the Neuhofen Beds and the middle Ottnangian “Glaucosande & Blättermergel” (glauconite sands and laminated marls) (Wenger 1987, Doppler et al. 2005, Pippèrr 2011, Fig. 1).

The microfossil assemblages (especially benthic foraminifers) of the OMM sediments in the study area have been described by Knipscheer (1952), Hagn (1953, 1981), Wenger (1987), Rupp et al. (2008) and Pippèrr (2011).
Beds contain poor to rich foraminiferal faunas. The Neuhofen Beds are characterized by a diverse and distinctive benthic foraminiferal assemblage, and can be correlated with the Ottnang Formation in Upper Austria (e.g. Wenger 1987, Rupp et al. 2008, Pippèrr 2011). The “Glaukonitsande & Blättermergel” contain benthic foraminiferal assemblages that decrease in diversity section upwards, with Ammonia being the most frequent taxon. This unit corresponds to the “Glaukonitische Serie” in Upper Austria (Ried Formation to Treubach Formation in Fig. 1B).

### 2.2 The Upper Brackish Molasse (OBM)

In the late Ottnangian, the sea gradually retreated from the NAFB. In the South German and Upper Austrian parts of the NAFB, brackish to limnic as well as terrestrial successions developed (Fig. 1), often collectively referred to as the Upper Brackish Molasse (e.g. Doppler and Schwerd 1996, Doppler et al. 2005, Pippèrr and Reichenbacher 2017: palaeogeographic maps). In the study area, in Upper Austria and in the Central Paratethys realm, the brackish Oncophora
Beds (Rzehakia (Oncophora) Formation sensu Papp et al. 1973) document the period during which the OBM accumulated (e.g. Čtyroký 1973a). The base of the Oncophora Beds is marked by an abrupt change in lithofacies, while the decrease in salinity occurred progressively (e.g. Schneider et al. 2011).

According to Pippèrr and Reichenbacher (2017), the Oncophora Beds are more or less time equivalent to the Grimmelfingen Formation in the SW German part of the Molasse Basin (see Fig. 1B). The OBM in this region can be subdivided into an upper Ottnangian regressive component (sediments containing the bivalve Rzehakia; Grimmelfingen Formation and equivalents) and a lower Karpatian transgressive segment (fossil-rich marls lacking Rzehakia; Kirchberg Formation and equivalents) (Fig. 1B).

3. Materials and methods

Lithostratigraphy: For lithostratigraphic descriptions two new OMM outcrops were studied in the area of the SE German Molasse Basin (Lower Bavaria) (Fig. 2). In the actively mined clay pit to the north of the village of Mitterdorf an approximately 12 m thick marly succession of the Neuhofen Beds was exposed in the years 2014 and 2015. Furthermore, the Beham section has not been described previously. It is currently the only outcrop that exposes a comparatively thick succession of the “Glaukonitsande & Blättermergel” unit (approximately 15–20 m).

Study sites: Samples for micropalaeontological and/or magnetostratigraphic investigations were taken from OMM and OBM sediments exposed at five locations in the SE German part of the Molasse Basin: Untersimbach (for details, see 4.1.1), Neuhofen and Mitterdorf (4.1.2), Beham (4.1.3) and a sunken lane near Prienbach-Dötting (4.1.4) (Fig. 2).

Micropalaeontology: To study their microfossil content, 14 samples were taken from the outcrop at Mitterdorf and one sample each from the outcrops at Neuhofen and Beham (Fig. 2). Fossil assemblages from Untersimbach and Neuhofen have been described in Pippèrr (2011) and those from the outcrop at Prienbach-Dötting in Schneider et al. (2011). The samples were first soaked in dilute hydrogen peroxide for several hours, then washed under running water through 63 μm and 200 μm mesh sieves. Microfossils were hand-picked under a stereomicroscope and sorted. Benthic foraminifers were identified to species-level (if possible), sorted and counted. Identification largely follows Wenger (1987), Cicha et al. (1998) and Rupp and Haunold-Jenke (2003).

Magnetostratigraphy: Samples for palaeomagnetic investigation were obtained from Untersimbach (21 OMM samples), Neuhofen (15 OMM samples), Mitterdorf (34 OMM samples), Beham (18 OMM samples), and Prienbach-Dötting (2 OMM and 14 OBM samples). At each outcrop bedding of the layers was sub-horizontal and the orientation of the drilled samples was measured using a standard Brunton compass.

The sampled material was treated with alternating-field (78%, 81 samples) and thermal (12%, 12 samples) demagnetization techniques at the University of Munich. Additionally, 7 samples from Neuhofen and 16 from Mitterdorf were demagnetized at paleomagnetic laboratory Fort Hoofddijk at Utrecht University. The demagnetization experiments were analysed by the least-squares approach of Kirschvink (1980, principal component analysis – PCA) using at least 6 consecutive demagnetization steps. Alternating-field demagnetization was carried out using the automated system at the University of Munich (Wack and Gilder 2012) and Utrecht University (Mullender et al. 2016). To investigate the magnetic polarity, the resulting declination and inclination of the PCA analysis were transformed into a virtual geomagnetic pole (VGP) latitude.
4. Results

4.1 Lithostratigraphy

The OMM sediments in the NAFB show considerable regional variation in facies, both from West to East and from South to North. As a result, a mixture of formal and informal names is currently used to describe the OMM deposits, and there is some disagreement with regard to the precise lithostratigraphic content of these units (Doppler et al. 2005, Heckeberg et al. 2010, Pippèrr 2011). Here, we introduce the formal lithostratigraphic names Untersimbach Formation and Neuhofen Formation following the recommendations of the International Stratigraphic Guidelines (Murphy and Salvador 1999, Steininger and Piller 1999). We further describe the “Glaukonitsande & Blättermergel”, for which we do not introduce a formation name since no section exists that fulfils the requirements for a type locality. Finally, we validate the name ʻOncophora Formation’ and give a short description of this formation. This unit has already been formally defined in Čtyroký et al. (1973a) under the name “Oncophora (Rzehakia) Formation.”

4.1.1 Untersimbach Formation (OMM)

Type locality: The sediments of the Untersimbach Formation (“Untersimbacher Schichten”) were first described by Wenger (1987), who had selected an outcrop near the small village of Untersimbach (Fig. 2), about 10 km SW of the city of Passau (GK: R 46 00 920, H 53 73 580), as the type section. In the past, the type section exposed about 10 m of sediment of the Untersimbach Formation, which was overlain by the marine marls of the Neuhofen Formation (transition to clay-rich and sand-poor marls; Wenger 1987). Today, the outcrop exposes the up to 10 m thick Untersimbach Formation, consisting of beige to brownish, laminated marls with intercalations of millimetre-thin layers of fine sands. Details of the litho- and biofacies, as well as the litho- and biostratigraphy of the Untersimbach section have been described in Wenger (1987), Pippèrr (2011), and Schneider et al. (2011).

Synonyms: The Untersimbach Formation encompasses the “Grobsande” [coarse sands] and “Sandmergel” [sandy marls] of Hagn (1953: Ortenburg drillings). The latter were named “Robulus-Schlier s.str.” by Knipscheer (1952: boreholes at Birnbach, Weihmörting, Füssing and elsewhere; see Wenger 1987). Moreover, the “Gerner Schichtenfolge” and the lower part of the “Alber Schichtenfolge”, described by Hölzl (1973), are equivalents of the Untersimbach Formation (see below). In many previous studies, the Untersimbach Formation was considered to be part of the Neuhofen Formation (e.g. Paulus 1963, Unger 1984, Doppler et al. 2005) and was not designated as a separate unit.

Age: The deposits of the Untersimbach Formation are assigned to the lowermost Ottnangian, based on benthic foraminiferal assemblages (Wenger 1987).

Description: The definition of the Untersimbach Formation follows the concept of the “Untersimbacher Schichten” introduced by Wenger (1987) because the foraminiferal assemblage clearly differs from that of the Neuhofen Beds (now Neuhofen Formation, see 4.1.2). However, the two formations can also be distinguished by their lithology. The deposits of the Untersimbach Formation include coarse to fine-grained sands in the lower part and sandy-marly, well bedded or finely laminated sediments in the upper part, whereas the clay-rich and sand-poor marls of the lowermost Neuhofen Formation are predominantly structureless.

The Untersimbach Formation occurs in the SE German part of the NAFB (roughly the area east of Munich; see Fig. 2). In Lower Bavaria (eastern Bavaria), several outcrops exposing the sediments of the Untersimbach Formation existed some decades ago (see Wenger 1987), but most of these sites are no longer extant. Apart from the type locality, only the abandoned clay pit to the north of the village of Wallham (about 1.3 km SW of Untersimbach, see Fig. 2C) still exposes approximately 3–4 m of laminated sandy-marly sediments of the Untersimbach Formation. Moreover, the Untersimbach Formation has also been described from several boreholes in Lower Bavaria (Table 1). According to the evidence from the three Ortenburg drillings (CF 1001, 1002, 1003; Hagn 1953, Wenger 1987), the thickness of the Untersimbach Formation increases from 51 m to 60.6 m to 83 m towards the south (see Table 1 and Fig. 2). Both the ‘coarse sand facies’ of the lowermost Untersimbach Formation and the overlying fine-grained ‘sandy-marly facies’ are identifiable in all three drillings. The maximal thickness of the Untersimbach Formation – 116 m – is reached in the borehole SW of Füssing (Aigner Forst; Wenger 1987). In the drilling undertaken NW of Füssing (Osterholzen), the ‘coarse sand facies’ (24.3 m) largely comprises coarse- to medium-grained, partially fine gravelly sands with abundant glauconite in the upper part. This is followed on top by fine-grained sands (15 m), and
sandy marls with intercalations of fine-grained sands (70 m) (Wenger 1993).

The Untersimach Formation can transgressively overlie Aquitanian (upper Egerian) sediments of the Lower Marine Molasse, the so-called “Aquitan-Fischschiefer” (e.g. boreholes Ortenburg CF 1001, 1002, Osterholzen). Hence, no deposits of Eggenburgian OMM are present at these locations (Wenger 1987). Otherwise, for example in the borehole Ortenburg CF 1003, the Untersimach Formation overlies sandy-marly OMM deposits of the “Planularia buergli Horizon” (based on the abundant occurrence of the benthic foraminifera *Planularia buergli*, now *Lenticulina buergli*). These sediments were correlated with the Eggenburgian by Pippèrr and Reichenbacher (2009). It thus appears that the Eggenburgian OMM deposits have been partially eroded in the area of Lower Bavaria (for details see Wenger 1987).

In Upper Bavaria (southern Bavaria), the OMM exposed in the Kaltenbachgraben [Kaltenbach valley] represents a facies-stratotype of the Ottngian stage (Papp et al. 1973). The section exposes strata equivalent to those of the Untersimach Formation (“Gerner Schichtenfolge” and parts of the “Alber Schichtenfolge” sensu Hözl 1973, in Papp et al. 1973). The Ottngian succession designated as the “Gerner Schichtenfolge” discordantly overlies Eggenburgian sediments (Hölzl 1973). It is about 30 m thick and composed of fine- to coarse-grained, sometimes gravelly sands with numerous bioclasts (e.g. marine bivalves and gastropods, bryozoans, corals) and some marly layers (Hölzl 1973). This is followed by a ‘sandy-marly facies’ (> 80 m; lower part of the “Alber Schichtenfolge”) with sediment structures such as parallel lamination or wavy bedding (Hölzl 1973 and own investigations). These sediments are in turn overlain by the marls of the Neuhofen Formation (upper part of the “Alber Schichtenfolge”, see Wenger 1987).

**Fossil assemblages**: Macrofossils are usually absent in the Untersimach Formation. A diverse assemblage of bivalves and gastropods is solely known from the Kaltenbachgraben (see above and Hölzl 1973). Planktonic and benthic foraminifera, as well as fragments of bryozoans, ostracods, nanoplankton, radiolarians and diatoms (*Coscinodiscus*) are rare to abundant in the Untersimach Formation (Wenger 1987, Pippèrr 2011). The benthic foraminiferal assemblage of the Untersimach Formation can be clearly distinguished from that of the Neuhofen Formation, and taxa characteristic of the latter (e.g. *Spiroplectammina pectinata*, *Sigmoilopsis ottnangensis*, and *Amphicoryna ottnangensis*) are sparsely represented (see Wenger 1987, Pippèrr 2011). In Lower Bavaria, *Lenticulina (= Robulus)* is the dominant taxon in the sandy-marly sediments of the Untersimach Formation (upper part of the formation).

At the type locality in Untersimach, the benthic foraminiferal assemblages are partially relatively diverse, with *Lenticulina inornata / L. melvilli* being most abundant (Wenger 1987: 80%; Pippèrr 2011: up to 66.3%). In addition, *Fursenkoina acuta*, *Nonion commune* and *Cibicidoides lopjanicus / C. tenellus* are relatively common (see Pippèrr 2011). In the uppermost part of the type locality, taxa characteristic of the Neuhofen Formation, i.e. *S. ottnangensis*, *S. pectinata*, and

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Untersimach Fm (coarse sand facies)</th>
<th>Untersimach Fm (sandy-marly facies)</th>
<th>Neuhofen Fm</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altdorf</td>
<td>OMM-Basisschichten: 10.7 m</td>
<td>33.35 m</td>
<td>Pippèrr &amp; Reichenbacher (2010)</td>
<td></td>
</tr>
<tr>
<td>Ortenburg CF 1003</td>
<td>38 m</td>
<td>13 m</td>
<td>14 m</td>
<td>Hagn (1953), Wenger (1987)</td>
</tr>
<tr>
<td>Ortenburg CF 1001</td>
<td>19.1 m</td>
<td>41.5 m</td>
<td>31.1 m</td>
<td>Hagn (1953), Wenger (1987)</td>
</tr>
<tr>
<td>Ortenburg CF 1002</td>
<td>8.2 m</td>
<td>74.8 m</td>
<td>49.9 m</td>
<td>Hagn (1953), Wenger (1987)</td>
</tr>
<tr>
<td>Bi./Wei./Füssing i.a.</td>
<td>up to ~ 20 m</td>
<td>~40 to 50 m</td>
<td>~30 m</td>
<td>Knipscheer (1952), Wenger (1987)</td>
</tr>
<tr>
<td>NW Füssing (Osterholzen)</td>
<td>Untersimach Fm: 109.3 m</td>
<td>68.5 m</td>
<td>Wenger (1993)</td>
<td></td>
</tr>
<tr>
<td>SW Füssing (Aigner Forst)</td>
<td>Untersimach Fm: at least 116 m</td>
<td>106.5 m</td>
<td>Wenger (1993)</td>
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</tr>
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</table>

Table 1 Thicknesses of the Neuhoen and Untersimach Formations in different boreholes (Bi./Wei./Füssing i.a. = boreholes Birnbach, Weihmörting, Füssing and others, described in Knipscheer 1952; NW Füssing = borehole to the northwest of Füssing; SW Füssing = borehole to the southwest of Füssing, described in Wenger 1993). According to Wenger (1987), the Untersimach Formation includes the series of coarse sands and sandy marls (“Grobsande” and “Sandmergel” sensu Hagn 1953) as well as the “Robulus-Schlier s. str. ” sensu Knipscheer (1952).
Fig. 3. Profiles of the outcrops Untersimbach, Neuhofen, Oberschwärzenbach and Höhenmühle with ranges of stratigraphically important benthic foraminiferal species (Pippèrr 2011) and palaeomagnetic data for the Untersimbach and Neuhofen sections (this study). For the sections Untersimbach (Untersimbach Formation) and Neuhofen (Neuhofen Formation) the measured VGP latitude is plotted versus stratigraphic height (left). Also shown are the mean directions for samples from all sections with their according overall mean directions for the normal and reverse polarities, respectively. In the polarity columns, the black zones indicate normal polarity.
A. ottnangensis, begin to appear, indicating the transition towards the Neuhofen Formation (Fig. 3).

Environment: The fining upwards most probably reflects a deepening of the sea resulting from the Ottnangian transgression. In the upper section of the Untersimbach Formation, benthic foraminiferal assemblages are indicative of a middle neritic environment (for details see Pippèrr 2011).

Correlations: The lower Ottnangian, extremely glauconite-rich, coarse-grained sands and gravels of the “OMM-Basisschichten” [OMM base layers] described from the borehole Altdorf by Pippèrr and Reichenbacher (2010) are comparable to the lowermost section of the Untersimbach Formation in the other boreholes (Table 1). The “OMM-Basisschichten” (Fig. 1) have also been described from the SW German part of the Molasse Basin (Doppler et al. 2005, Pippèrr et al. 2016). In Upper Austria, the lower Ottnangian sediments of the Vöckla and Atzbach Formations (Rupp et al. 2008, here Fig. 1) are most probably equivalents of the Untersimbach Formation. Moreover, the benthic foraminiferal assemblage of the upper Untersimbach Formation, especially the abundance of Lenticulina, is comparable to that of the sandy-marly sediments of the “Robulus-Schlier” in Upper Austria (sensu Rupp et al. 2011). These sediments have been correlated with the lowermost Ottnangian and are contemporaneous with the Vöckla Formation (Rupp et al. 2011).

4.1.2 Neuhofen Formation (OMM)

Type locality: The marls of the Neuhofen Formation were first described by Neumaier and Wieseneder (1939) as “Mergel östlich von Neuhofen” [marls east of Neuhofen]. The type locality ( GK: R 45 94 563, H 53 70 071) is an abandoned clay pit near the small village of Neuhofen, about 7 km SW of the Untersimbach section (Fig. 2). The outcrop has been categorized by the Bavarian Environment Agency as a geotope (Geotope Number: 275A025). Today, the outcrop comprises only the lowermost part (about 5 m) of the previously accessible 20–30 m thick sediment succession (Neumaier and Wieseneder 1939). Nevertheless, the marls of the Neuhofen Formation are still recognizable below tree roots in the hillside above the outcrop. The Neuhofen section has been described by several authors (e.g. Neumaier and Wieseneder 1939, Unger 1984, Wenger 1987). Its deposits consist of massively bedded, homogeneous, medium-grey, clay-rich and sand-poor marls. Occasionally, indistinct stratification and lamination occur. The most recent study of the type section has been presented by Pippèrr (2011), who provided detailed data for the currently exposed succession, including descriptions of sediments and microfossils (especially foraminifers).

Reference section: The actively mined clay pit (GK: R 45 94 947, H 53 74 261) to the north of the village of Mitterdorf (Fig. 2), which is owned and run by the “Tonwarenfabrik und Granitwerke Fürstenzell Ferdinand Erbersdobler”, is the only available reference section of the Neuhofen Formation in Lower Bavaria. In the years 2014 and 2015, an approximately 12 m thick marly succession was exposed in the clay pit (Fig. 4). This can be subdivided into two parts based on slight differences in the lithofacies. The lower segment, some 7.5 m thick, is composed of medium grey, massively bedded and homogeneous clayey-to-silty marls. Macrofossils are sparse, comprising occasional small bivalves and gastropods. This is the typical lithofacies of the Neuhofen Formation as present at their type section. Above a mining floor, medium-grey to bluish-grey marls with an increasing sand content characterize the upper part of the section (Fig. 4). The sediments are structureless, but pieces of consolidated marls with narrow intercalations of sand occur at places. In the uppermost part of this segment, the marls are often disturbed and large (up to 1 m) boulders of “Quarzkonglomerat” [quartz conglomerate] typical of the Upper Freshwater Molasse are also found (Fig. 4). This is most probably due to Pleistocene soil creeps and slides that have led to the mixture of stratigraphically different layers, as can be observed at several other places in the region (see Unger 1984).

Synonyms: Since the study by Neumaier and Wieseneder (1939), the sediments have been referred to as “Neuhofener Schichten”, “Neuhofener Mergel” or Neuhofen Beds by most subsequent authors. However, the lithostratigraphic content of the Neuhofen Beds in these studies is not always specific, as most authors did not consider the sediments of the Untersimbach Formation as separate from the “Neuhofen Beds” (see above). Moreover, the upper part of the “Alber Schichtenfolge”, described by Hözel (1973), is an equivalent of the Neuhofen Formation (see below).

Age: The sediments of the Neuhofen Formation are characterized by rich and diverse benthic foraminiferal assemblages, which are indicative for the lower Ottnangian (e.g. Knipscheer 1952, Hagn 1953, 1981, Wenger 1987, Pippèrr and Reichenbacher 2010, Pippèrr 2011). Characteristic lower Ottnangian taxa are
Sigmoilopsis ottnangensis, Spiroplectammina pectinata, Lenticulina inornata/L. melvilli, and Amphicoryna ottnangensis, and these species are all abundantly represented in the lower section of the Neuhofen Formation (e.g., outcrop Neuhofen, see Pippèrr 2011, here Fig. 3). In contrast, in the uppermost part of the Neuhofen Formation (e.g., outcrops Oberschwärzenbach and Höhenmühle; Fig. 3) these taxa become less common. Very rare occurrences of the above-mentioned species have only occasionally been documented from the lowermost part of the middle Ottnangian “Glaukonitsande & Blättermergel” that overlie the Neuhofen Formation (Wenger 1987, Pippèrr 2011).

**Description:** The Neuhofen Formation overlies the Untersimbach Formation without discontinuity. However, each formation is characterised by a distinct lithofacies. In contrast to the Untersimbach Formation (see 4.1.1), the Neuhofen Formation is dominated by a massively bedded and homogeneous succession of clayey marls. The Neuhofen Formation is restricted to the SE German part of the NAFB (i.e., the area to the east of Munich, see Fig. 2B).

In **Lower Bavaria**, several outcrops exposing the sediments of the Neuhofen Formation existed some decades ago (see Wenger 1987, Pippèrr 2011), but most of these sites (e.g., Oberschwärzenbach and Hö-
henmühle, Fig. 3) are no longer accessible. In the abandoned clay pit Höhenmühle, the gradual transition from the Neuhofer Formation to the facies of the middle Ottnangian “Glaubonitsande & Blättermergel” was visible until a few years ago. It revealed a 3 m thick segment of the Neuhofer Formation, composed of marls with very thin laminae (~1 mm) and lenses (up to ~3 mm) of fine sand. This facies then shifted to an 8-to-10 m thick “Blättermergel” succession of laminated or thinly interbedded marls and sands (Schneider et al. 2011). Furthermore, the Neuhofer Formation was described from several boreholes in Lower Bavaria, where it usually overlies the Untersimbach Formation and varies in thickness from 14 m in the north to 106.5 m in the south (Table 1). In the borehole Altdorf (Pippèrr and Reichenbacher 2010), the Neuhofer Formation overlies a transgressive OMM-basis layer (“OMM-Basisschichten”, see 4.1.1). Above the Neuhofer Formation, the lithofacies of the middle Ottnangian “Glaubonitsande & Blättermergel” follows in all boreholes.

In Upper Bavaria, homogeneous successions of medium grey, clayey-to-silty or sandy marls with the typical benthic foraminiferal assemblages of the Neuhofer Formation (see above) are exposed at several places along the upright southern edge of the autochthonous Foreland Molasse. Important outcrops include those at the Kaltenbach site (Wenger 1987; Neuhofer Formation as upper part of the “Alber Schichtenfolge”), the exposures in the Simssee area (unpublished data of M.P.) and the profiles along the valleys of the rivers Prien and Sur (Wenger 1987). The Neuhofer Formation can reach thicknesses of more than 100 m in this area, and is overlain by middle Ottnangian glauconitic sands and silty to sandy marls (Hölzl 1973, Wenger 1987, Pippèrr et al 2007). The borehole Endorf 1, located in the Simssee area (see Fig. 2B), revealed a 275 m thick marine succession of “Unteres Helvétien” (= lower Ottnangian OMM) consisting of grey clayey or sandy marls (Paulus 1963). The foraminiferal assemblage that is typical of the Neuhofer Formation can be recognised in the uppermost 100 m, whereas the sediments below yielded few fossils (Paulus 1963) and probably represent the Untersimbach Formation.

Fossil assemblages: Thin macrofossil-rich layers occur only occasionally and can contain fish otoliths (e.g. from myctophid fishes), teeth of bony fishes and sharks, bivalves, scaphopods, brachiopods and bryozoans (Schneider et al. 2011, Pollerspöck and Straube 2017, Tescher and Reichenbacher 2017). The most abundant microfossils in the Neuhofer Beds are foraminifers. Additionally, ostracods (see Hagn 1981), nanoplankton (see Martini 1981), radiolarians and diatoms (Coscinodiscus) occur (see Pippèrr 2011).

The Neuhofer Formation is characterised by its rich and characteristic benthic foraminiferal assemblages (see 4.2; Figs. 3 and 4), which have been described in many studies (e.g. Knipscheer 1952, Hagn 1953, 1959, 1981, Wenger 1987, Pippèrr and Reichenbacher 2010, Pippèrr 2011). Here we present a new comprehensive data set from the reference section Mitterdorf (see 4.2).

Environment: The benthic foraminiferal assemblages indicate that the Neuhofer Formation represents the deep neritic basin facies of the early Ottnangian Central Paratethys Sea (Wenger 1987, Pippèrr 2011). Studies in eastern Bavaria have shown a regressive trend during the sedimentation of the Neuhofer Formation (Hagn 1981, Wenger 1987, Pippèrr and Reichenbacher 2010, Pippèrr 2011). The sand-poor marls at the type locality represent the lowermost Neuhofer Formation and were deposited during a sea-level highstand, with a water depth of >100 m (Pippèrr 2011). Upwards follows a regressive phase with an increasing content of fine sand and a gradual change in the biofacies (see Wenger 1987, Pippèrr and Reichenbacher 2010).

Correlations: Macro- and microfossil-rich marginal marine or nearshore equivalents of the Neuhofer Formation have been reported from the north-eastern margin of the South German part of the NAFB. Examples include the outcrops Holzbach and Höch (Wenger 1987), Neustift and Dommelstadl (Pippèrr 2011) and Gurlarn (Frieling et al. 2009, Schneider et al. 2011). In Neustift and Gurlarn, the marine sediments occur directly above the granitic basement of the Bohemian Massif.

In the SW German part of the NAFB, the Kalkofen Formation (introduced in Heckeberg et al. 2010) is an equivalent of the Neuhofer Formation (Hagn 1961, Pippèrr 2011). In Upper Austria, the Ottnang Formation can be correlated with the Neuhofer Formation (Rupp et al. 2008).

4.1.3 Glaukonitsande and Blättermergel

Description: In the SE German sector of the NAFB (Lower Bavaria), the “Glaubonitsande & Blättermergel” (glauconite sands and laminated marls) succession, up to 70 m thick, overlies the Neuhofer For-
formation or its marginal marine nearshore equivalents (e.g. Holzbach: Hagn 1981; Neustift: Schneider et al. 2011; Gurlarn: Frieling et al 2009). As indicated by its name, this informal lithostratigraphic unit comprises two lithofacies, i.e. glauconitic sands (“Glaukonitsande”) and grey-brown marls with thin sand-silt layers (“Blättermergel”), which are intercalated or interfinger laterally (Salvermoser 1999, Doppler et al. 2005). The glauconitic facies consists of fine- to medium-grained sands with abundant mud clasts or thin marly layers in places. The sands are either structureless or exhibit various kinds of sedimentary structures, such as horizontal lamination, wavy bedding, or cross-bedding (Salvermoser 1999).

**Beham section:** The Beham section (Figs. 2 and 5; GK: R 45 86 894, H 53 53 425) has not been described previously and is currently the only outcrop that exposes a comparatively thick succession of the “Glaukonitsande & Blättermergel” unit. It is located in a narrow and almost inaccessible valley near the small hamlet of Beham (Fig. 2B). The approximately 15–20 m thick OMM succession consists of alternating medium-grained sands and brownish, finely layered to laminated sandy marls (“Blättermergel” facies). OBM deposits (Oncophora Formation, “Mehlsande”) follow above an estimated > 20-m outcrop gap.

**Age:** The “Glaukonitsande & Blättermergel” have commonly been correlated with the middle Ottnangian (e.g. Hagn 1981, Wenger 1987, Pippèrr 2011). However, in some cases – above all in marginal marine settings – the rarity or complete lack of micro- and macrofossils hampers proper correlation and at such sites a middle Ottnangian age is uncertain.

**Fossil assemblages:** Macrofossils are for the most part absent in the “Glaukonitsande & Blättermergel”, however, some sections in Lower Bavaria expose a fossiliferous sandy facies. A description of these fossiliferous sediments and a comprehensive list of the macrofauna (27 bivalve species and 9 gastropods) have been provided by Schneider and Mandic (2014). In addition, the “Glaukonitsande & Blättermergel” contain locally rich benthic foraminiferal assemblages (e.g. glauconitic sands of Gänshall: Wenger 1987, Pippèrr 2011) and ostracods can also occur (e.g. borehole Altdorf: Pippèrr and Reichenbacher 2010). However, in most cases foraminifers occur rarely and Ammonia is the most abundant taxon (e.g. Hagn 1981, Wenger 1987, Pippèrr and Reichenbacher 2010).

**Environment:** The “Glaukonitsande & Blättermergel” generally contain benthic foraminiferal assemblages typical of very shallow (marginal marine to in-
ner neritic) environments. The middle Ottnangian was a period during which marine life conditions declined due to shallowing and freshwater influx (e.g. Wenger 1987, Pippèrr and Reichenbacher 2010).

Correlations: The “Glaукonitsande & Blättermergel” correspond to the “Glaукonitische Serie” in Upper Austria (Ried Formation to Treubach Formation in Fig. 1B). In Upper Bavaria (Simssee area), middle Ottnangian lithostratigraphic units include the Achen and Ulperting Formations (see Pippèrr et al. 2007). In the SW German Molasse Basin, the Baltringen and Steinhöfe Formations are more or less contemporaneous with the middle Ottnangian “Glaукonitsande & Blättermergel” (see Heckeberg et al. 2010) (Fig. 1).

4.1.4 Oncophora Formation (OBM)

Type locality: The six type sections (facies-stratotypes) of the Oncophora Formation in Lower Bavaria – Loderham, Hinterholzer Bach, Brombach, Türkemberg, Kühstetten and Walksham – are located between the rivers Inn and Rott, near Simbach am Inn (Čtyroký et al. 1973a).

Description: In Lower Bavaria and Upper Austria, the Oncophora Formation (Rzehakia (Oncophora) Formation sensu Papp et al. 1973) overlies the OMM deposits (“Glaукonitsande & Blättermergel” in Germany and the “Glaукonitische Serie” in Austria). The name of the formation (= Oncophora Schichten or Oncophora Beds, Oncophora-Sande or Oncophora sands) derives from the bivalve Rzehakia (previously Oncophora), which is abundant in this lithostratigraphic unit. The name Oncophora Formation is retained here, although formal lithostratigraphic units should consist of an appropriate geographic name and not of a fossil. However, the International Stratigraphic Guide (Murphy and Salvador 1999) recommends that traditional or well established names – like the name Oncophora Formation – should not be abandoned when they are or may become well defined or characterised. Since the Lower Bavarian Oncophora Formation is well established and has been described in detail by several authors (e.g. Čtyroký et al. 1973a, Schlickum and Strauch 1968, Schlickum 1971, Lemcke 1988, Reichenbacher 1993, Rupp et al. 2008), the name should be retained for the OBM sediments in Lower Bavaria and Upper Austria.

The Oncophora Formation can reach a thickness of up to 70 m (Rupp et al. 2008). A further subdivision was established by Schlickum and Strauch (1968), who distinguished the lower Oncophora Formation (including “Mehlsande”, “Schillhorizont” and “Glimmersande”) from the upper Oncophora Formation (comprising “Aussüßungshorizont”, “Schillsand” and “Lakustrische Schichten”). The individual beds are characterized both by their lithofacies and fossil assemblages (see below). The lower Oncophora Formation is predominantly sandy, while the upper Oncophora Formation is less sandy and mainly comprises silts and marls.

In Upper Bavaria (Simssee area, see Fig. 2B), the OBM sediments and their fossil contents are clearly distinct from the Oncophora Formation in Lower Bavaria. Therefore, a new unit – the Aschaholz Formation – was introduced by Pippèrr et al. (2007).

Prienbach-Dötling section: Currently, the lower part of the Oncophora Formation is well exposed in a sunken lane (GK: R 45 78 941, H 53 50 783) near the small hamlet of Prienbach-Dötling (Schneider et al. 2011, here Figs. 2 and 6), which is situated in the Inn Valley about 4 km northeast of the town of Simbach a. Inn. Close to the lower end of this hollow way, a small outcrop (about 2 m) exposes the uppermost part of the marine “Glaукonitsande & Blättermergel” (OMM) and the flanks of the hollow way itself reveal an approximately 30 m thick succession of the lower brackish Oncophora Formation (Fig. 6).

Age: In the NAFB, deposits with abundant Rzehakia have been regarded as characteristic for the late Ottnangian (e.g. Schlickum 1971, Papp et al. 1973, Reichenbacher 1993, Rupp et al. 2008, Pippèrr and Reichenbacher 2017).

Fossil assemblages: Bivalves and gastropods as well as ostracods, fish otoliths and charophytes, in the “Mehlsande” also benthic foraminifers, can be abundant in the Oncophora Formation (see Schlickum and Strauch 1968, Čtyroký et al. 1973a, Reichenbacher 1993, Rupp et al. 2008). Rzehakia guembeli is the most abundant faunal constituent in the lower Oncophora Formation and is sometimes found together with Limnopageta bavarica, Mytilopsis rottensis and several gastropods (Schlickum 1971, Schneider et al. 2011). Mytilopsis rottensis and Limnopageta are the most abundant taxa in the upper Oncophora Formation, while Rzehakia is absent or occurs sparsely; several species of gastropods are also present (Schlickum and Strauch 1968, Reichenbacher 1993).

Environment: The sediments of the Oncophora Formation were deposited in a shallow brackish environ-
Correlations: According to Pippèrr and Reichenbacher (2017), the lower Oncophora Formation (Lower Bavaria and Upper Austria) is more or less time equivalent to the Grimmelfingen Formation in the SW German part of the Molasse Basin (Fig. 1). In Lower Austria, the Traisen Formation is an equivalent of the Oncophora Formation (see Gebhardt et al. 2013). The sediments of the Traisen Formation are largely decalcified and fossil-free and thus clearly different from the Oncophora Formation.

4.2 New micropalaeontological data

The foraminiferal assemblages and other fossils from the sites Untersimbach and Neuhofen were previously described in detail in Pippèrr (2011). The micro- and macrofauna from the Prienbach-Dötling outcrop is indicated in Schneider et al. (2011). For this study one new sample was taken from sediments in the hillside approximately 20 m above the outcrop Neuhofen. This sample yielded a number of well-preserved benthic foraminifera, whereas planktonic foraminifers are rare and corroded. In addition numerous well-preserved ostracods occur. The benthic foraminiferal assemblage contains *Sigmoilopsis ottnangensis*, *Spiroplectammina pectinata*, *Lenticulina inornata/L. melvilli*, *Amphicoryna ottnangensis*, and other taxa (e.g. *Laevidentalina communis*, *Fursenkoina acuta*) known to be typical for the Neuhoen Formation (see also Fig. 3).

Only limited data is available in the literature for the OMM strata near Mitterdorf. A now vanished exposure – close to the clay pit described here – was reported by Hagn (1981) and Wenger (1987). The microfossil assemblages of the sediments in the new clay pit at Mitterdorf have not been described before. The most abundant microfossils in the 12 studied samples are usually well-preserved benthic foraminifers (Table 2) and ostracods. Tests of planktonic foraminifers are sparsely distributed in most samples (see Table 2) and are often not well preserved. The assemblages contain *Globigerina praebulloides*, *G.ottnangensis*, *G.lentiana*, and *Tenuitellinata angustumbilicata*. In addi-
Table 2 Foraminifers from Mitterdorf. List of benthic foraminiferal species and absolute numbers found in the samples, as well as numbers of benthic and planktonic foraminifers per sample. *Bulimina* spp. = *Bulimina elongata* d’Orb./*B. schischkinskayae* Samoilova; *Cibicoides* spp. = *Cibicoides lopjanicus* (Myatlyuk)/*C. renellus* (Reuss) and other species; planktonic foraminifera = *Globigerina praebulloides* Blow, *G. ottnangensis* Rögl, *G. lentiana* Rögl, *Tenuitellinata angustiumbilicata* (Boll.).

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<th>Samples Mitterdorf</th>
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<td>70</td>
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<td>75</td>
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<td><em>Bolivina dilatata</em> Reuss</td>
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<td><em>Bolivina scitula</em> Hofmann (partly cf.)</td>
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<td>83</td>
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<td><em>Bolivina</em> sp. indet.</td>
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<td><em>Amphicoryna ottnangensis</em> (Toula)</td>
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<td><em>Silostomella perscripta</em> (Egger)</td>
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<td><em>Elphidium crispum</em> (Linne)</td>
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<td><em>Elphidium fichteliamum</em> (d’Orb.)</td>
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<td><em>Elphidium glabratum</em> Cushman</td>
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<td><em>Elphidium cf. hauerinum</em> (d’Orb.)</td>
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<td><em>Elphidium macellum</em> (Fichtel &amp; Moll)</td>
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<td><em>Elphidium ortenburgense</em> (Egger)</td>
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<td><em>Elphidium subtypicum</em> Papp</td>
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<td><em>Elphidium matzenense</em> Papp</td>
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<td><em>Elphidium</em> sp. indet.</td>
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<td><em>Elphidiella heteropora</em> (Egger)</td>
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<td><em>Elphidiella semincisa</em> Wenger</td>
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<td><em>Nonion commune</em> (d’Orb.)</td>
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<td><em>?Pullenia quinqueloba</em> (Reuss)</td>
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<td><em>Melonis pomplioides</em> (Fichtel &amp; Moll)</td>
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tion, some fragments of molluscs or balanids, echinoid spines, shark teeth, and fish otoliths occur in several samples. The benthic foraminiferal assemblage is relatively diverse (more than 65 species, Table 2) and hyaline taxa are most abundant. The agglutinated group is represented by only three taxa (Textularia, Siphotextularia and Spiroplectammina). Miliolids occur with Sigmoilopsis (partly very abundant), Sigmoilinita (very rare) and Quinqueloculina (a few fragments). In the samples Mitterdorf 2015/01 to 2014/11 (Fig. 4), the assemblages of benthic foraminifera are mainly dominated by large-sized specimens of L. inornata/L. melvilli (2 to 259 individuals per sample), small- to large-sized S. ottnangensis (0 to 146 individuals per sample), and/or small-sized Bolivina scitula (21 to 250 individuals per sample). Other common taxa include Textularia gramen, Spiroplectammina pectinata, Laevidentalia communis, Amphimorphina haueriana, Fursenkoina acuta, Fursenkoina mustoni, Amphicoryna ottnangensis, and Alabamina tangentialis (Table 2). Well-preserved and sometimes large-sized specimens of Elphidium occur only in the upper part of the outcrop (samples 2014/8 to 12), whereas in the lower part only a few small-sized and corroded tests of Elphidium were found.

Overall, the Mitterdorf samples contain benthic foraminiferal assemblages that are characteristic for the Neuhofen Formation (Fig. 4). The sand-poor marls in the lower part of the outcrop include foraminifera that are typical for the lower section of the Neuhofen Formation (abundant S. ottnangensis, S. pectinata, L. inornata/L. melvilli, and A. ottnangensis, Fig. 4). The upper part of the outcrop shows a striking increase in the abundance of Elphidium, which is a general characteristic of the upper section of the Neuhofen Formation.

The glauconitic sands and sandy marls of Beham (“Glaukonitsande & Blättermergel”) contain few benthic and planktonic foraminifers. Ammonia is most abundant, while Elphidium, Elphidiella minuta, Nonion commune and Cibicidoides also occur. Foraminiferal assemblages of such low diversity are typical for middle Ottnangian sediments in the NAFB.

### 4.3 Magnetostratigraphic data

In all cases thermal and AF (alternating field) demagnetization results show similar behaviour. In Mitterdorf only about 60% of the demagnetization experiments show interpretable results, whereas all samples from the other sections yielded coherent demagnetization data and were used for further interpretation (Fig. 7). Each individual polarity interval, which was initially identified by AF demagnetization, was confirmed by at least one thermally demagnetized sample. We point out that it has been shown and discussed previously that even if the lithology differs quite extensively in this kind of sediments, the magnetic signal is ideal for magnetostratigraphic investigations (Kirsch-
Fig. 7. Results of stepwise thermal and alternating field (AF) demagnetization experiments, shown on orthogonal vector endpoint diagrams (Zijderveld 1967), of representative samples from all studied sections. Open (closed) symbols indicate projections onto the vertical (horizontal) plane. Heating steps and AF steps are indicated in °C and mT, respectively. Also shown are all remagnetization great circles based on samples from the Mitterdorf section (MI-GC), which yield a reversed polarity. The mean direction is noted together with the most likely endpoint direction of each great circle. US = Untersimbach, NE = Neuhofen, MI = Mitterdorf, BE = Beham, PR = Prienbach.
er et al. 2016, Sant et al. 2017). In addition to that, plotting directions from all sections yields mean directions of normal and reverse polarity, which are antipodal within error limits (Fig. 3). This is a good indication for the primary origin of the magnetic signal.

**Untersimbach** (21 samples) – All samples from the approximately 10 m thick succession of the Untersimbach Formation at the type locality (see 4.1.1) show normal polarity (Fig. 3).

**Neuhofen** (15 samples) – The 5 m thick Neuhofen Formation at the type locality (see 4.1.2) consistently show normal polarity (Fig. 3).

**Mitterdorf** (34 samples) – The lower part of the 12 m thick section (≈ 8 m) show reversed polarity. On top of that, there is a segment (about 3 m thick) with normal polarity. However, the lower (reversed) and upper (normal) parts of the outcrop may not represent a continuous succession, because a mining floor is present between them and because Pleistocene soil mixtures might have influenced and disturbed the upper (normal polarity) part of the section (see 4.1.2 and Fig. 4). Therefore, it is not clear whether the normal polarity of the upper part represents a primary signal or a secondary and possibly much younger age of acquisition compared to the underlying part.

**Beham** (18 samples) – The samples were taken from an approximately 15–20 m thick sandy-to-marly succession of the middle Ottnangian “Glaukanitsande & Blättermelgel” (glauconite sands and laminated marls). Above this, there is an outcrop gap of > 20 m, followed by the onset of OBM deposits (Oncophora Formation, “Mehlsande”). Sampling of this part was not possible due to the steepness of the slopes. The marly segments of the “Glaukanitsande & Blättermelgel” comprise about 18 m of normal polarity, while three samples show reversed polarity at the top (Fig. 5).

**Prienbach-Dötting** – Two samples from the uppermost section of the “Glaukanitsande & Blättermelgel” and 14 samples from the ≈ 20 m thick “Mehlsande” (= lowermost part of the Oncophora Formation) were taken from the outcrop Prienbach-Dötting (Fig. 6). The virtual geomagnetic pole (VGP) latitudes reveal normal polarity for all studied samples.

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Fig. 8. (A) Stratigraphic overview of the late Early Miocene and early Middle Miocene in the South German Molasse Basin (according to Reichenbacher et al. 2013 and Sant et al. 2017, modified). (B) Interpretation of the magnetostratigraphy of the outcrops Untersimbach, Neuhofen, Mitterdorf, Beham and Prienbach-Dötting based on magneto-litho-biostratigraphic studies (OMM = Upper Marine Molasse; OBM = Upper Brackish Molasse). Polarity pattern of the outcrop Ottnang-Schanze in Upper Austria according to Grunert et al. (2010). Based on benthic foraminiferal assemblages, the marls of the outcrop at Ottnang-Schanze (Ottnang Formation; Grunert et al. 2010, 2012) are more or less time equivalent to those of the outcrop Mitterdorf in Lower Bavaria (Neuhofen Formation; this study).
5. Discussion

5.1 Stratigraphic correlation

5.1.1 Upper Marine Molasse (OMM)

Biostratigraphy: Due to the low diversity of calcareous nannoplankton assemblages in the deposits of the Untersimbach Formation, correlation with global biostratigraphic zonation schemes is difficult (nannoplankton determinations by E. Martini in Pippèrr 2011). However, *Helicosphaera ampliaperta*, which is present in samples from the outcrop Untersimbach studied in Pippèrr (2011), points to a correlation with Nannoplankton Zones NN2 to NN4 (Figs. 1 and 8) and thus to a Burdigalian to early Langhian age (Gradstein et al. 2012). The nannoplankton assemblage of the Neuhofer Formation (from Oberschwärzenbach and the now vanished exposure close to the clay pit at Mitterdorf) was studied by Martini (1981) and has been assigned to the interval encompassing upper NN3 to lower NN4. For the top of NN3 an absolute age of 17.95 Ma has been suggested by Hilgen et al. (2012) (Fig. 8 and Table 3).

Stratigraphic considerations based on planktonic foraminifers are constrained by the fact that, in the Paratethys, most of the tropical and Mediterranean zonal markers are either very rare or absent (e.g. 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), but these do not permit secure assignment to any specific Lower Miocene Central Paratethys stage. For instance, the most abundant Ottnangian species *Globigerina ottnangiensis* also occurs in Eggenburgian and Karpatian strata.

Nevertheless, a subdivision of the Burdigalian in the Central Paratethys based on benthic foraminifers is possible (see Papp et al. 1973, Wenger 1987, Cicha et al. 1998, Rupp et al. 2008, Pippèrr and Reichenbacher 2009, Pippèrr 2011, Grunert et al. 2010, 2013). The Eggenburgian/Ottnangian boundary is clearly recognizable based on the last occurrence of *Lenticulina buergli* (index fossil for the Eggenburgian) and the first occurrence of *Amphicoryna ottnangensis* (index species for the Ottnangian), and the Karpatian stage is marked by the first appearance of *Uvigerina graciliformis* (Cicha et al. 1998). *A. ottnangensis* has been described from the lower Ottnangian Untersimbach Formation by Wenger (1987). Moreover, this species occurs frequently in the overlying Neuhofer Formation (Figs. 3 and 4). Further Ottnangian marker species include *Sigmoilopsis ottnangensis* and *Bolivina scitula*, both of which are abundant in the marls of the Neuhofer Formation (Figs. 3 and 4; Table 2).

Furthermore, the rich and diverse benthic foraminiferal assemblage represented in the Neuhofer Formation...
tion is very similar to that of the Ottnang Formation (Fig. 1) at the type locality Ottnang-Schanze in Upper Austria (e.g. Wenger 1987, Pippèrr 2011, Grunert et al. 2012). According to Grunert et al. (2010, 2012), the sandy-silty marls of the Ottnang-Schanze outcrop (see here Fig. 2) correspond to the lower part of the Ottnang Formation (onset of the regressive phase) and the suggested time interval falls within the lowermost part of NN4 (Grunert et al. 2014).

**Magnetostratigraphy:** The Ottnangian deposits of the Ottnang-Schanze section have been correlated with the polarity chron C5Dr.2r (18.06–17.74 Ma) (Grunert et al. 2010). Based on the reversed polarity and the presence of a comparable benthic foraminiferal assemblage, these sediments should be chronologically more or less equivalent to those of the Neuhoen Formation in Mitterdorf (onset of the regressive phase) studied here (Fig. 8). The sediments of the uppermost Untersimbach Formation (outcrop Untersimbach, see 4.1.1) and the lowest Neuhoen Formation (Neuhoen section, see 4.1.2) display a normal polarity and we correlate these, based on the biostratigraphic data, with chron C5En, which extends from 18.52 to 18.06 Ma (Fig. 8). The lower limit is given by the lower boundary of the Ottnangian stage in the Central Paratethys (see 5.2) and the upper limit by the base of the middle Ottnangian sediments in the Simssee area in Upper Bavaria, which dates to 17.8 ± 0.3 Ma (Pippèrr et al. 2007). The middle Ottnangian sandy-to-marly OMM succession in Beham (“Glaukonitsande & Blättermelgel”) is characterized by around 18 m of normal polarity, which is topped by a reversed interval (Fig. 5). Based on the magnetostratigraphic correlation of the underlying Neuhoen Formation, assignment of these sediments to chron C5Dr.n (17.74–17.72 Ma) to C5Dr.1r seems plausible (Fig. 8), although this would imply a very high sedimentation rate (~80 cm/ka).

**5.1.2 Upper Brackish Molasse (OBM)**

**Biostratigraphy:** The Molasse Basin of SE Germany (Lower Bavaria) and Upper Austria documents the transition from the marine OMM deposits (“Glaukonitsande and Blättermelgel” and equivalents, Fig. 1) to the brackish Oncophora Formation. In the sandy beds of the lower Oncophora Formation, *Rzehakia guembeili* is the most abundant faunal constituent (see 4.1.4). This taxon is regarded as characteristic for the late Ottnangian in the North Alpine and Western Carpathian Molasse Basins (Central Paratethys) (Čtyroký et al. 1973b, Ćorić and Rögl 2004, Mandic and Ćorić 2007, Piller et al. 2007, Pippèrr and Reichenbacher 2017). The faunal composition of the Oncophora Formation – and in particular the abundance of *Rzehakia* – thus provides evidence for a late Ottnangian age.

Based on the presence of *Rzehakia*, the lower Oncophora Formation can be correlated with the Grimmelfingen Formation in the SW German Molasse Basin (Fig. 1 and 8A; see also Pippèrr and Reichenbacher 2017). *Rzehakia* is absent or rare in the upper Oncophora Formation (Schlickum and Strauch 1968, Reichenbacher 1993). Therefore, the uppermost beds of the Oncophora Formation are possibly contemporaneous with the lower Karpitian Kirchberg Formation (Lemcke 1988, Pippèrr and Reichenbacher 2017).

**Magnetostratigraphy:** The magnetostratigraphic data from the outcrop Prienbach-Dötling (Fig. 6) fits well with the assumed late Ottnangian age for the lower Oncophora Formation. Both the top of the OMM and the lowermost OBM (“Mehlsande”) display normal polarity, which can be correlated with chron C5Dn (17.53–17.24 Ma) based on the biostratigraphic data (Fig. 8). This implies that the uppermost OMM sediments (top “Glaukonitsande & Blättermelgel”) in the SE German part of the NAFB may be contemporaneous with the lowermost OBM sediments (lowest section of the Grimmelfingen Formation, Fig. 8A) in its SW German sector because, according to bio- and magnetostratigraphic data (Fig. 8), the base of the Grimmelfingen Formation was deposited most probably during chron C5Dr.1r (Reichenbacher et al. 2013, Pippèrr and Reichenbacher 2017, Sant et al. 2017: model 2). Furthermore, our new results clearly show that the lower Oncophora Formation (normal polarity) is not time-equivalent to the Kirchberg Formation (largely reverse polarity, Figs. 1 and 8) as previously assumed by most authors (e.g. Reichenbacher 1993, Kuhlemann and Kempf 2002, Doppler et al. 2005). Thus, our data confirm the assumption of Pippèrr and Reichenbacher (2017) that the lower Oncophora Formation is more or less contemporaneous with the Grimmelfingen Formation.

**5.2 The lower boundary of the Ottnangian stage**

The Miocene Central Paratethys stages have been defined on the basis of characteristic fossil assemblages (e.g. foraminifers, bivalves), which are often endemic in the Paratethys Sea. Because of the rarity of radiometric age constraints and magnetostratigraphic stud-
ies, the putative ages assigned to the stage boundaries can vary widely, and correlation with the standard GTS is still difficult (Krijgsman and Piller 2012). For example, the base of the Ottnangian is dated to 18.12 Ma in Grunert et al. (2014), 18.2 Ma in Piller et al. (2007) and Krijgsman and Piller (2012), 18.25 Ma in Reichenbacher et al. (2013), 18.5 Ma in Abdul Aziz et al. (2010), and 18.7 Ma in Vakarcs et al. (1998).

According to Piller et al. (2007), the regional Miocene time scale of the Central Paratethys is based on correlations with the global sea-level curve of Haq et al. (1988) and the sequence stratigraphic cycles of Hardenbol et al. (1998) (Fig. 1). Accordingly the base of the Ottnangian Stage is correlated with the global sea-level lowstand Bur3 at 18.2 Ma (see also Krijgsman and Piller 2012). This sea-level lowstand is compatible with our findings in the SE German Molasse Basin, where the lowermost Ottnangian sediments of the Untersimbach Formation transgressively overlies marine Eggenburgian or Egerian sediments (see 4.1.1). In addition, earlier data (e.g. Piller et al. 2007, Kovác et al. 2004, Pipperr and Reichenbacher 2010, Pipperr 2011), as well as the results of this study, provide evidence for a single transgressive-regressive phase during the Ottnangian in the SE German part of the NAFB and in the Central Paratethys in general. Furthermore, it is known that the sequence stratigraphic subdivision of the SE German Molasse was strongly influenced by eustatic sea-level fluctuations (Zweigel et al. 1998). However, no consensus exists regarding the precise age of the Bur3 sea-level lowstand (Table 3). Snedden and Liu (2010) have recalibrated the stratigraphic cycles of Hardenbol et al. (1998) into the 2004/2008 time scale and the Bur3 sea-level lowstand (18.7 Ma in Hardenbol) is now correlated to an absolute age of 18.49 Ma (Table 3).

Based on our new magnetostratigraphic results, an age of 18.2 Ma or older for the lower boundary of the Ottnangian stage is most likely, because the top of the (up to > 100 m thick) lower Ottnangian Untersimbach Formation (exposed at Untersimbach) and the subsequent lower part of the Neuhofen Formation (exposed at Neuhofen) can be correlated to chron C5En (18.52–18.06 Ma). However, given that the calcareous nannoplankton of Ottnangian deposits in the Central Paratethys is dated to upper NN3 (18.28–17.95 Ma, Fig. 8, Table 3) and lower NN4 (Steininger et al. 1976, Martini 1981, Cicha et al. 1998, Piller et al. 2007), an age much older than ~18.2 Ma seems unlikely. Therefore, based on the present bio- and magnetostratigraphic data, a date of around 18.2 Ma for the lower limit of the Ottnangian stage seems plausible – though it must be pointed out that the nannoplankton assemblages of the OMM strata (Eggenburgian and Ottnangian) often contain few age-diagnostic species (e.g. Untersimbach Formation, see 5.1.1).

6. Summary and conclusions

In the SE German sector of the NAFB, the Ottnangian Upper Marine Molasse (OMM) transgressively overlies Eggenburgian OMM sediments or upper Egerian Lower Marine Molasse deposits. The lower Ottnangian Untersimbach Formation begins with a ‘coarse sand facies’, which is overlain by a ‘sandy-marly facies’. This changed into the ‘marly facies’ of the lower Ottnangian Neuhofen Formation, which then grades upwards into the glauconitic sands and sandy-marly sediments of the middle Ottnangian “Glaukanitsande & Blättermergel”. The lower Oncophora Formation is a regressive brackish facies containing a characteristic mollusc association – the Rzehakia fauna – which is indicative for the upper Ottnangian.

The sediments of the Untersimbach Formation and the lowest section of the Neuhofen Formation (outcrop Neuhofen) can be correlated with polarity chron C5En (18.52–18.06 Ma), whereas the initial regressive phase of the Neuhofen Formation in Germany (outcrop Mitterdorf, this study) and of the Ottnang Formation in Upper Austria (outcrop Ottnang-Schanze, Grunert et al. 2010) lies within chron C5Dr.2r (18.06–17.74 Ma). The uppermost marine deposits and the lowermost brackish sediments (Oncophora Formation) are correlated with polarity chron C5Dn (17.53–17.24 Ma).

The new magnetostratigraphic data clearly indicate that the lower Oncophora Formation (SE German part of the NAFB) is not contemporaneous with the Kirchberg Formation (SW German part of the NAFB) as commonly assumed. The uppermost OMM strata (top “Glaukanitsande & Blättermergel”) and the lower Oncophora Formation (OBM) most probably represent time-equivalents of the OBM/Grimmelfingen Formation in the SW German sector of the NAFB. This would imply that the OMM Sea persisted longer in the SE than in the SW German Molasse Basin.

Moreover, the transgressive base of the Ottnangian stage is shown here to lie within polarity chron C5En and we consider an absolute age of around 18.2 Ma to be most plausible because of the constraints suggested by nannoplankton data.
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