Early Burdigalian infill of the Puchkirchen Trough (North Alpine Foreland Basin, Central Paratethys): Facies development and sequence stratigraphy

Patrick Grunert [a],[*], Ralph Hinsch [b], Reinhard F. Sachsenhofer [c], Achim Bechtel [c], Stjepan Ćorić [d], Mathias Harzhauser [e], Werner E. Piller [a], Hanns Sperl [b]

[a] Institute for Earth Sciences, University of Graz, Heinrichstraße 26, A-8010 Graz, Austria
[b] Rohöl-Aufsuchungs AG, Schwarzenbergplatz 16, A-1015 Vienna, Austria
[c] Department of Applied Geosciences and Geophysics, Montanuniversität Leoben, Peter-Tunner Straße 5, A-8700 Leoben, Austria
[d] Geological Survey of Austria, Neulinggasse 38, A-1030 Vienna, Austria
[e] Natural History Museum Vienna, Geological-Paleontological Department, Burgring 7, A-1014 Vienna, Austria

ARTICLE INFO

ABSTRACT

To improve the prediction of gas and oil in strata along the tectonically imbricated southern margin of the Puchkirchen Trough (North Alpine Foreland Basin, Central Paratethys), a better understanding of facies distribution and stratigraphic control of the basin is essential. The present study provides bio- and chemofacies analyses and a biostratigraphic evaluation for the pelitic Hall Formation from the borehole Hochburg 1 in the central part of the Puchkirchen Trough. A statistical evaluation of benthic foraminiferal assemblages together with geochemical proxy records (TOC, sulphur, hydrogen index, $\delta^{13}C_{TOC}$, $\delta^{15}N_{TN}$) reveals a succession of early Burdigalian depositional environments.

Following a major subaqueous erosional hiatus, conglomeratic sands at the base of the section, which contain reworked Chattian and Aquitanian foraminiferal assemblages, record the reactivation of a basin-axial channel system. During the early Burdigalian eustatic sea-level rise, the channel was cut off from its sediment sources on the shelf and a deepening bathyal environment was established. Agglutinated foraminiferal assemblages with abundant *Bathysiphon filiformis* developed that were adapted to an unstable environment with frequent deposition of turbidites. The middle part of the Hall Formation is characterized by prograding high-relief clinoforms, which are fed by the Wachtberg Delta of the Paleo-Inn river. High sedimentation rates are interpreted and increased input of terrestrial-derived organic matter is documented with a strong correlation of TOC and TOC/S and low HI values, as well as frequent occurrences of *Ammodiscus* spp. and other opportunistic agglutinating foraminifers. A renewed transgression reestablished a eutrophic and suboxic bathyal environment, followed by the development of an oxygenated outer−middle neritic shelf environment heralding the ultimate infill of the deep-water basin.

Based on a comparison of the revealed development to existing sequence stratigraphic models for the Puchkirchen Trough, three sequences and their corresponding systems tracts can be identified for the lower, middle and upper Hall Formation. Biostratigraphic evidence from benthic foraminifers and calcareous nannoplankton indicates that they correspond to the regional substages of the middle and upper Eggenburgian and lower Ottnangian, and to global 3rd-order sequences Bur 1−3. The observations suggest a primary control of eustatic sea-level on the Puchkirchen Trough rather than Alpine tectonics during the Burdigalian.

1. Introduction

Upper Oligocene to Lower Miocene deposits of the Puchkirchen Trough in the North Alpine Foreland Basin (=Molasse Basin of several authors) contain prolific natural gas reservoirs (Malzer et al., 1993; Wagner, 1998). Current exploration is focused on the imbricated southern margin of the basin along the Alpine thrust front (Hinsch, 2008). In order to predict reservoir distribution, detailed information on stratigraphy and facies in the undisturbed central and northern part of the basin is essential. Initial depositional models derived from subsurface data, including several hundred exploration wells and 2D-seismic lines, described a deep-marine paleoenvironment mainly controlled by tectonically induced deposition of turbidite fans (Malzer et al., 1993; Wagner, 1996, 1998). Recent studies based on sedimentological

* Corresponding author. Tel.: +43 (0) 316 380 8735; fax: +43 (0) 316 380 9871.
E-mail address: patrick.grunert@uni-graz.at (P. Grunert).

core-description, provenance analysis, well-log data and 3D-seismic surveys improved predictive depositional models significantly (Linzer, 2001; Kuhlemann and Kempf, 2002; Brügel et al., 2003; De Ruig, 2003; Hubbard et al., 2005; Borowski, 2006; De Ruig and Hubbard, 2006; Hinsch, 2008; Covault et al., 2009; Hubbard et al., 2009; Bernhardt et al., 2012). Several attempts have been made to incorporate the observed development of depositional environments into a sequence stratigraphic framework for the Puchkirchen Trough (Jin et al., 1995; Zweigel, 1998; Peña, 2007; Hinsch, 2008). Poor bio- and chronostratigraphic control is a major limitation of the previous studies. Age determination is largely based on lithostratigraphic correlation and few attempts have been made to correlate the lithostratigraphic units to the global chronostratigraphic framework (Papp, 1960; Rögl et al., 1979; Grunert et al., 2010a).

The purpose of the present study is to apply quantitative micropalaeontology and geochemical analysis to better constrain the sequence stratigraphic framework of the Puchkirchen Trough. Analysis of benthic foraminiferal assemblages, as well as geochemical proxies are applied to the lower Burdigalian Hall Formation that records the terminal infill of the deep-marine trough. Trends in bio- and chemofacies are deduced and integrated with existing sequence stratigraphic models in order to identify the individual sequence boundaries and systems tracts more precisely. In combination with calcareous nannoplankton biostratigraphy, the new data sheds insight into correlation of the Hall Formation to the international time scale (Lourens et al., 2004). The evaluation of the relatively poorly constrained, terminal sedimentary infill of the deep-marine Puchkirchen Trough will document an important part of basin history that has largely been neglected so far (see in contrast the high number of publications on the Chattian and Aquitanian deposits, e.g. De Ruig and Hubbard, 2006; Covault et al., 2009; Hubbard et al., 2009; Bernhardt et al., 2012 and references therein) and the results will serve as a reference for future studies along the imbricated southern part of the basin.

2. Geological setting

2.1. The Puchkirchen Trough

During Late Oligocene and Early Miocene deep marine sedimentation in the North Alpine Foreland Basin (NAFB) was mainly confined to the Puchkirchen Trough and the southeastern margin of the Bohemian Massif (Rögl et al., 1979; Kollmann and Malzer, 1980; Wagner, 1998; Kuhlemann and Kempf, 2002; Grunert et al., 2010b, c). The Puchkirchen Trough extends from Bavaria (SE Germany) to the border of Upper Austria and Lower Austria in the east and parallels the Alpine thrust front with a west–east trending axis (Figs. 1, 2; Malzer et al., 1993; Kuhlemann and Kempf, 2002). It is confined by the Bohemian Massif to the north and east, by the thrust complexes of the Helvetic Unit, the Rhenodanubian Flysch and the Northern Calcareous Alps to the south and east, and by the Bavarian shelf to the west (Wenger, 1987; Malzer et al., 1993; Wagner, 1998; Kuhlemann and Kempf, 2002; De Ruig, 2003). Large parts of the southern Puchkirchen Trough have been incorporated in the Alpine thrust sheets as part of the tectonised "Imbricated Molasse" (Wagner, 1998).

During the Chattian to early Burdigalian the Puchkirchen Trough was a deep-marine basin with water depths of 500–1500 m (Rögl et al., 1979; Wagner, 1998). Vast shelf and slope areas confined the trough to the north and west, while a steep and tectonically active slope was present in the south adjacent to the Alpine thrust front (Zweigel, 1998; Kuhlemann and Kempf, 2002; De Ruig, 2003). Sediment distribution was strongly controlled by an extensive sinuous basin-axial channel that was 3–5 km wide and 10s of kilometres long (Figs. 1b, 2a; De Ruig and Hubbard, 2006; Hubbard et al., 2009; Bernhardt et al., 2012). Major rivers entered the basin from the south and west and delivered large amounts of sediment into the basin. Increasing sedimentation rates and decreasing subsidence led to the final infill of the Puchkirchen Trough by the middle Burdigalian (Fig. 2b, c; Zweigel, 1998; Brügel et al., 2003; Borowski, 2006; Hinsch, 2008).

2.2. The Hall Formation: sedimentology, microfauna, stratigraphy

The Upper Oligocene and Lower Miocene marine deposits of the Puchkirchen Trough are several thousand metres thick, and comprise the Lower and Upper Puchkirchen formations, the Hall Formation and the Innviertel Group (Malzer et al., 1993; Wagner, 1998). The pelitic Hall Formation was deposited in the deep-marine Puchkirchen Trough during the early Burdigalian (Rögl et al., 1979; Wagner, 1998). It consists of greenish-grey marls with locally thick intercalations of sandstone and conglomerate,
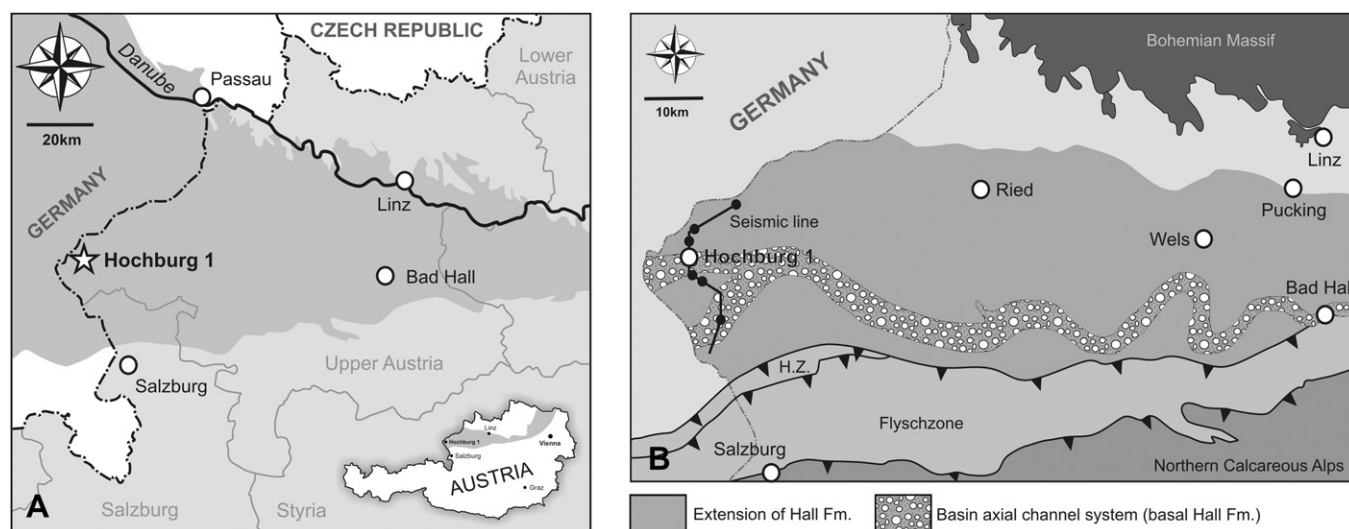

Figure 1. (A) Location of the borehole Hochburg 1 in Upper Austria. The distribution of Oligocene–Miocene marine sediments in the area is indicated in dark grey. (B) Location of the seismic line used for the present study and distribution of the Hall Formation in the study area based on Wagner (1998). H.Z. = Helvetic Zone.
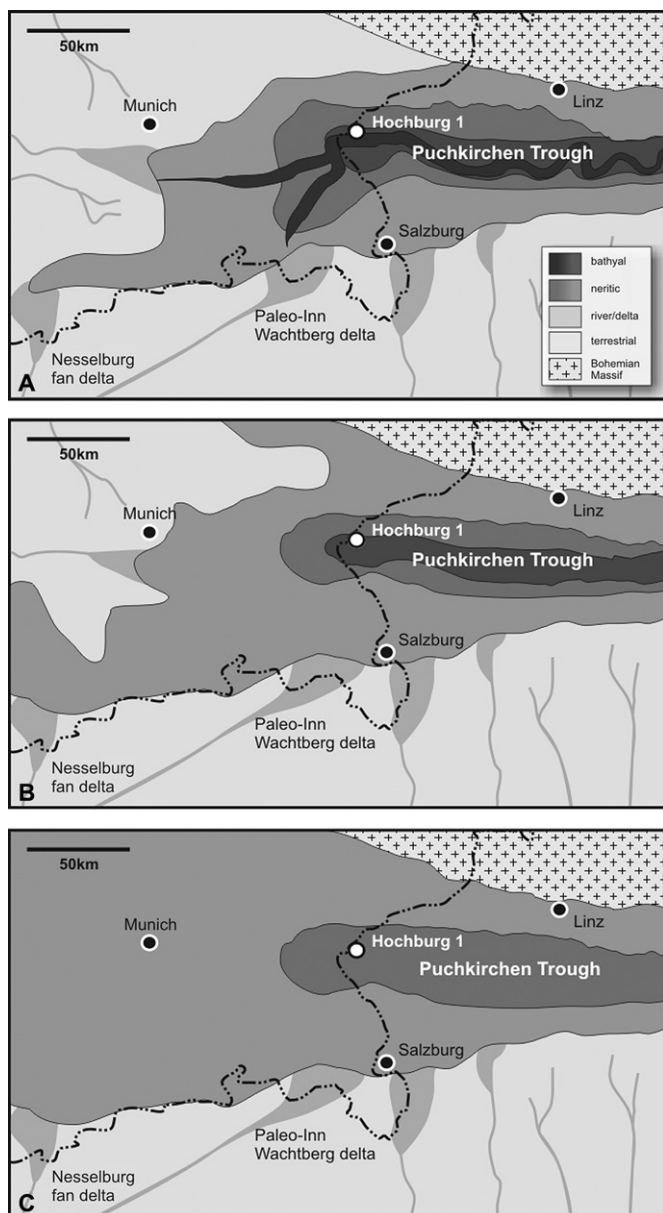
Figure 2. Early to middle Burdigalian (middle Eggenburgian to early Ottnangian) palaeogeography of the Puchkirchen Trough compiled from Wenger (1987), Kuhlemann and Kempf (2002) and Hinsch (2008). (A) Middle Eggenburgian, LST 5 with Puchkirchen Channel System; basal Hall Formation; (B) Middle Eggenburgian, mfs 5; middle Hall Formation (C) Early Ottnangian, mfs 6; maximum extension of the middle Burdigalian shelf sea after the infill of the Puchkirchen Trough; uppermost Hall Formation and Innviertel Group.

predominantly in its lower part, and is up to 800 m thick (Bürgl, 1949; Aberer, 1958, 1959; Wagner, 1998).

Based on a change on lithology and a distinct turnover in foraminiferal assemblages, the Hall Formation has been subdivided into a lower and upper portion (Petters, 1936; Bürgl, 1949; Aberer, 1958, 1959; Braumüller, 1959; Cicha et al., 1998; Wagner, 1998). The lower part consists of grey marls, conglomerate and locally mollusc coquinas, suggesting a dynamic depositional environment with strong sediment transport and intense reworking (Braumüller, 1959; Küpper and Steininger, 1975; Wagner, 1998). The depositional setting at the onset of the basal Hall Formation deposition is characterized by a large basin-axial deep-water channel belt that

distributed turbiditic mass-flow deposits within the basin (De Ruig and Hubbard, 2006; Hubbard et al., 2009; Bernhardt et al., 2012). Foraminiferal faunas are typically composed of large agglutinated astrorhizid and lituolid species (Bürgl, 1949; Aberer, 1959). Calcareous tests are rare and mainly consist of *Lenticulina* spp., *Ammonia* spp. and globigerinids (Aberer, 1959; Küpper and Steininger, 1975).

The upper part of the Hall Formation consists of yellow–grey sands and clayey marls (Aberer, 1959). Sedimentation in the basin was strongly controlled by the progradation of high relief clinoforms that have been related to major river systems along the southern basin margin (Zweigel, 1998; Borowski, 2006; Hinsch, 2008). Foraminiferal faunas show reduced diversity and are dominated by calcareous forms including *Ammonia beccarii*, *Heterolepa dutemplei*, *Lenticulina inornata*, *Melonis pompilioides* and *Globigerina bulloides* (Aberer, 1959).

The age of the Hall Formation has been determined as Burdigalian based on macro- and microfaunal assemblages (Bürgl, 1949; Aberer, 1958, 1959; Braumüller, 1959; Papp, 1960, 1975). Within the regional stratigraphic concept of the Central Paratethys, the Hall Formation belongs to the Eggenburgian stage while the subsequent Innviertel Group represents the Ottnangian (Fig. 3; Rögl et al., 1979; Cicha et al., 1998; Wagner, 1998).

The Hall Formation was originally termed "Schlier of Hall" referring to the characteristic sandy clays of the type area close to the town of Bad Hall in Upper Austria (Fig. 1; Petters, 1936; Aberer, 1959; Braumüller, 1959). In the course of developing a regional stratigraphic framework for the Central Paratethys, Papp (1968) introduced the term Hall Formation to account for the "Schlier of Hall" and coeval deposits in Salzburg and Upper Austria. A more comprehensive "Hall Group" was proposed by Wagner (1998) and Piller et al. (2004), which unites lower Burdigalian (Eggenburgian) formations from different basins and tectonical units in the Austrian part of the NAFB. The Hall, Lindach and Lukasedt formations of the Hall Group correspond to the Hall Formation of Papp (1968). The term Hall Formation is used in the present paper as defined by Papp (1968), as it is still the most widely accepted lithostratigraphic unit and facilitates comparison with previous studies.

2.3. Borehole Hochburg 1

The sample material of the present study originates from the borehole Hochburg 1 in Upper Austria that was drilled by Rohöl-Aufsuchungs AG (RAG) in 1983 (Figs. 1, 4). A 3400 m-thick sequence of Jurassic–Pleistocene sediments was penetrated during drilling. The differentiation of the lithological units by RAG is largely based on the evaluation of well-log and seismic data and supported by a qualitative analysis of benthic foraminifers from 26 drill cutting samples. The Hall Formation is 750.8 m thick at a depth of 790–1540.8 m. Several informal units are distinguishable in the formation (Fig. 5): (1) clayey sandstone and conglomerate in the lower part are designated as "Basal Silts" ("Basis Silte", 1540.8–1323 m; Lindach Formation of Wagner (1998)); and (2) overlying silty-sandy clays of the "Hall Series" ("Haller Serie", 1323–790 m; Hall Formation of Wagner, 1998). The "Gendorf Sands" ("Gendorfer Sande", 1221–1201.8 m) represent a distinct sandstone package present over a broad area in the western Puchkirchen Trough, which define a prominent seismic reflector.

3. Material and methods

The present study is based on 67 drill cutting samples from the Hall Formation each representing 2 m of sediment. Micropaleontological and geochemical analyses were carried out on the same sample where possible. In some cases the amount of sediment was not sufficient for micropaleontological evaluation and only
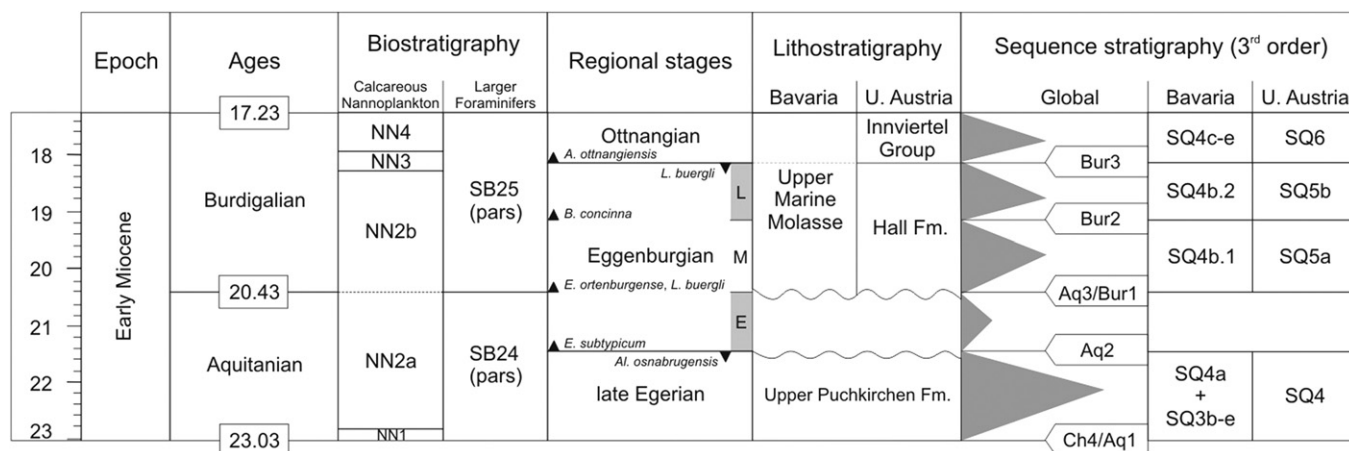
Figure 3. Global and regional stratigraphy of the Aquitanian and early–middle Burdigalian according to Lourens et al. (2004) and Piller et al. (2007). Parathethyan biostratigraphy is based on Wenger (1987), Cicha et al. (1998) and Pippèrr and Reichenbacher (2009). The Upper Marine Molasse deposits are subdivided into Eggenburgian and Ottnangian portions, the latter comprising the lower Ottnangian Untersimbach and Neuhofen Beds, and the middle Ottnangian Glaukonitsande and Blättermergel in the study area (Pippèrr, 2011). Bavarian sequences are adopted from Peña (2007), Austrian sequences are derived from Hinsch (2008) and herein presented results. See text for discussion of sequence stratigraphic correlation.

geochemical measurements were performed. All samples from 790 and 980 m as well as individual samples between 990 and 1540 m had to be excluded from geochemical analysis due to the limited amount of sample material or potential contamination in the drilling process.

3.1. Micropalaeontology

56 samples from the Hall Formation were used for foraminiferal analysis. 75 g of each sample were treated with diluted H_2O_2 for several hours and wet sieved under running tap water. Fractions < 125 μm were not included in the analysis as small specimens show a lower fossilization potential than larger specimens and would bias the results (Kender et al., 2008). Foraminiferal taxonomy follows Wenger (1987) and Cicha et al. (1998).

The morphogroup concept of Kaminski and Gradstein (2005) was applied to agglutinated foraminifers. Introduced by Jones and Charnock (1985) and subsequently refined, the morphogroup concept provides palaeoecological information based on the relationship between test morphology and environment (Nagy et al., 1995; Van den Akker et al., 2000; Kaminski and Gradstein, 2005). A list of morphogroups, representative taxa and their palaeoecological implications are given in Table 1. Hyaline foraminifers were grouped according to their microhabitat and oxygen dependency (Appendix B; see Jorissen et al., 2007; Pippèrr and Reichenbacher, 2010; Pippèrr, 2011; Grunert et al., 2012 and references therein).

Statistical analysis was carried out by using the software PAST (Hammer et al., 2001). Cluster analysis (Ward's Method) and Non-metrical multidimensional scaling (NMDS; Bray–Curtis similarity) were performed on the foraminiferal data to group the samples based on their similarity in composition (Hammer et al., 2001).

A complementary biostratigraphic analysis of nannoplankton assemblages was conducted on 7 samples from the Hall Formation Smear slides were prepared using standard methods and examined with a light microscope (cross and parallel nicols) with 1000× magnification.

3.2. Geochemistry

49 powdered bulk sediment samples from the Hall Formation were used for geochemical analysis. Sulphur content (S) and total

organic carbon (TOC) were determined by using a Leco CS-300 analyzer. RockEval pyrolysis (Espitalié et al., 1977) was carried out with a Rock-Eval 2+ instrument. With this method, the amount of hydrocarbons (mgHC/grock) present in the rock sample (S_1) and released from kerogen during gradual heating (S_2) is determined. The S_2 content was normalized against TOC to give the Hydrogen Index (HI = S_2*100/TOC).

23 samples contained a sufficient amount of organic material to perform carbon and nitrogen isotope analyses of organic matter ($\delta^{13}C_{TOC}$, $\delta^{15}N_{TN}$). Carbonates were removed from the samples using standard techniques. Successively, the samples were placed into tin foil boats and combusted in excess of oxygen at 1020 °C using an elemental analyzer (Flash EA 1112). The resulting N_2 and CO_2, separated by column chromatography, were analysed online by the DELTA-V ir-MS, mentioned above. The $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotope ratios of the CO_2 and N_2 from a sample were compared with the corresponding ratio of reference gases, calibrated against the PDB and the Air standards, respectively. The reproducibility of the total analytical procedure is in the range of 0.1–0.2‰.

4. Results

4.1. Trends in benthic foraminifers

The encountered foraminiferal taxa are listed in Appendix B. A summary of the most important taxa is given in Table 2 and trends in agglutinated and hyaline foraminifers are shown in Figures 6–8. Representative taxa of the foraminiferal assemblages are shown on Plate 1. Identification at the species level was often complicated by the preservation of the foraminiferal tests: agglutinated taxa primarily consist of tests with a proteinaceous or mineralized matrix that are heavily compressed. Hyaline and miliolid tests frequently show signs of transport, and heavily compressed and broken specimens are present in the lower part of the section.

Agglutinated and hyaline tests dominate the foraminiferal assemblages; miliolid taxa are very rarely present (Fig. 6). Hyaline taxa show highest abundances in the lower (1540–1330 m) and upper (880–800 m) parts of the section while agglutinated taxa dominate the assemblages with abundances >80% from 900 to 1242 m.

Within agglutinated foraminifers, M1 is the most abundant morphogroup and almost exclusively represented by *Bathysiphon*
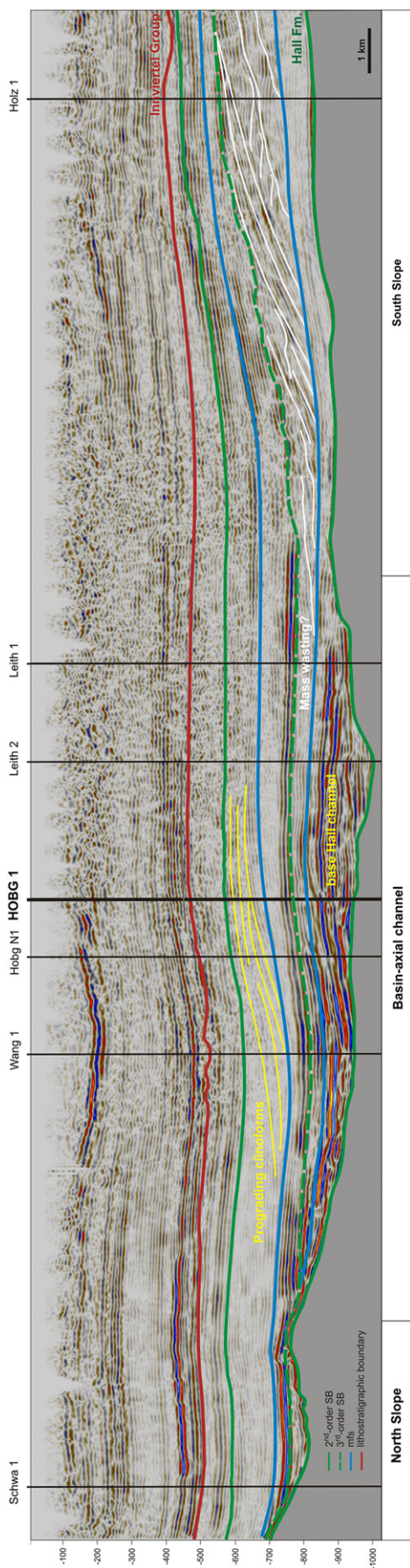
Figure 4. Seismic line of the study area (see Fig. 1b for location). Sequence stratigraphic boundaries and maximum flooding surfaces discussed in the present study are indicated for the Hall Formation and the lowermost Innviertel Group. See Figure 12 for details.

filiformis (Fig. 7). Abundance increases from the base upwards until a first peak is reached at 1200 m; a second maximum is present between 980 and 900 m. Abundance subsequently declines rapidly and M1 vanishes together with the rest of agglutinated foraminifers at 840 m. Brownish tests of M1, which are considered reworked (Kender et al., 2005), are restricted to the lower part of the Hall Formation.

Morphogroups M3a and M4b are important constituents of the foraminiferal fauna in distinct intervals of the Hall Formation. M4b, mainly represented by species of *Gaudryinopsis*, shows significant occurrences between 1540 and 1402 m and 1242 and 1150 m and disappears in the uppermost Hall Formation. M3a consists of various species of *Ammodiscus*. In contrast to M4b, M3a is rare to absent in the lower part of the Hall Formation, becoming abruptly abundant between 1120 and 990 m. In this interval the abundances of M1 and M3a are inversely correlated (Fig. 7). Subsequently, abundance of M3a decreases rapidly with an irregular pattern.

Other agglutinated morphogroups (M2b, M2c, M3b, M4a) are minor constituents of the Hall Formation and show occasional peaks in abundance.

Hyaline taxa at the base of the Hall Formation are composed of numerous infaunal suboxic indicators, including the highly abundant *Uvigerina* spp., of which many are reworked Chattian and Aquitanian (Egerian) taxa. Subsequent samples up to 1250 m are primarily composed of *A. beccarii* gr., and the abundance of epifaunal oxic and infaunal suboxic indicators is low. This trend is only briefly interrupted between 1322 and 1282 m where assemblages with highly abundant infaunal suboxic indicators (e.g., *M. pompilioides*, *L. inornata*) and reworked tests are present.

The interval of very low hyaline abundance is characterized by strongly variable abundances of *A. beccarii* gr., *Cibicidoides lopjanicus*, *Lenticulina* spp. and *M. pompilioides*, and result in a very irregular pattern of infaunal suboxic indicators.

Finally, the hyaline faunas from the top of the Hall Formation are composed of varying portions of *A. beccarii* gr., *C. lopjanicus*, *H. dutemplei*, *L. inornata* and *M. pompilioides*, and show an upward trend from infaunal suboxic towards epifaunal oxic indicators.

4.2. Benthic foraminiferal assemblages

Cluster analysis and NMDS allow the distinction of eight benthic foraminiferal assemblages (Figs. 9, 10). The distribution of the foraminiferal assemblages in the Hall Formation reflects the trends in agglutinated and hyaline tests (Figs. 6, 9). Assemblages 1–4 mainly occur in the middle part of the section and include samples that are dominated by agglutinated forms ($A = 89\%$, $\sigma = 11\%$). Differences between assemblages are mainly attributed to variations in the abundance of morphogroups M1 and M3a. In contrast, a predominance of hyaline tests over agglutinated tests ($A = 65\%$, $\sigma = 23\%$) characterizes assemblages 5–8 which mainly occur in the lower and uppermost parts of the section. Differences between assemblages are largely caused by varying abundances of *A. beccarii* gr. For assemblage 8, the scattered distribution of samples in the NMDS diagram (Fig. 10) reflects the high variability within this assemblage (see also Appendix B) and indicates that the corresponding cluster is not very robust. Two outliers from the base (1540 m, 1512 m) and the top (850 m, 830 m) of the Hall Formation suggest an internal subdivision into assemblages 8a–c (Fig. 9).

4.3. Geochemistry

Based on the revealed bulk geochemical data, the depth interval between 1540 and 900 m depth is subdivided into three units (Table 3, Fig. 11):
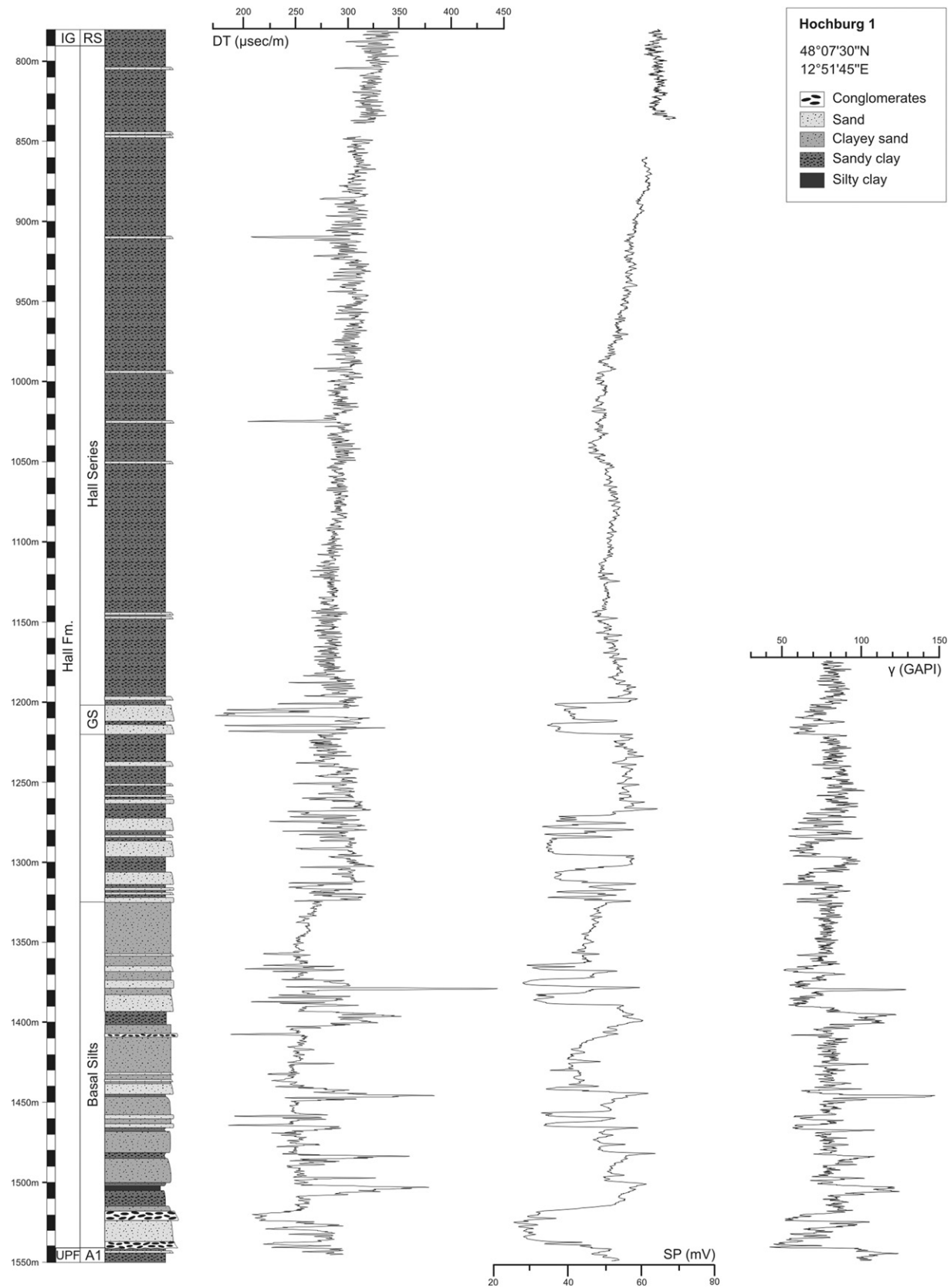
Figure 5. Lithology, lithostratigraphy (including informal units used by RAG; see text) and geophysical well-log data (sonic log − DT; spontaneous potential − SP; gamma ray − γ) of the Hall Formation. UPF = Upper Puchkirchen Fm; A1 = marl at top of the Upper Puchkirchen Formation; GS = Gendorf Sands; IG = Innviertel Group; RS = Robulusschlier.

Table 1
Characterization of the herein applied agglutinated morphogroups based on Van den Akker et al. (2000) and Kaminski et al. (2005).

Morphogroup	Test shape	Life position	Feeding habitat	Environment	Taxa of present study
M1	Tubular	Erect epifauna	Suspension feeding	Bathyal to abyssal; high sedimentation rates, turbidites, bottom currents	*Bathysiphon Psammosiphonella Rhizammina*
M2a	Globular	Shallow infauna	Suspension feeding – passive deposit feeding	Bathyal and abyssal	
M2b	Rounded trochospiral and streptospiral, or Planoconvex trochospiral	Surficial epifauna	Active deposit feeding	Shelf to deep marine	*Alveolophragmium Budashevaella Cribrostomoides*
M2c	Elongate keeled	Surficial epifauna	Active deposit feeding	Shelf to marginal marine	*Spiroplectammina Spirorutilus*
M3a	Flattened trochospiral, or Flattened planispiral and streptospiral	Surficial epifauna	Active and passive deposit feeding	Lagoonal to abyssal; floculent bottom layer	*Ammodiscus Glomospira Siphonaperta*
M3b	Flattened irregular	Surficial epifauna	Passive deposit feeding	Bathyal to abyssal	*Discammina*
M4a	Rounded planispiral	Surficial epifauna – shallow infauna	Active deposit feeding	Inner shelf to upper bathyal	*Cyclammina Haplophragmoides Reticulophragmium Trochammina*
M4b	Elongate subcylindrical, or Elongate tapered	Deep infauna	Active deposit feeding	Inner shelf to upper bathyal; high organic matter flux	*Ammobaculites Gaudryinopsis Karreriella Textularia Verneulinulla*

Unit 1 (1540–1390 m) is characterized by strongly varying values of TOC (0.23–0.97%), S (0.1–0.8%), TOC/S ratios (1.0–3.3) and HI (16–151 mgHC/gTOC). For samples with low TOC, HI values might be biased by the mineral-matrix effect (Espitalié et al., 1985). Graphs of S_2 (pyrolizable hydrocarbons) versus TOC show that the "true" average HI of organic matter is about 160, classifying the organic matter as kerogen type III, derived mainly from landplants (Langford and Blanc-Valleron, 1990). The $\delta^{13}C_{TOC}$ values of the organic-rich samples and vary from −24.0 to −23.3‰. The $\delta^{15}N_{TN}$ values fall within the narrow range of 1.6 to 2.5‰.

Unit 2 (1382–1190 m) shows TOC values between 0.26 and 0.97% with a subtle upward increasing trend. The latter is more obvious in the HI values (12–122 mgHC/gTOC). In contrast, sulphur contents (0.1–0.3 %) remains rather uniform. In the upper part of Unit 2, $\delta^{13}C_{TOC}$ fall in the range between −24.4 and −23.4‰ without any depth-related trend. The $\delta^{15}N_{TN}$ values are slightly higher compared to Unit 1 and vary in a narrow range between 2.4 and 3.0‰.

Unit 3 (1160–990 m) is characterized by maximum TOC values (up to 1.54%) at its base and a subsequent decrease in TOC upwards. The trend in TOC is parallelled by tendencies towards isotopically lighter values in $\delta^{13}C_{TOC}$ (−23.2 to −24.6‰) and $\delta^{15}N_{TN}$ (3.8–2.1‰) with decreasing depth. In contrast, an upward increase in HI values occurs (13–84 mgHC/gTOC). Sulphur contents shows minor variations (0.15–0.45%), thus TOC/S ratios (1.7–9.3) are controlled by varying TOC values.

4.4. Biostratigraphy

Samples from the Hall Formation consist mostly of well-preserved calcareous nannoplankton assemblages that allow a biostratigraphic interpretation (Table 4; Fig. 6). Age determination largely relies on the overall composition of the assemblages due to the absence of the stratigraphically important sphenoliths *Sphenolithus delphix*, *Sphenolithus disbelemnos* and *Sphenolithus belemnos*. An early Burdigalian age (nannoplankton zones upper NN2 and MNN2b) is clearly indicated for the basal Hall Formation based on the continuous occurrence of *Helicosphaera ampliaperta* and rare specimens of *Triquetrorhabdulus carinatus* (Fornaciari and Rio, 1996; Lourens et al., 2004). The absence of the latter taxon in

the upper part of the Hochburg section (800–1310 m, Hall Formation and Innviertel Group) is consistent with NN3/MNN3a (18.28–17.95 Ma; Fornaciari and Rio, 1996; Lourens et al., 2004). A clear differentiation between the upper NN2 and NN3 zones cannot be drawn.

Benthic foraminiferal assemblages allow a biostratigraphic determination within the framework of the regional stratigraphic concept (Fig. 3; Wenger, 1987; Cicha et al., 1998). The first occurrences (FO) of *Elphidium subtypicum* (FO 1522 m), *Elphidium ortenburgense* (FO 1442 m) and *Lenticulina buergli* (FO 1040 m) suggest a middle–late Eggenburgian age for the interval between 1540 and 850 m (Wenger, 1987; Cicha et al., 1998; Rupp and Haunold-Jenke, 2003; Pippèrr and Reichenbacher, 2009). *Uvigerina posthantkeni*, which has also been suggested as an index species for the Eggenburgian, is commonly found at the base of the Hall Formation. In the same interval several index species for the Egerian occur (*Almaena osnabrugensis*, *Bolivina beyrichi beyrichi*, *Bolivina versatilis*, *Fursenkoina halkyardia*) and suggest intense reworking. The stratigraphic range of *U. posthantkeni* is under debate as similar occurrences in reworked assemblages of the Hall Formation and the Innviertel Group have been reported from the study area (Rupp and Haunold-Jenke, 2003). Its stratigraphic value is all the more questionable as Wenger (1987) describes *U. posthantkeni* from Egerian deposits in Bavaria.

An early Ottnangian age is suggested for the uppermost part of the section. The composition of assemblage 7, restricted to the interval from 840 m to the top of the section, shows strong similarities with the widespread foraminiferal faunas of the lower Ottnangian Innviertel Group (Rupp and Haunold-Jenke, 2003; Rupp et al., 2008; Grunert et al., 2010a; Pippèrr, 2011; Grunert et al., 2012). The lower Ottnangian index taxon *Amphicoryna ottnangensis* has not been found (Wenger, 1987).

5. Discussion

5.1. Depositional environment

While the depositional environment of the basin-axial channel is well documented for the basal Hall Formation (De Ruig and

Hubbard, 2006; Hubbard et al., 2009; Bernhardt et al., 2012), little is known about the middle and upper parts of the Hall Formation (Borowski, 2006; Hinsch, 2008). In the present study the combined records of benthic foraminifers, geochemical proxies and seismic images allow to distinguish seven facies types that continuously document paleoenvironmental changes from the base to the top of the Hall Formation.

5.1.1. Facies 1: base Hall channel (1540–1400 m)

The basal Hall Formation represents the youngest and final stage of a long-lived, sinuous, basin-axial channel belt (De Ruig and Hubbard, 2006; Hubbard et al., 2009). While coarse-grained conglomeratic debris flows and turbidite deposits characterize the channel fill, the overbank deposits consist of fine-grained turbiditic sands (Hubbard et al., 2009). Two major tributaries to the channel system have been identified: (1) the Paleo-Inn river that entered the basin from the south-southwest, and (2) a canyon that intersected the Bavarian shelf in the west (Figs. 1, 2; Wagner, 1998; Brügel et al., 2003; De Ruig and Hubbard, 2006).

Seismic data reveals that the channel was approximately 4.5 km wide in the study area with Hochburg 1 located towards its centre (Figs. 2, 4, 12). The interval of channel deposition is situated in the basal 140 m of the section based on lithology and well-log data and reflected in the foraminiferal and geochemical data (Figs. 5, 6). The distribution of assemblages 5, 6, 8a and 8c and the strongly irregular geochemical records in these strata originate from an alternation of reworked pre-Burdigalian deposits and Burdigalian shelf deposits, the later most likely derived from mass-wasting at the basin margins (cf. Hubbard et al., 2009), resulting in displaced shallow-marine fauna.

Reworked deposits consist of Chattian to lower Aquitanian strata of the Upper and Lower Puchkirchen formations within conglomeratic sands at the base (1540–1490 m) and upper parts (1410 m) of the channel infill. Foraminiferal assemblages 5, 8a and 8c with astrorhizids, textulariids, buliminds, bolivinids, fursenkoinids and uvigerinids resemble microfossil faunas described from the eutrophic and strongly suboxic paleoenvironment of the organic-rich Upper Puchkirchen and Ebelsberg formations (Küpper and Steininger, 1975; Wenger, 1987; Cicha et al., 1998; Grunert et al., 2010b). With *A. osnabrugensis*, *B. beyrichi beyrichi*, *B. versatilis* and *F. halkyardia* the assemblages contain a number of regional Chattian and Aquitanian (Egerian) index fossils (Plate 1; Wenger, 1987; Cicha et al., 1998). Strongly varying, and partly high TOC, S and HI values reflect the intense reworking episodes (Fig. 11). Similar to the foraminiferal assemblages they indicate a eutrophic and suboxic environment characteristic for Aquitanian shales in the basin (Küpper and Steininger, 1975; Cicha et al., 1975; Wagner, 1998; Grunert et al., 2010b). The high $\delta^{13}C_{TOC}$ values obtained from the organic carbon rich sediments fall within the range obtained from Neogene marine organic matter (Lewan, 1986, Hertelendi and Vetö, 1991). However, the carbon isotope data do not preclude contributions from higher land plants (Deines, 1980; Hoefs, 1987) and the $\delta^{15}N_{TN}$ are in agreement with significant contributions of land plants to organic matter. Although the low $\delta^{15}N$ values ($<2.5‰$) could also be explained by abundant nitrogen-fixing cyanobacteria (Meyers, 2003), the frequent occurrence of the inner to middle neritic *Ammonia* spp. additionally indicates that sediment delivered from the Burdigalian shelf is mixed with the reworked deposits (Murray, 2006).

Sandy deposits between 1472 and 1432 m and at 1402 m are primarily shelf-derived based on the very high abundances of *Ammonia* spp. in assemblage 6. Low TOC, S and HI values additionally indicate a well-oxygenated shelf environment as a source.

As large parts of the foraminiferal fauna are allochthonous, conditions at the basin floor are mainly inferred from the occurrence of *B. filiformis*. This suspension-feeding species is most abundant in eutrophic bathyal areas along the continental shelf where bottom-currents advect large amounts of nutrients (Gooday et al., 1992, 1997). Together with other extant and fossil species of *Bathysiphon* it has been frequently reported from turbiditic environments and submarine canyons (Miller, 1988, 2005; Koho et al., 2007; De Leo et al., 2010). There they show highest abundances in the upper canyon terraces close to the continental margin during episodes of reduced turbidity currents and minor mass-flow deposition (Koho et al., 2007; De Leo et al., 2010). Episodically increased abundances of *B. filiformis* (1450 m, 1410–1402 m) might thus reflect phases of benthic recolonization in-between turbidite deposition (Miller, 1988). Its generally low abundance suggests an upper bathyal environment (Jones and Charnock, 1985) that agrees well with estimated water depths of 500 m for coeval turbiditic deposits (Wagner, 1998).

5.1.2. Facies 2: turbiditic upper bathyal 1 (1392–1330 m)

Facies 2 is representative of the upper part of the "Basal Silts" in the lower Hall Formation and contains sandy sediments overlying Facies 1. The outer neritic and bathyal morphogroups M1, M2b and M4b suggest an upper bathyal environment (Kaminski and Gradstein, 2005). Turbiditic transport to the basin floor is documented in assemblages 5 and 8c with increased abundances of *A. beccarii* gr. Indicators for reworking are low and mainly consist of brown specimens of *Bathysiphon* (Kender et al., 2005). Increased turbiditic transport and reduced reworking reflect a major change in the depositional environment: Channel deposition ended as sea-level rose and flooded the Bavarian shelf, which resulted in cut off of the main sediment supply (Hinsch, 2008). Sedimentation was instead controlled by tectonically induced turbidites from the southern shelf (Wagner, 1998; Hinsch, 2008).

The frequent abundance of *B. filiformis* indicates high nutrient flux of shelf-derived organic matter to the sea-floor (Gooday et al., 1992, 1997; Kaminski et al., 2005; Murray, 2006; Kender et al., 2008). Most samples from this interval reveal rather low TOC values and strongly decreased HI values. The very low HI values indicate poor preservation of the organic matter (type IV kerogen; Espitalié et al., 1977). As the very low TOC/S ratios suggest oxygen-depleted conditions, degradation of organic material probably took place already within the water column.

5.1.3. Facies 3: turbiditic upper bathyal 2 (1322–1250 m)

Facies 3 comprises sediments directly above the "Basal Silts" that show an increased portion of silts and clays (Fig. 5). The sedimentological change is accompanied by a change in benthic foraminifers. Agglutinated foraminifers dominate for the first time over hyaline forms. Assemblages 3 (which occurs for the first time) and 8c suggest an upper bathyal environment with the occasional deposition of turbidites.

Increased abundances of M1, M2b and M4b indicate high organic-matter flux and temporarily decreased bottom-water oxygenation (Van den Akker et al., 2000; Kaminski and Gradstein, 2005). Similar to facies 2, the frequent abundance of *B. filiformis* indicates high input of shelf-derived organic matter to the sea-floor (Gooday et al., 1992, 1997; Kaminski et al., 2005; Murray, 2006; Kender et al., 2008). TOC values of facies 3 are low and the organic matter is mainly composed of terrestrially-derived organic matter (Espitalié et al., 1977). A subtle increase in HI indicates either improving conditions for organic matter preservation or a slightly increased contribution of autochthonous marine organic material (Espitalie et al., 1977). Low TOC/S ratios suggest continuing oxygen-depleted conditions (Berner, 1984).

Based on the abundance of *A. beccarii* gr., facies 3 is subdivided in facies 3a and 3b. In strong contrast to facies 2, *A. beccarii* gr. or

Table 2
Relative abundance of the most important foraminiferal morphogroups and taxa (≥5% in at least one sample). The same matrix was used for multivariate statistical analysis.

Sample	M1	M2b	M2c	M3a	M3b	M4a	M4b	Reworked agglutinated foraminifers	Ammonia beccarii gr.	Amphicoryna spp.	Bolivina spp.	Bulimina/Caucasina spp.
790 m	0	0	0	0	0	0	0	0	**21**	0	0	0
800 m	0	0	0	0	0	0	0	0	**17**	0	2	0
810 m	0	0	0	0	0	0	0	0	**15**	0	0	**5**
820 m	0	0	0	0	0	0	0	0	**14**	**14**	0	0
830 m	**8**	0	0	**8**	0	**8**	0	0	0	0	0	0
840 m	0	**17**	0	0	0	0	0	0	0	0	0	0
850 m	**15**	0	0	**15**	0	0	0	0	**15**	0	0	0
870 m	**50**	0	0	0	0	**8**	0	0	0	0	0	0
880 m	**33**	**8**	0	**25**	0	0	0	0	0	0	0	0
900 m	**64**	4	0	4	0	**9**	0	0	0	0	0	0
920 m	**70**	3	0	3	0	4	0	0	0	4	0	0
960 m	**67**	2	0	1	0	4	**11**	0	0	0	0	0
970 m	**71**	0	0	4	0	**6**	**10**	0	0	0	0	0
980 m	**65**	1	0	**13**	0	**10**	1	0	0	0	0	0
990 m	**38**	**5**	0	**35**	0	4	**6**	0	1	0	0	0
1000 m	**36**	1	0	**31**	0	2	**5**	0	4	0	0	0
1010 m	**33**	1	0	**39**	0	**5**	**6**	0	1	0	0	0
1020 m	**42**	2	0	**37**	0	4	3	0	**5**	0	0	0
1030 m	**21**	**5**	0	**46**	0	**5**	**8**	0	3	0	0	0
1040 m	**24**	1	0	**58**	0	3	**5**	0	0	0	0	0
1060 m	**41**	1	0	**45**	0	3	**8**	0	0	0	0	0
1070 m	**42**	3	0	**28**	0	4	**5**	0	4	0	0	0
1080 m	**42**	2	0	**44**	0	1	1	0	2	0	0	0
1090 m	**36**	3	0	**36**	0	1	**6**	0	0	0	0	0
1102 m	**25**	**15**	0	**28**	0	1	**8**	0	**6**	0	0	0
1110 m	**33**	**7**	0	**37**	2	4	**11**	0	2	0	0	0
1120 m	**22**	**24**	0	**28**	0	**9**	2	0	**7**	0	0	0
1140 m	**36**	2	0	**15**	0	2	**16**	0	0	0	0	0
1150 m	**47**	**5**	1	**11**	0	4	**14**	0	1	0	0	0
1200 m	**86**	3	0	1	0	1	**6**	0	0	0	0	0
1220 m	**48**	**20**	0	0	0	0	**30**	0	0	0	0	0
1232 m	**63**	1	0	**8**	0	0	**10**	0	4	0	0	0
1242 m	**48**	1	0	**7**	0	2	**28**	1	**8**	0	0	1
1250 m	**38**	1	0	**7**	0	0	**9**	0	**22**	1	0	0
1262 m	**30**	0	0	**5**	0	1	**11**	**10**	**23**	0	0	2
1282 m	**53**	**7**	0	1	0	1	1	4	**7**	0	0	4
1300 m	**17**	**12**	0	3	0	1	**7**	**19**	1	0	0	0
1310 m	**40**	**18**	0	2	0	1	**11**	**9**	1	0	0	0
1322 m	**21**	**9**	0	0	0	3	**9**	**18**	0	0	0	0
1330 m	**12**	**9**	0	2	0	2	4	**8**	**14**	0	0	**7**
1350 m	**15**	3	0	0	0	1	0	**7**	**26**	0	0	3
1362 m	**15**	2	0	4	0	0	4	**9**	**32**	0	0	4
1382 m	**28**	**6**	0	**6**	0	2	**8**	**7**	**25**	0	0	1
1392 m	**22**	**8**	0	1	0	3	**14**	**10**	**18**	0	0	0
1402 m	**10**	1	0	1	0	0	2	**6**	**38**	0	0	1
1410 m	**9**	0	0	2	2	2	**12**	**5**	3	**5**	**9**	**7**
1432 m	2	0	0	0	0	0	1	0	**54**	3	0	2
1442 m	**6**	0	0	1	0	1	1	1	**61**	0	0	1
1450 m	**15**	**7**	0	2	0	0	**8**	2	**33**	0	1	2
1462 m	2	0	0	0	0	0	1	0	**63**	0	0	1
1472 m	4	0	0	0	0	0	4	1	**51**	0	0	0
1502 m	2	0	0	0	0	0	1	4	**30**	0	0	4
1512 m	0	0	0	0	0	0	0	2	**6**	1	2	3
1522 m	2	0	1	0	0	0	2	0	**31**	1	1	**7**
1532 m	**23**	0	0	0	0	0	**7**	0	3	3	0	**10**
1540 m	2	0	0	1	0	1	**6**	2	**7**	3	0	2

Bold values indicate abundances of ≥5%.

other shelf indicators are rare in facies 3a (1322–1300 m). Parallel, suboxic hyaline indicators and eutrophic morphogroups M2b and M4b are highly abundant (Kaiho, 1994; Kaminski and Gradstein, 2005). Facies 3b (1282–1250 m) shows similarities to facies 2 with increased abundance of *A. beccarii* gr. and reduced abundance of suboxic indicators. These differences in the composition of the assemblages are attributed to different sources of the deposited material: Minor sediment delivery from the inner and middle shelf is indicated for facies 3a, while the rich shallow-water assemblages of facies 3b indicate frequent deposition of shelf-derived sediment.

5.1.4. Facies 4: eutrophic upper–middle bathyal (1242–1160 m)

Facies 4 is present the middle part of the Hall Formation and contains the widespread Gendorf Sands. Foraminiferal assemblages 3 and 4 resemble the Paleogene "flysch-type biofacies" (Kaminski and Gradstein, 2005). This biofacies is dominated by tubular foraminifers of morphogroup M1 and characterizes upper–middle bathyal depositional environments with high sedimentation rates or strong contouritic currents advecting nutrients. In contrast to facies 1, 2 and 3b, *A. beccarii* gr. and other shelf-derived taxa occur very rarely and indicate less frequent turbiditic transport.

Cibicidoides austriacus/ungerianus	Cibicidoides lopjanicus	Cibicidoides spp.	Elphidium spp.	Fissurina sp.	Fursenkoina halkyardia	Grigelis pyrula	Gyroidinoides/Hansenisca spp.	Hanzawaia boueana	Heterolepa dutemplei	Laevidentalina spp.	Lagenidae indet.
0	**42**	4	4	0	0	0	0	0	**13**	0	0
0	**29**	**5**	0	0	0	0	**5**	0	2	0	0
0	**50**	0	0	0	0	0	0	0	**5**	0	0
0	**14**	**29**	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	**8**	0	0
0	0	**17**	0	0	0	0	0	0	0	0	0
0	**7**	4	0	0	0	0	0	0	0	4	0
0	0	0	8	0	0	0	0	0	**17**	0	0
0	**8**	**8**	0	8	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	2	0
0	0	0	1	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	0	0	0	0	0	0	0	0	0
0	2	0	1	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0
0	3	0	0	0	0	0	3	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	1	2
0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	2
0	2	0	0	0	0	0	0	0	0	0	0
0	0	2	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	3	1	3	0	0	0	1	0	0	1	0
0	0	0	2	0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	1	0	0	1	0
2	0	0	1	0	0	0	0	0	1	1	0
1	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	**6**	0	0	0	0
0	0	1	1	0	0	0	3	0	0	2	0
0	0	0	3	0	0	4	3	0	0	1	0
0	3	0	0	0	0	0	0	0	0	2	0
0	0	0	2	0	0	0	0	0	1	2	0
0	1	0	1	0	0	0	0	0	0	1	0
1	1	0	1	0	0	0	0	0	0	3	0
0	2	0	0	0	0	0	0	0	3	2	0
0	2	**6**	1	0	0	0	0	0	0	0	0
0	1	3	3	0	0	0	0	0	1	2	0
0	2	1	3	0	0	0	0	0	0	1	0
0	0	0	3	0	0	0	0	0	1	0	0
0	0	0	1	0	0	0	0	0	1	4	0
0	1	2	1	0	0	0	0	0	2	3	0
1	0	1	0	0	**8**	0	0	2	0	1	0
1	1	2	1	0	0	0	2	2	0	4	0
0	0	**7**	0	0	0	0	0	3	3	0	0
0	2	**9**	0	0	0	0	0	2	0	2	0

Increased abundances of M1, M2b and M4b indicate high input of organic matter and temporarily decreased bottom-water oxygenation (van den Akker, 2000; Kaminski et al., 2005). TOC contents are similar to those in facies 3. While the $\delta^{13}C_{TOC}$ data fall in the range usually obtained from marine phytoplankton, the $\delta^{15}N_{TN}$ values argue for moderate contributions of terrigenous organic matter and/or cyanobacteria (Lewan, 1986; Hertelendi and Vetö, 1991; Meyers, 2003). Low HI values reflect input of terrestrial organic matter and degradation of marine organic matter due to intense bioturbation (Pratt,

1984). The average TOC/S ratio (3.0) in the interval between 1242 and 1160 m further supports a temporary decrease in bottom-water oxygenation (Berner and Raiswell, 1984; Berner, 1984).

5.1.5. Facies 5: prograding delta-fed clinoforms (1150–990 m)

Benthic foraminiferal assemblages 1 and 2 of facies 5 are dominated by agglutinated foraminifers and are characterized by the high abundance of M3a, a morphogroup which is rare in other portions of the Hall Formation (Figs. 6, 7). The large bathymetric

Table 2 (continued)

Lenticulina spp.	Melonis pompilioides	Myllostomella recta	Nonion spp.	Oridorsalis umbonatus	Porosononion spp.	Protelphidium roemeri	Pullenia bulloides	Sphaeroidina bulloides	Stilostomella sp.	Uvigerina spp.	Valvulineria spp.
13	0	0	0	0	0	0	0	0	0	0	4
14	2	0	0	0	5	0	0	0	0	0	0
10	10	0	5	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0
8	31	0	0	0	0	0	0	0	0	0	8
50	0	0	0	0	0	0	0	0	0	0	0
4	30	0	0	0	0	0	4	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	8	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	1	0	0	0	0	0	0	0	0
1	2	0	1	0	0	0	0	0	0	0	0
1	0	0	1	0	0	0	0	0	1	0	0
0	2	0	1	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	2	0	0	0	0	0	0	0	0	0	0
1	1	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
2	5	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0	0	0	0	0
0	2	0	3	3	0	0	0	0	0	0	0
2	1	0	2	0	0	1	0	0	0	0	0
3	4	0	1	0	0	0	0	0	0	0	0
1	3	0	0	1	0	0	2	1	1	3	0
0	5	0	0	0	0	0	1	0	0	2	0
0	12	0	3	0	0	0	0	0	0	0	0
4	5	0	2	0	0	0	3	0	0	1	0
0	3	0	4	1	1	1	0	0	0	3	0
0	6	0	4	0	0	1	2	0	5	0	0
1	0	0	0	0	0	0	1	0	1	1	1
1	1	0	0	1	1	1	1	0	1	0	0
1	3	0	1	2	0	1	1	0	0	1	0
2	0	0	2	2	0	0	2	2	5	0	2
1	0	0	2	0	0	2	0	1	3	0	0
1	0	0	1	0	1	0	0	0	3	0	1
0	2	0	0	0	1	0	0	0	0	0	0
2	3	0	4	0	1	1	0	0	0	1	0
1	1	0	1	1	3	0	1	0	0	0	0
2	4	0	3	0	1	1	1	0	2	22	0
5	1	0	1	0	0	0	0	0	2	43	0
1	0	0	2	0	1	0	0	0	0	11	1
0	3	3	0	0	0	0	3	0	0	17	0
2	0	0	0	0	2	0	1	2	1	29	0

range of morphogroups M3a and M2b and the lowered abundances of M1 probably suggests a shallowing towards outer neritic–upper bathyal water depths (Jones and Charnock, 1985; Van den Akker et al., 2000). The shallowing trend is most evident in the high abundance of small-sized (<0.25 mm) tests of *Ammodiscus* spp. Previous studies indicate that the test-size of ammodiscids roughly correlates with water depth: while large-sized species are mainly described from deep-water settings (e.g., Hart, 1988; Cicha et al., 1998; Govindan, 2004; Kaminski and Gradstein, 2005; Kaminski et al., 2005; Filipescu and Kaminski, 2008), small-sized species seem to occur preferably in delta-influenced shelf settings and even

restricted lagoonal environments (e.g., Alve and Nagy, 1986; Nagy and Johansen, 1991; Nagy and Berge, 2008; Nagy et al., 2010).

The new results are indicative of fluviatile input and increased sedimentation rates. Exceptionally high abundances of agglutinated foraminifers have been previously observed in deltaic environments with high sedimentation rates and strong terrestrial input (e.g., Kaminski et al., 1988; Jones, 1999; Kender et al., 2005; Jones, 2006; Kender et al., 2008). Epifaunal, vagile species of morphogroups M2b, M3a and M4a that live on the flocculent bottom surface layer, together with infaunal morphogroup M4b, are all adapted to high organic matter flux and show high
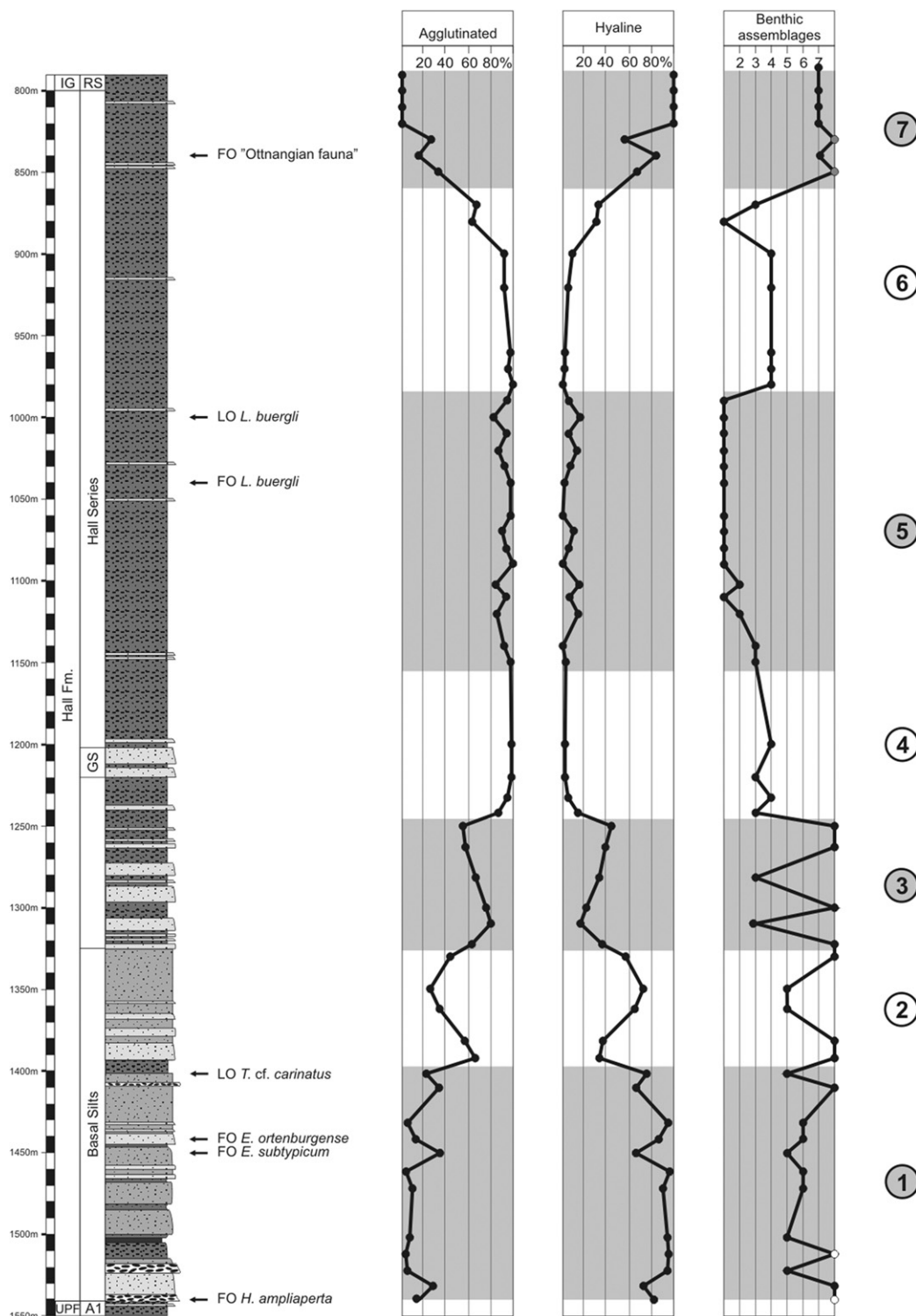
Figure 6. Biostratigraphic index species, relative abundances of agglutinated and hyaline foraminifers, and distribution of benthic foraminiferal assemblages 1–8. Grey circles = assemblages 8b; white circles = assemblage 8c. Numbers on the right indicate facies 1–7.

abundances in this part of the section (Kaminski et al., 1988; Nagy, 1992; Kaminski et al., 2005). *B. filiformis* is diminished relative to facies 4. Although its occurrence reflects high organic matter input, *B. filiformis* might have had more difficulties to adapt to the high sedimentation rates than more opportunistic forms like *Ammodiscus* (Bąk, 2000). The strong correlation between high TOC

and TOC/S ratios together with low HI values further suggest high input of terrestrial organic matter (Espitalié et al., 1977; Berner, 1984). Previous studies show that TOC/S ratios >2.8 result from major input of refractory terrestrial organic matter, which cannot be metabolized efficiently by sulphate-reducing bacteria (Berner and Raiswell, 1984; Berner, 1984).
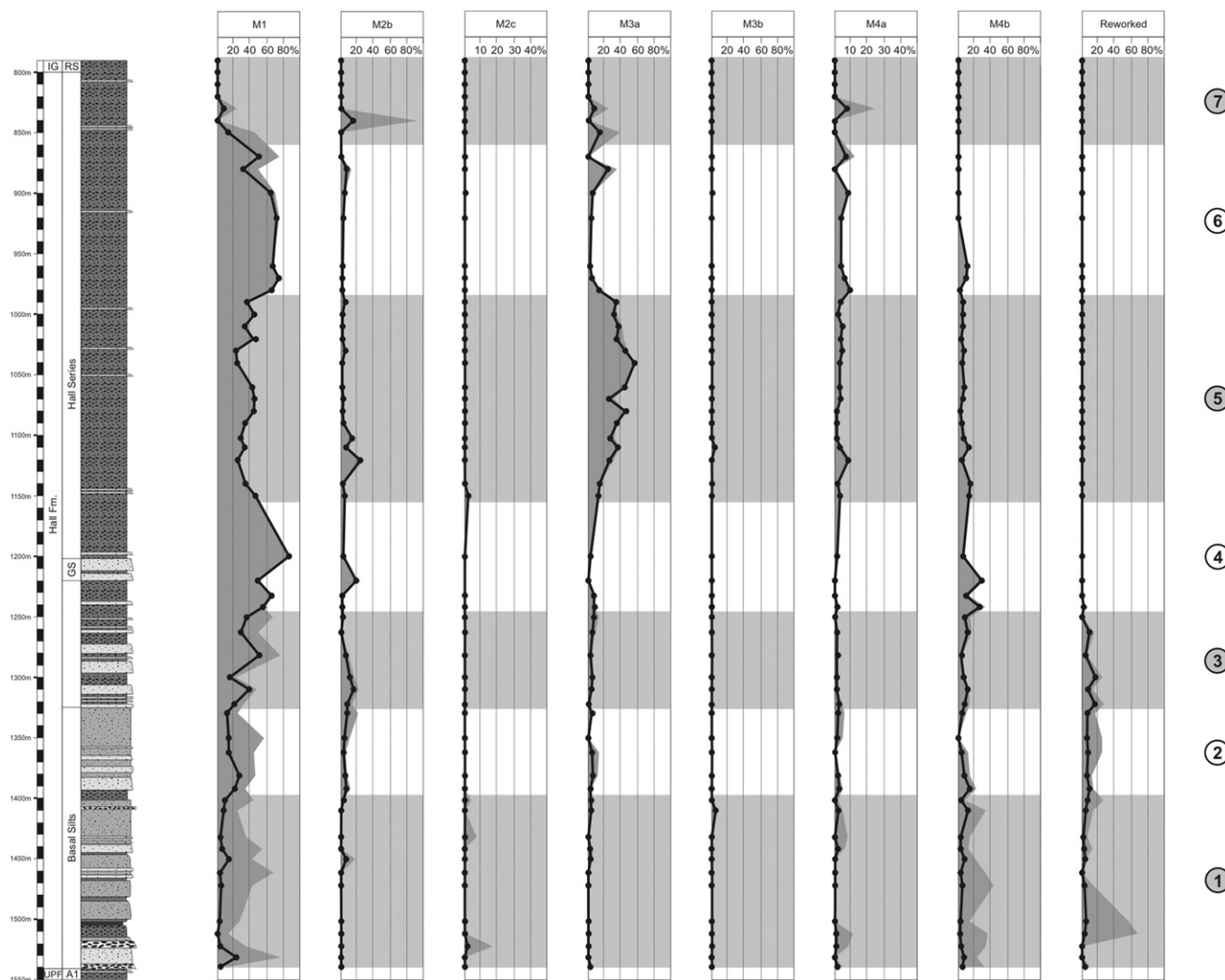
Figure 7. Relative abundances of agglutinated morphogroups in the Hall Formation. The black line shows the abundance for the whole benthic assemblage, the abundance within agglutinated assemblages is indicated in grey. Numbers on the right indicate facies 1–7. See Table 1 for characterization of the morphogroups.

Hinsch (2008) describes a series of northeast prograding high relief clinoforms from the same interval in the Hall Formation and interprets them to be fed by the Wachtberg Delta of the Paleo-Inn river. These prograding clinoforms, which are >200 m thick, are also observed in the seismic data of the present study (Fig. 4) and the clear indications towards increases in fluviatile input, delivery of terrestrial organic matter and sedimentation rates strongly support the interpretation of Hinsch (2008). The development of delta-fed clinoforms marks a major change in the depositional environment that contrasts the turbidity-controlled environment of the lower Hall Formation. This trend is also visible in the well-log data: while the lower Hall Formation (1190–1540 m) is characterized by irregular signals with high amplitude variations resulting from the frequent sandy and conglomeratic turbidites, the middle Hall Formation with facies 5 reveals a rather stable trend with minor variations (Fig. 5).

Within the clinoforms, upward decreasing TOC values most likely reflect increasing dilution of organic matter by detrital minerals shed by the Wachtberg Delta. At the same time, increasing HI values show better preservation of organic matter, probably the combined effect of shorter travel times of organic matter within the shallower water column and more rapid coverage. The decreasing trends $\delta^{13}C_{TOC}$ and $\delta^{15}N_{TN}$ probably reflect the increasing amount of terrestrial organic matter delivered to the study area as the delta-fed clinoforms advance to the northeast. However, differences in bioproductivity and in the extent of organic matter remineralization under varying redox conditions could be also responsible for the observed tendencies (Meyers, 1997). A subtle trend towards lower values in the spontaneous potential (SP) record and the intercalation of sandy deposits might reflect an increase in coarser material delivered during clinoform progradation (Fig. 5; Asquith and Krygowki, 2004).

5.1.6. Facies 6: eutrophic upper bathyal (990–870 m)

Facies 6 follows above the delta-fed deposits of facies 5 and shows similarities to facies 4. Foraminiferal assemblages 3 and 4, dominated by morphogroup M1, resemble the Paleogene "flysch-type biofacies" that characterizes upper–middle bathyal environments with high sedimentation rates or strong contouritic currents advecting nutrients (Kaminski and Gradstein, 2005). The generally rare occurrence of M3a indicates reduced
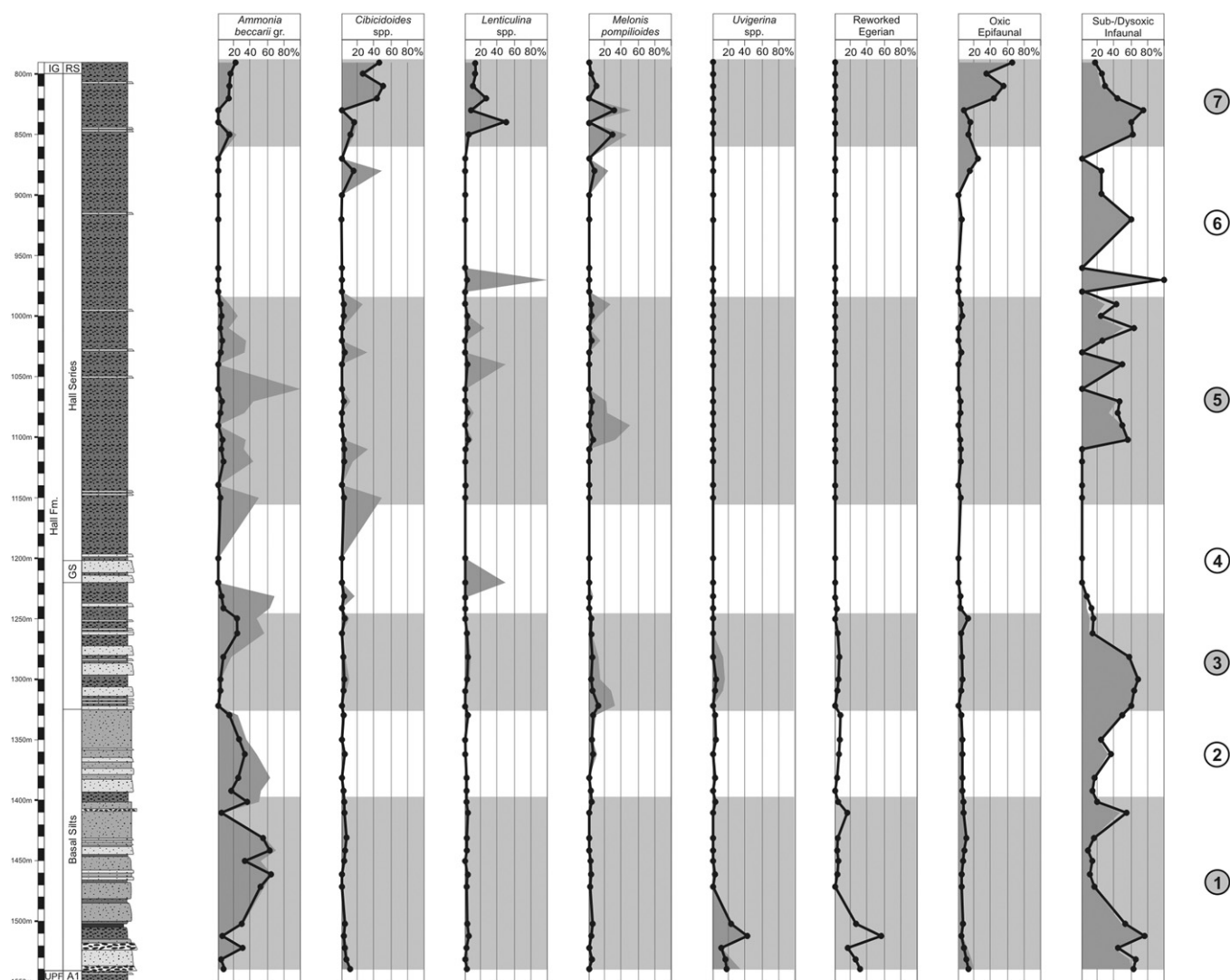
Figure 8. Relative abundances of selected hyaline foraminifers in the Hall Formation. The black line shows the abundance for the whole benthic assemblage, the abundance within hyaline assemblages is indicated in grey. The abundance of reworked foraminiferal tests, epi- and infaunal species and index taxa for bottom-water oxygenation refer to the hyaline assemblages. Oxic, sub- and dysoxic indicators: black line; epi-, infaunal species: grey. Numbers on the right indicate facies 1–7.

sedimentation rates compared to facies 5 and strong contouritic currents might have served as the main source of nutrients. High advection of organic matter and temporary decreased bottom-water oxygenation are suggested at Hochburg 1 by increased abundances of M1, M2b, M4a and M4b (Van den Akker et al., 2000; Kaminski et al., 2005). In the upper part of facies 6 an increase in M3a and a parallel reduction in M1 indicate a minor shallowing trend that heralds the neritic environment of facies 7 (see below).

5.1.7. Facies 7: outer–middle neritic (850–790 m)

Mixed agglutinated and hyaline faunas of assemblage 8b indicate the transition from the upper bathyal facies 6 into a eutrophic and suboxic outer neritic environment (Fig. 6; Kaiho, 1994; Murray, 2006). In general, the hyaline foraminiferal assemblages with A. beccarii gr., C. lopjanicus, L. inornata and M. pompilioides from the top of the Hall Formation resemble the characteristic widespread neritic fauna of the early Ottnangian (e.g., Wenger, 1987; Rupp and Haunold-Jenke, 2003; Pippèrr, 2011; Grunert et al., 2012). Towards the top, increasing abundances of C. lopjanicus and A. beccarii gr. and a parallel decrease in infaunal suboxic

indicators suggest a further shallowing towards a well-oxygenated middle neritic environment as described from the overlying basal Innviertel Group (Faupl and Roetzel, 1987; Krenmayr, 1991; Rupp and Haunold-Jenke, 2003; Rupp and van Husen, 2007; Rupp et al., 2008).

Facies 7 in the uppermost Hall Formation record the final infill of the deep-marine Puchkirchen Trough and the development of the middle Burdigalian (Ottnangian) shelf sea (Hinsch, 2008; Grunert et al., 2012).

5.2. Sequence stratigraphic implications

The bio- and chemofacies development of the Hall Formation through Hochburg 1 together with data from seismic lines that intersect the well Hochburg 1 (Figs. 4, 12), leads to the development of a sequence stratigraphic interpretation that is compared to the existing sequence stratigraphic framework for the Puchkirchen Trough (Jin et al., 1995; Zweigel, 1998; Peña, 2007; Hinsch, 2008). Based on a review of sedimentological and seismic data from internal studies by RAG, Hinsch (2008) summarized a sequence stratigraphic interpretation for the Austrian part of the
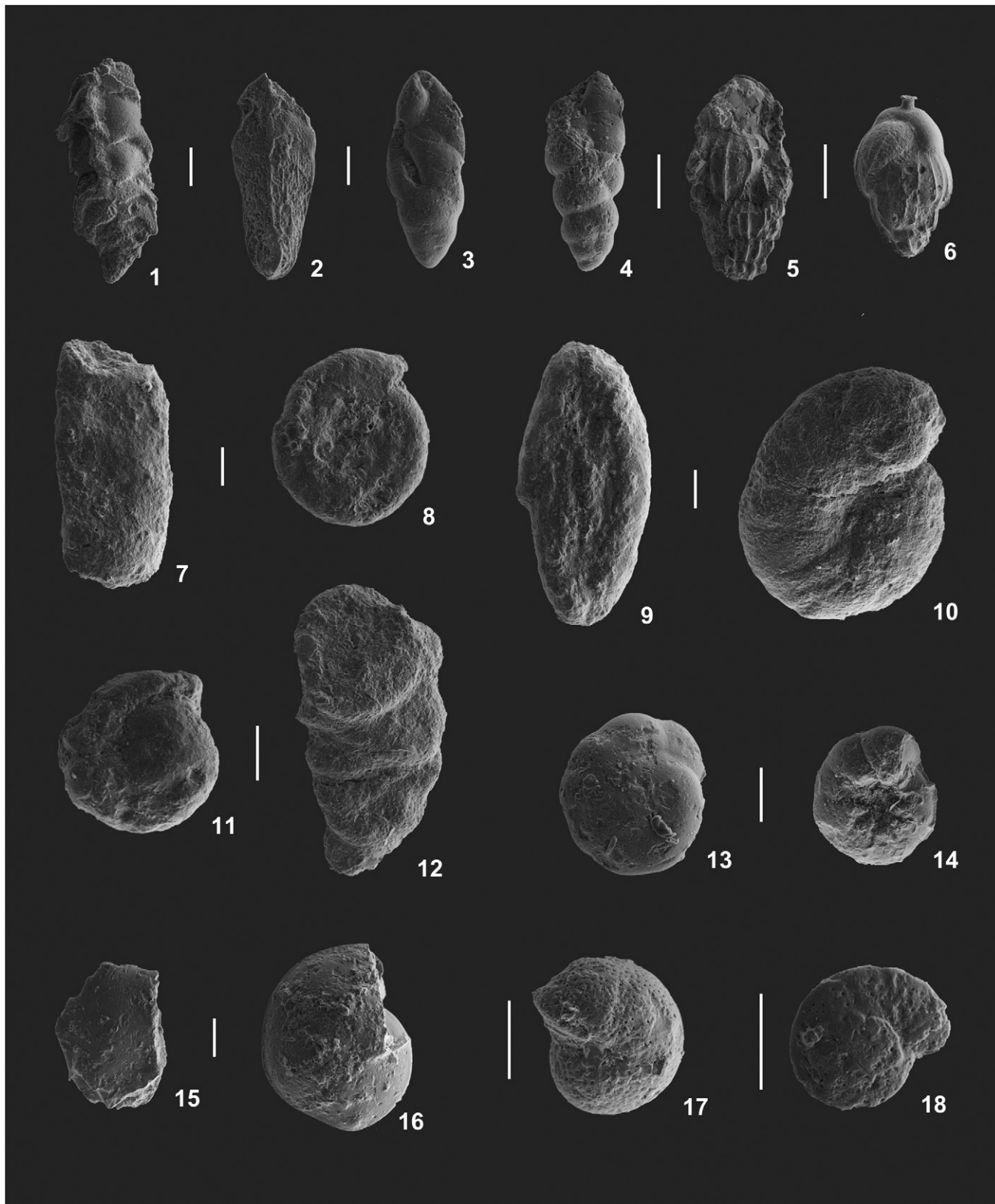
Plate 1. Common benthic foraminifers of the Hall Formation at Hochburg 1. 1–6: Reworked hyaline foraminifers from the basal Hall Formation. 1: *Bolivina beyrichi beyrichi* Reuss; note the strongly compressed test; 1512 m. 2: *Bolivina vaceki vaceki* Schubert; 1512 m. 3: *Fursenkoina halkyardi* (Cushman); 1512 m. 4: *Bulimina elongata* d'Orbigny; 1512 m. 5: *Uvigerina* cf. *posthantkeni* Papp; note the strongly compressed test; 1512 m. 6: *Uvigerina posthantkeni* Papp; 1512 m. 7–12: Most common agglutinated foraminifers, representative for the indicated morphogroups. 7: *Bathysiphon filiformis* Sars; M1; 1140 m. 8: *Ammodiscus miocenicus* Karrer; M3a; 1040 m. 9: *Ammodiscus peruvianus* Berry; M3a; 1060 m. 10: *Reticulophragmium rotundidorsatum* (Hantken); M4a; 1020 m. 11: *Cribrostomoides* sp.; M2b; note the strongly compressed test; 1102 m. 12: *Gaudryinopsis* sp.; M4b; note the strongly compressed test; 1300 m. 13–14: *Ammonia beccarii* gr., an important indicator of sediment delivery from the shelf. 13: spiral side; 1432 m. 14: *Ammonia beccarii* gr.; umbilical side; 1432 m. 15: *Lenticulina buergli* (Wenger); 1040 m. 16–18: Characteristic foraminifers of the Ottnangian fauna. 16: *Lenticulina inornata* (d'Orbigny); 800 m. 17: *Melonis pompilioides* (Fichtel and Moll); 830 m. 18: *Cibicidoides lopjanicus* (Myatlyuk); 800 m. Scale bar = 100 μm.
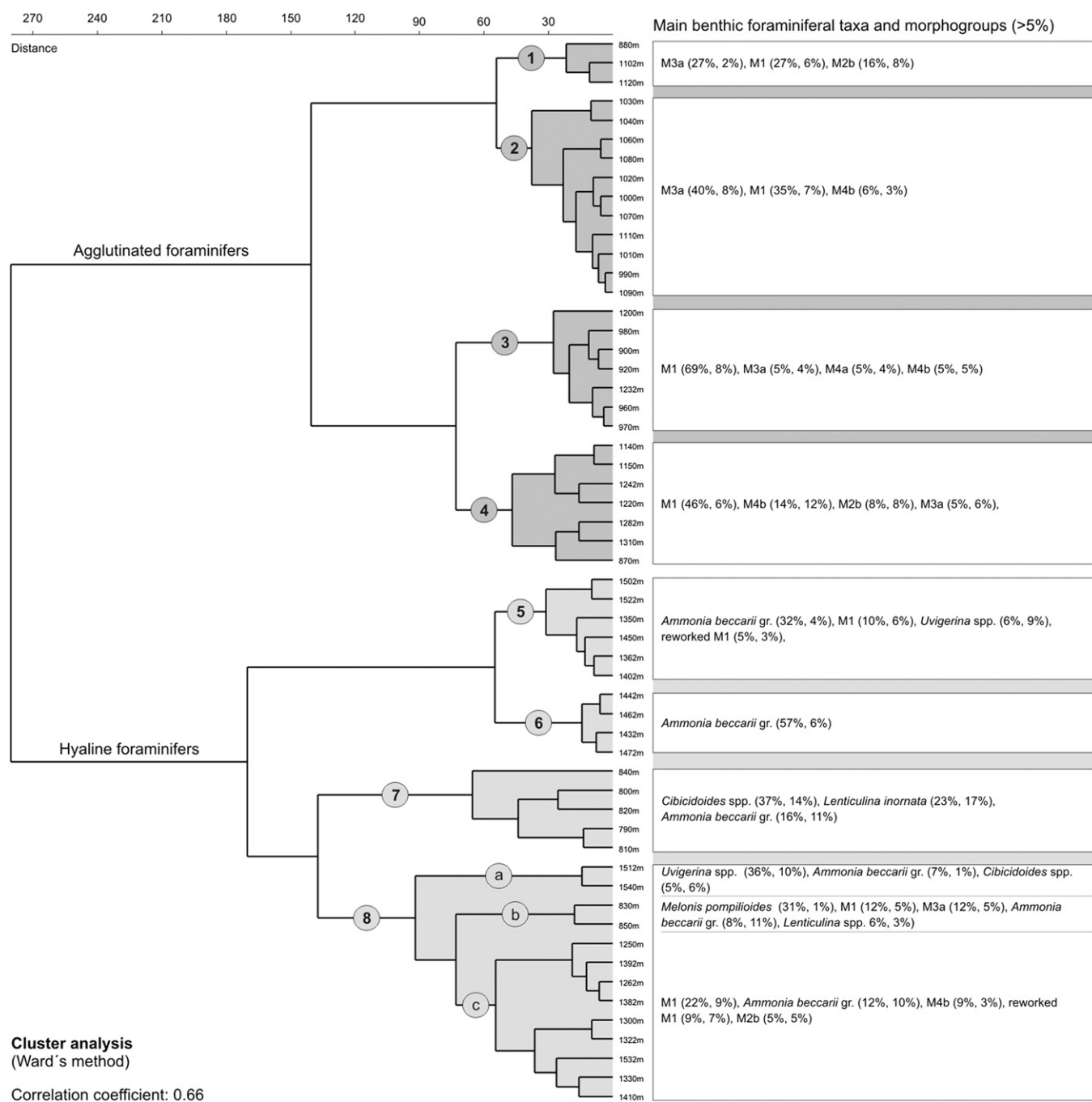
Figure 9. Cluster analysis of the benthic foraminiferal assemblages. The most important foraminiferal taxa and morphogroups (≥5%) are indicated on the right; percentage values indicate mean abundance and standard deviation for all samples in each cluster.

Puchkirchen Trough that attributes the lower Hall Fm. to the 2nd-order sequence SQ 5 (Van Wagoner et al., 1990). In Bavaria, based on extensive well-log and seismic data, Jin et al. (1995), Zweigel (1998) and Peña (2007) suggested that one 2nd-order sequence SQ 4 comprised the marine Burdigalian sediments (Upper Marine Molasse; Fig. 3) in the Bavarian NAFB. The results from Hochburg 1 provide valuable information on depositional environment and age control, that models derived from seismic surveys lack. Furthermore, the sequence stratigraphic models for Upper Austria and Bavaria have been developed separately and a correlation of the Burdigalian sequences based on the new data is attempted herein.

5.2.1. Sequence boundaries and systems tracts

A first sequence boundary (SB) is represented by the erosional hiatus between the Upper Puchkirchen Formation and the Hall Formation that is clearly indicated by strongly mixed lithologies and high amplitude variations in seismic data (Fig. 5). This surface has been observed throughout the Puchkirchen Trough and is linked to major subaqueous erosion (Wagner, 1998). The erosional surface has been interpreted as SB 5 in Upper Austria and SB 4 in Bavaria (Jin et al., 1995; Zweigel, 1998; Peña, 2007; Hinsch, 2008).

The succession of facies 1 to 5 (1540−990 m) is interpreted as one 2nd-order sequence. The lowstand systems tract (LST) is
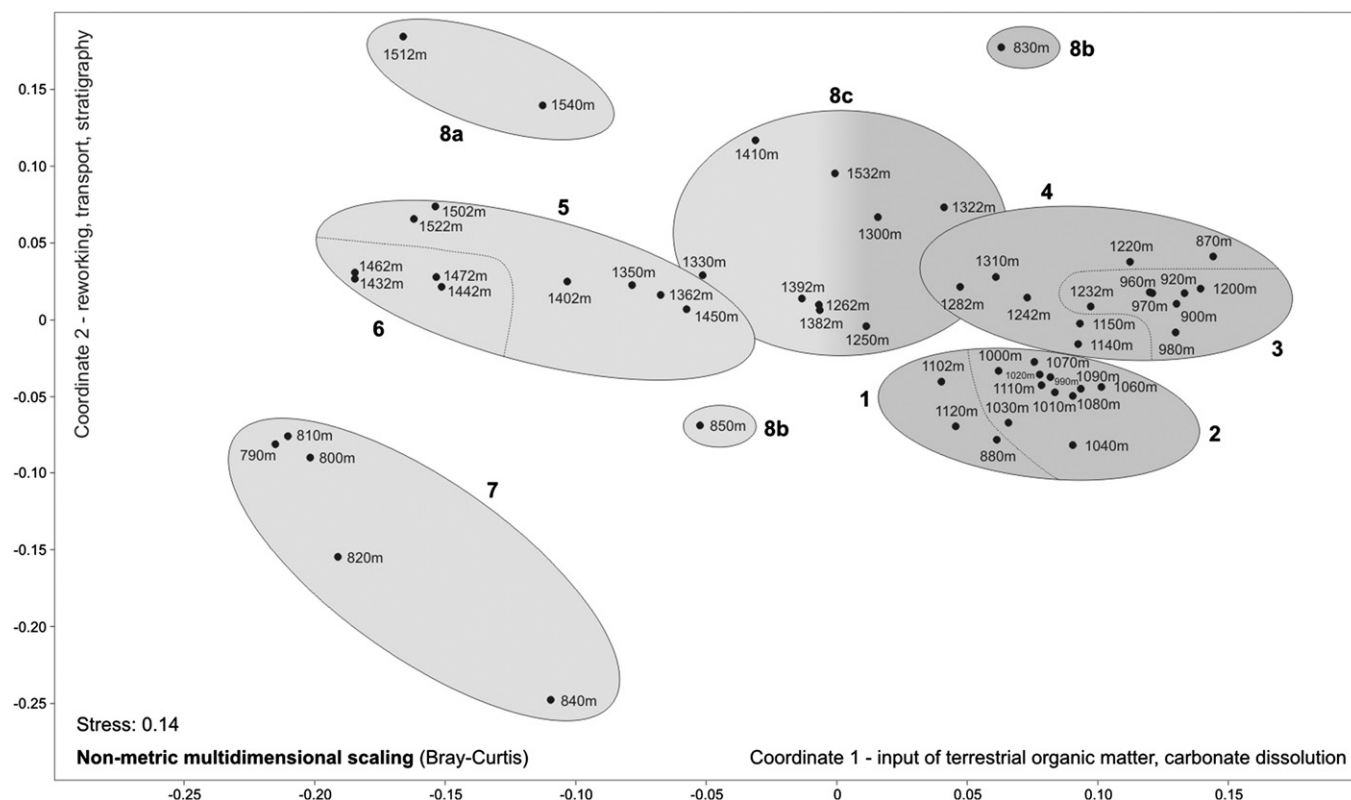
Figure 10. Non-metric multidimensional scaling of the benthic foraminiferal assemblages. Potential factors determining the distribution of the samples in the diagram are indicated for each of the two coordinates.

identified in the basal Hall Formation. High sediment supply by erosion and reduced accommodation space on the shelf resulted in the reactivation of the basin axial channel and the deposition of the intensively reworked sediments of facies 1. This situation is characteristic for the LST deposits of many deep marine basins (Van Wagoner et al., 1990). Facies 2 through 4 document the transgressive systems tract (TST) and record a deepening bathyal environment, the flooding of the Bavarian shelf and the drowning of the base Hall channel. Delta-fed prograding clinoforms of facies 5 characterize late highstand (HST; Van Wagoner et al., 1990; Carvajal and Steel, 2006; Steel et al., 2008). The maximum flooding surface (mfs) of the sequence is present between 1330 and 1300 m. Positioned above the coarse grained basal Hall Formation and below the onset of the HST this interval is characterized by facies 3a and the absence of A. beccarii gr. and shelf-derived material. The new data indicate that with increased accommodation space during maximum sea-level sediment was sequestered on the shelf rise and that sediments delivered to the basin floor mainly originate from the slope (Van Wagoner et al., 1990).

The results of this study correlate well with the concepts of Hinsch (2008). In this model, the LST and TST of SQ 5 correspond to the terminal phase of axial channel belt deposition in the basal Hall Formation. Sediment input to the basin during the subsequent HST, represented by the prograding delta-fed clinoforms, primarily consisted of silt and mud, with limited coarse-grained detritus (Brügel et al., 2003; Hinsch, 2008; see also Section 5.1.5. for trends in lithology and well-log data).

Within SQ 5, two 3rd-order sequences, separated by the Gendorf Sands, have been interpreted from the seismic data in Hinsch (2008), named SQ 5a and SQ 5b herein. At Hochburg 1, SQ 5a (1540–1222 m) is characterized by prevalent turbiditic

deposition and the assemblages show a mixture of agglutinated and calcareous foraminiferal tests. SQ 5b (1222–990 m) is more clayey and contains almost exclusively agglutinated tests that reflect high sedimentation rates and increased fluviatile influence. However, it is hard to distinguish the two sequences in the bathyal setting suggested for Hochburg 1 and future paleoenvironmental studies will need to focus on the northern shelf and western shelf areas to describe the sequence boundary in greater detail.

Additional evidence for a subdivision of the 2nd-order sequence observed in Upper Austria is available from Bavaria. There, SQ 4 is further subdivided into several 3rd-order sequences. In this study, we follow the terminology of the most recent approach by Peña (2007). SQ 4a ("Aquitanian Fish Shales") is excluded from the analysis as it is considered to correspond to the widespread fish shales intercalated with the Upper Puchkirchen Formation (Fig. 3; Wagner, 1998). Instead, 3rd-order sequence SQ 4b.1 is regarded as the base of the lower Burdigalian (Eggenburgian) deposits, corresponding to SQ 5a in Upper Austria. Marine deposits are dominated by turbidites and restricted to the southeastern Puchkirchen Trough (Peña, 2007). SQ 4b.2 correponds to SQ 5b and begins with a transgression to the NW. The HST is characterized by delta progradation from the NW and SW (Zweigel, 1998; Peña, 2007).

A second sequence boundary is indicated by the rapid deepening of the depositional setting, recorded in the sudden occurrence of bathyal facies 6 directly above the delta-influenced clinoforms. Not expressed in lithology and well-log data, the sequence boundary is evident in the faunal assemblages and highlights the importance of micropaleontological analysis for sequence stratigraphic evaluation. In continuation of Hinsch (2008) this 3rd-order sequence is termed SQ 6 for the Austrian

Table 3
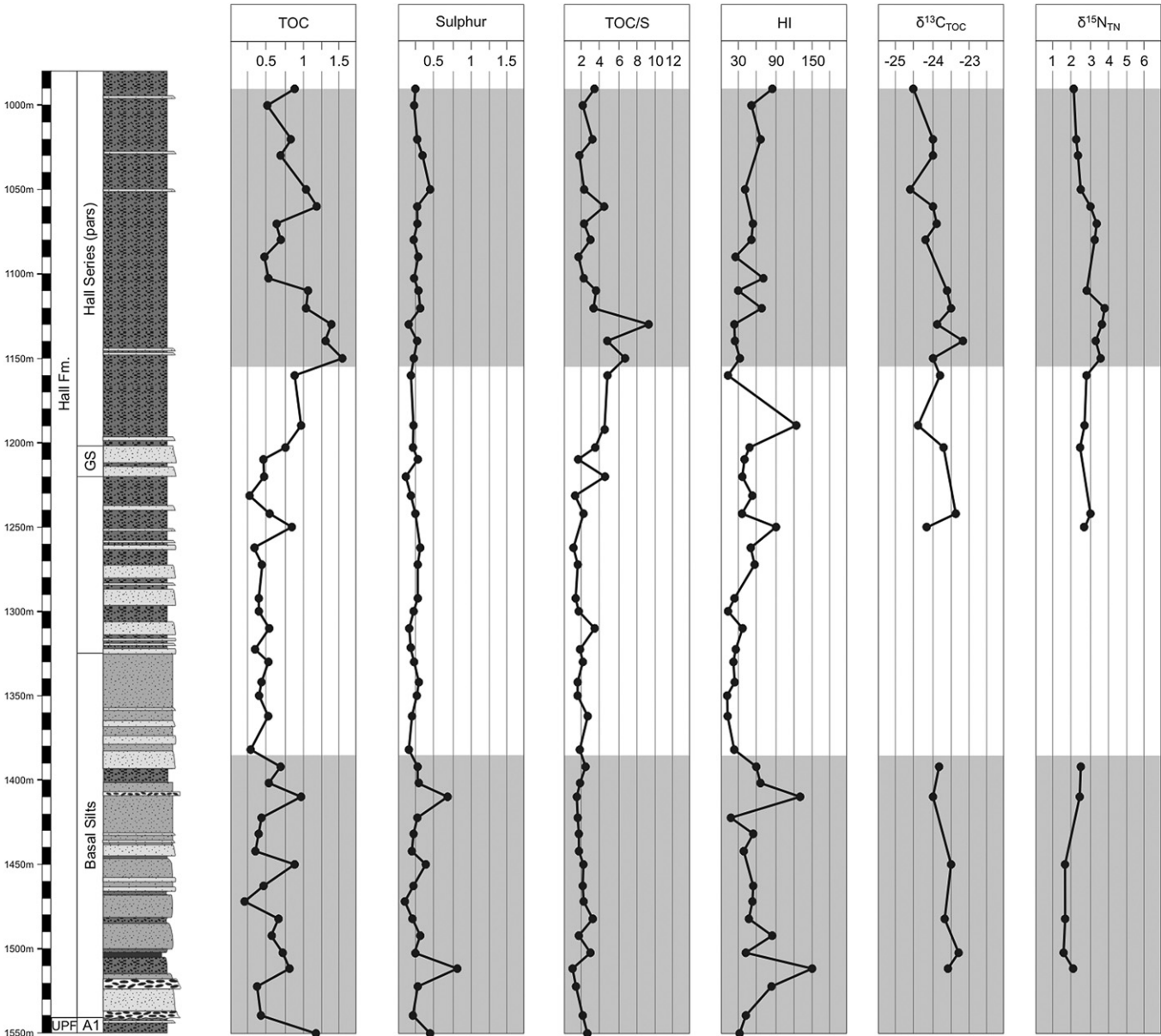TOC (wt. %), S (wt. %), TOC/S, HI, $\delta^{13}C_{TOC}$ (‰) and $\delta^{15}N_{TN}$ (‰) values of the lower and middle Hall Formation.

Depth	Informal unit	TOC	S	TOC/S	HI	$\delta^{13}C_{TOC}$	$\delta^{15}N_{TN}$
990 m	Hall Series	0.86	0.25	3.4	84	−24.5	2.1
1000 m	Hall Series	0.51	0.24	2.1	51		
1020 m	Hall Series	0.82	0.26	3.2	64	−24.0	2.2
1030 m	Hall Series	0.68	0.35	1.9		−24.0	2.3
1050 m	Hall Series	1.03	0.45	2.3	43	−24.6	2.5
1060 m	Hall Series	1.18	0.26	4.5		−24.0	3.0
1070 m	Hall Series	0.62	0.27	2.3	56	−23.9	3.3
1080 m	Hall Series	0.68	0.23	3.0	53	−24.2	3.2
1090 m	Hall Series	0.49	0.29	1.7	28		
1102 m	Hall Series	0.53	0.24	2.2	70		
1110 m	Hall Series	1.05	0.29	3.6	30	−23.6	2.8
1120 m	Hall Series	1.02	0.31	3.3	67	−23.5	3.8
1130 m	Hall Series	1.39	0.15	9.3	24	−23.9	3.7
1140 m	Hall Series	1.28	0.26	4.9	26	−23.2	3.2
1150 m	Hall Series	1.54	0.23	6.7	31	−24.0	3.5
1160 m	Hall Series	0.89	0.18	4.9	13	−23.8	2.8
1190 m	Hall Series	0.97	0.22	4.4	122	−24.4	2.7
1202 m	Gendorf Sands	0.75	0.21	3.6	47	−23.7	2.4
1210 m	Gendorf Sands	0.47	0.28	1.7	43		
1220 m	Gendorf Sands	0.49	0.11	4.5	35		
1232 m	Hall Series	0.26	0.18	1.4	54		
1242 m	Hall Series	0.54	0.25	2.2	35	−23.4	3.0
1250 m	Hall Series	0.79			90	−24.2	2.8
1262 m	Hall Series	0.32	0.3	1.1	50		
1272 m	Hall Series	0.44	0.27	1.6	59		
1292 m	Hall Series	0.39	0.28	1.4	38		
1300 m	Hall Series	0.39	0.23	1.7	13		
1310 m	Hall Series	0.54	0.16	3.4	35		
1322 m	Hall Series	0.34	0.18	1.9	24		
1330 m	Basal Hall Silts	0.52	0.24	2.2	19		
1342 m	Basal Hall Silts	0.45	0.29	1.6	22		
1350 m	Basal Hall Silts	0.41	0.26	1.6	12		
1362 m	Basal Hall Silts	0.52	0.19	2.7	13		
1382 m	Basal Hall Silts	0.29	0.15	1.9	21		
1392 m	Basal Hall Silts	0.67	0.27	2.5	60	−23.8	2.5
1402 m	Basal Hall Silts	0.52	0.27	1.9	71		
1410 m	Basal Hall Silts	0.97	0.65	1.5	128	−24.0	2.4
1422 m	Basal Hall Silts	0.43	0.27	1.6	16		
1432 m	Basal Hall Silts	0.39	0.22	1.8	56		
1442 m	Basal Hall Silts	0.35	0.2	1.8	40		
1450 m	Basal Hall Silts	0.86	0.39	2.2		−23.5	1.7
1462 m	Basal Hall Silts	0.48	0.23	2.1	54		
1472 m	Basal Hall Silts	0.23	0.1	2.3	52		
1482 m	Basal Hall Silts	0.66	0.2	3.3	47	−23.7	1.7
1492 m	Basal Hall Silts	0.55	0.31	1.8	84		
1502 m	Basal Hall Silts	0.72	0.24	3.0	44	−23.3	1.6
1512 m	Basal Hall Silts	0.78	0.79	1.0	151	−23.6	2.1
1522 m	Basal Hall Silts	0.37	0.27	1.4	84		
1540 m	Basal Hall Silts	0.41	0.2	2.1	44		

study area. The deepening is linked to a rapid transgression that is also expressed as a subtle increase in SP values, which probably reflects increasing delivery of clayey sediment (Fig. 5; Asquith and Krygowki, 2004). The transition into facies 7 and stable SP values indicate a gradual shallowing of the environment and a turning point in the sea-level cycle (Figs. 5, 6; Van Wagoner et al., 1990).

The uppermost Hall Formation and the Innviertel Group were not included in the sequence stratigraphic evaluation of Hinsch (2008). Support for our interpretation comes from Bavaria, where 3rd-order sequence SQ 4c and several potential higher-order sequences have been described from upper Eggenburgian and Ottnangian deposits (Jin et al., 1995; Peña, 2007; Pippèrr and Reichenbacher, 2010; Pippèrr, 2011). Along the Bavarian shelf, the transgression begins with the lower Ottnangian Untersimbach Beds culminating in the Neuhofen Beds that represent the maximum flooding surface and HST deposits (Fig. 3; Wenger, 1987; Pippèrr and Reichenbacher, 2010; Pippèrr, 2011). Towards the basin centre, the Neuhofen Beds directly overlie the Eggenburgian strata that are often characterized by accumulations of *L. buergli* (Wenger, 1987; Peña, 2007). At Hochburg 1 a similar pattern is observed within the Hall Formation: the transgressive facies 6 follows directly above facies 5 (with *L. buergli*) and indicates a correlation of the uppermost Hall Formation and the lower Innviertel Group to SQ 4c in Bavaria. Similar to 4th-order sequences SQ 4c.1 and 4c.2 in Bavaria, a further subdivision of SQ 6 into two higher order sequences is indicated by the presence of two fining upward cycles in the uppermost Hall and lower Innviertel Group in Upper Austria (Peña, 2007; Rupp and van Husen, 2007; Rupp et al., 2008). Consequently, facies 6 and 7 represent TST and HST deposits of SQ 6a.

5.2.2. Correlation to global sequence stratigraphy

Paratethyan stratigraphy does not follow the GSSP concept of Hedberg (1976). As a result, the regional stages are defined by holostratotypes that represent a characteristic depositional setting of the particular stage and do not delineate the stage boundary (Piller et al., 2007). The occurrence of many endemic marker species additionally complicates correlation to the global stratigraphic record. To overcome these problems Piller et al. (2007) proposed an updated age model for the Central Paratethys based on a correlation of the regional stages to global 3rd-order sequence stratigraphy. For the North Alpine Foreland Basin, eustatic sea-level has been discussed as the primary agent for generation of the internal lower Burdigalian sequence boundaries (Zweigel, 1998; Genser et al., 2007; Frieling et al., 2009). This is in strong contrast to the situation during the Oligocene and early Aquitanian, when the advance of the Alpine thrust front resulted in a complex interplay of tectonics, sedimentary input and eustasy (Zweigel, 1998; Genser et al., 2007; Hinsch, 2008). For the early Burdigalian, the authors suggest that the basin remained under-filled when thrusting in the Eastern Alps ceased, as a result of viscoelastic relaxation. A minor increase in subsidence during the middle Burdigalian (Ottnangian) is related to increased sedimentary input as the topography of the rising Alpine mountains evolved (Genser et al., 2007; Kuhlemann, 2007). Consequently, the new data from bio- and sequence stratigraphy allow a calibration of the Hall Formation and coeval deposits from Bavaria to the age model of Piller et al. (2007) and to global stratigraphy (Fig. 3).

Reports of nannoplankton zones NN1 and lowermost NN2 for the Upper Puchkirchen Formation (Rögl et al., 1979), and generally rare occurrences of upper Aquitanian (lower Eggenburgian) marine deposits in the study area (Wenger, 1987), indicate a correlation of the erosional hiatus between the Upper Puchkirchen Formation

Table 4
Nannoplankton species identified from selected samples of the Hall Formation.

Sample	Abundance	Preservation	*Braarudosphaera bigelowii*	*Coccolithus miopelagicus*	*Coccolithus pelagicus*	*Cricolithus jonesii*	*Cyclicargolithus floridanus*	*Helicosphaera ampliaperta*	*Helicosphaera ampliaperta* (small)
800 m	C	G			f	x	x	x	x
900 m	F	G			c		x	x	x
1200 m	R	G			c	x			x
1310 m	R	G			x				
1402 m	F	G	x	x	x		x	x	f
1450 m	R	G			c	x			
1512 m A	R	G			c		x		x
1512 m B	C	G		x	c		x		
1512 m C	C	G			x		x	x	x
1540 m	F	G			c		x	x	x

f = frequent, c = common, x = occurring.

Figure 11. TOC (wt. %), S (wt. %), TOC/S, HI, $\delta^{13}C_{TOC}$ (‰) and $\delta^{15}N_{TN}$ (‰) values of the lower and middle Hall Formation.

Helicosphaera carteri	Helicosphaera euphratis	Helicosphaera scissura	Helicosphaera scissura (small)	Pontosphaera multipora	Reticulofenestra bisecta	Reticulofenestra excavata	Reticulofenestra gelida	Reticulofenestra lockeri
x			x	x	x	f	f	x
				x	x	f	x	x
x				x	x	x		
	x	x		x	x	x		
x								x
x				x		x	x	x
x				x	x		cf.	
x		x		x	x	x		x
f	x	x		x			cf.	x

and the Hall Formation with 3rd-order sequence Aq 2 (Fig. 3; Abreu and Haddad, 1998; Piller et al., 2007).

The Burdigalian age deduced for the Hall Formation corresponds well with previous reports by Papp (1960, 1975), who described *Miogypsina intermedia* from the lower part of the Hall Formation indicating Shallow Benthic Zone 25 (Cahuzac and Poignant, 1997; Lourens et al., 2004). Additionally, a Burdigalian age is supported by macro- and microfossil studies by Aberer and Braumüller (1949) and Aberer (1958). The base of the Hall Formation is linked to 3rd-order sequence Bur 1, which corresponds to a major sea-level rise at the base of the Burdigalian that is observed in records from all over the world (Wenger, 1987; Haq et al., 1988; Abreu and Haddad, 1998; Haq and Al-Qahtani, 2005; Miller et al., 2005; Kominz et al., 2008). Outside the Puchkirchen Trough, this transgression that initiated the Burdigalian Seaway is well documented from the Bohemian Massif (Holcová, 2002; Mandic and Steininger, 2003) and Switzerland (Schlunegger et al., 1997).

Biostratigraphy indicates a correlation of SQ 5a and 5b to the middle and upper Eggenburgian, respectively (Wenger, 1987; Pippèrr and Reichenbacher, 2009). Nannoplankton zones upper NN2-NN3 suggest a correspondence of sequence boundary 5b to the global 3rd-order sequence Bur 2 (Rögl et al., 1979; Piller et al., 2007).

The base of SQ 6 can be reliably correlated to 3rd-order sequence Bur 3 based on its lower Ottnangian age and nannoplankton zone NN3 (Rögl et al., 1979; Abreu and Haddad, 1998; Piller et al., 2007). As a consequence, the base of the Ottnangian stage in Upper Austria does not correspond to the base of the Innviertel Group as commonly assumed (e.g. Wagner, 1998; Rupp et al., 2008) but is instead located in the uppermost Hall Formation. A similar discrepancy between the lithostratigraphic and chronostratigraphic base of the Ottnangian has been observed by Piller et al. (2007) at the SE Bohemian Massif in Lower Austria.
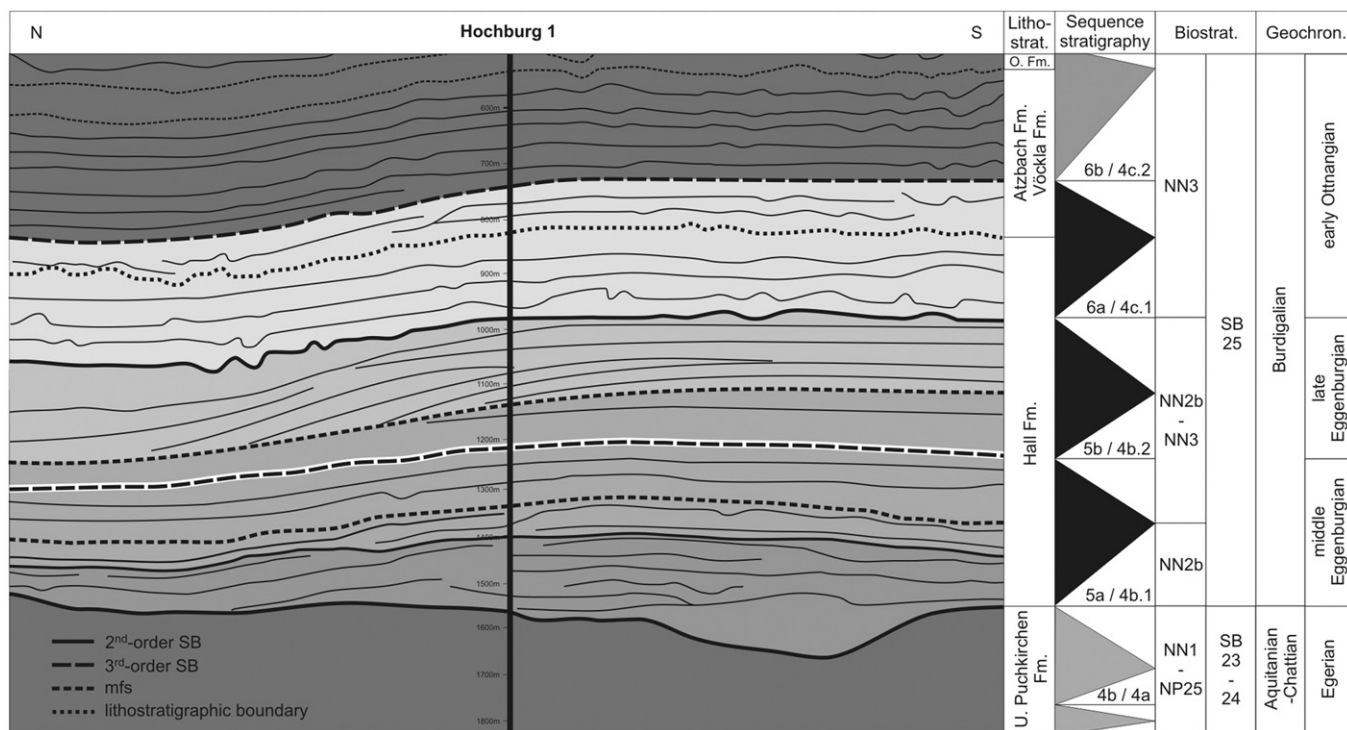

Figure 12. Schematic interpretation of seismic facies along a 4 km long N–S directed transect of the seismic line indicated in Figure 1. Lithostratigraphy is adopted from Papp (1968) and Rupp et al. (2008). Terminology of the identified 3rd-order sequences follows Hinsch (2008) for Upper Austria and Peña (2007) for Bavaria. Biostratigraphy is based on Papp (1960), Rögl et al., (1979), Cicha et al. (1998) and Lourens et al. (2004). O.Fm. = Ottnang Formation. See discussion in the text for details on the sequence stratigraphic interpretation.

Table 4 (continued)

Reticulofenestra minuta	Reticulofenestra pseudoumbilica	Reticulofenestra sp.	Sphenolithus dissimilis	Sphenolithus moriformis	Triquetrorhabdulus carinatus	Thoracosphaera saxea	Thoracosphaera sp.	Zyghrablithus bijugatus
f				x				x
x	x							
				x				
x	x		x		x	x		
	x						x	
	x	x			x			x
x	x	x	x	x				
	x	f		x				

6. Conclusions

The results of the present study contribute to ongoing research aimed at improving hydrocarbon exploration success in the North Alpine Foreland Basin. Based on benthic foraminiferal assemblages and geochemical proxy records, refined constraints for the depositional setting and biostratigraphy of the pelitic Hall Formation provide insights into the early Burdigalian history of the Puchkirchen Trough.

Following widespread submarine erosion of Aquitanian deposits, a rise in eustatic sea-level during the earliest Burdigalian reactivated a turbiditic basin-axial channel system that was dominant during deposition of the older Lower and Upper Puchkirchen formations. Reworked foraminiferal assemblages and strongly varying geochemical records are evidence of intense reworking of these Chattian and Aquitanian sediments in the basal Hall Formation. The channel system was finally cut off from its sediment sources on the shelf during a major transgression; a deepening bathyal environment with frequent deposition of turbidites from the southern basin margin established. Associated deposits are characterized by agglutinated flysch-type foraminiferal assemblages with abundant *B. filiformis*, adapted to the unstable setting. Subsequently, NE prograding delta-fed clinoforms established, heralding the infill of the Puchkirchen Trough. High sedimentation rates and increased input of terrestrial-derived organic matter are indicated by a strong correlation of TOC and TOC/S together with low HI and $\delta^{15}N_{TN}$ values, as well as the frequent occurrences of *Ammodiscus* and other opportunistic agglutinating foraminifers. A eutrophic and suboxic bathyal environment is re-established during a renewed transgression followed by the development of an outer to middle neritic shelf environment with improved bottom-water oxygenation.

The evidence presented strongly supports the notion that eustatic sea-level fluctuations were a primary control on sedimentation in the Puchkirchen Trough rather than Alpine tectonics during the Burdigalian. Three 3rd-order sequences are identified and their corresponding systems tracts are deduced from assemblages of benthic foraminifers and calcareous nannoplankton in the lower, middle and upper Hall Formation. The analysis indicates that the sequences correspond to the regional substages of the middle and upper Eggenburgian and lower Ottnangian, and to global 3rd-order sequences Bur 1—3.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marpetgeo.2012.08.009.

Appendix B

Absolute abundances of all benthic foraminifers and relative abundances of epifaunal, infaunal, oxic and suboxic foraminifers. See Jorissen et al. (2007), Pippèrr and Reichenbacher (2010), Pippèrr (2011), and Grunert et al. (2012) and references therein for further information on microhabitat and oxygen-dependency.

References

Abreu, V.S., Haddad, G.A., 1998. Glacioeustatic fluctuations: the mechanism linking stable isotope events and sequence stratigraphy from the Early Oligocene to Middle Miocene. In: Graciansky, C.-P., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. Sedimentary Geology Special Publication, vol. 60. Society for Sedimentary Geology, Tulsa, pp. 245—260.

Aberer, F., 1958. Die Molassezone im westlichen Oberösterreich und in Salzburg. Mitteilungen der Geologischen Gesellschaft in Wien 50, 23—93.

Aberer, F., 1959. Das Miozän der westlichen Molassezone Österreichs mit besonderer Berücksichtigung der Untergrenze und seiner Gliederung. Mitteilungen der Geologischen Gesellschaft in Wien 52, 7—16.

Aberer, F., Braumüller, E., 1949. Die miozäne Molasse am Alpennordrand im Oichten- und Mattigtal nördlich Salzburg. Jahrbuch der Geologischen Bundesanstalt 92, 129—145.

Alve, E., Nagy, J., 1986. Estuarine foraminiferal distribution in Sandebukta, a branch of the Olso fjord. Journal of Foraminiferal Research 16 (4), 261—284.

Asquith, G., Krygowki, D., 2004. Spontaneous potential. In: Asquith, G., Krygowki, D. (Eds.), Basic Well Log Analysis. AAPG Methods in Exploration, vol. 16, pp. 21—30.

Bąk, K., 2000. Biostratigraphy of deep-water agglutinated foraminifera in Scaglia Rossa-type deposits of the Pieniny Klippen Belt, Carpathians, Poland. In: Grzybowski Foundation Special Publication 7, pp. 15—41.

Berner, R.A., 1984. Sedimentary pyrite formation: an update. Geochimica et Cosmochimica Acta 48, 605—615.

Berner, R.A., Raiswell, R., 1984. C/S method for distinguishing freshwater from marine sedimentary rocks. Geology 12, 365—368.

Bernhardt, A., Stright, L., Lowe, D.R., 2012. Channelized debris-flow deposits and their impact on turbidity currents: the Puchkirchen axial channel belt in the Austrian Molasse Basin. Sedimentology. http://dx.doi.org/10.1111/j.1365-3091.2012.01334.x.

Borowski, K., 2006. Lithofacies and Depositional Environment of the Upper Hall Formation, Alpine Molasse basin, Upper Austria. Diploma thesis., Technical University Bergakademie Freiberg, Germany. 175 pages.

Braumüller, E., 1959. Der Südrand der Molassezone im Raume von Bad Hall (The Southern Rim of the Molasse Zone in the Bad Hall Area). Erdöl-Zeitschrift für Bohr- und Fördertechnik 75, 122–130.

Brügel, A., Dunkl, I., Frisch, W., Kuhlemann, J., Balogh, K., 2003. Geochemistry and Geochronology of Gneiss Pebbles from Foreland Molasse Conglomerates: geodynamic and Paleogeographic Implications for the Oligo-Miocene Evolution of the Eastern Alps. The Journal of Geology 111, 543–563.

Bürgl, H., 1949. Zur Stratigraphie und Tektonik des oberösterreichischen Schliers. Verhandlungen der Geologischen Bundesanstalt, 123–151.

Cahuzac, B., Poignant, A., 1997. Essai de biozonation de l'Oligo-Miocène dans les bassins Européens à l'aide des grands foraminifers néritiques. Bulletin Societe géologique de France 168, 155–169.

Carvajal, C.R., Steel, R.J., 2006. Thick turbiditic successions from supply-dominated shelves during sea-level highstand. Geology 34, 665–668.

Cicha, I., Čtyroká, J., Horváth, M., 1975. Foraminiferen des Egerien. In: Baldi, T., Seneš, J. (Eds.), OM – Egerien. Die Egerer, Pouzdraner, Puchkirchener Schichtengruppe und die Bretkaer Formation. Chronostratigraphie und Neostratotypen. Miozän der Zentralen Paratethys, vol. 5. Verlag der Slowakischen Akademie der Wissenschaften, pp. 233–277.

Cicha, I., Rögl, F., Rupp, C., Ctyroká, J., 1998. Oligocene-Miocene foraminifers of the Central Paratethys. Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft 549, 1–325.

Covault, J.A., Hubbard, S.M., Graham, S.A., Hinsch, R., Linzer, H.-G., 2009. Turbidite-reservoir architecture in complex foredeep-margin and wedge-top depocenters, Tertiary Molasse foreland basin system, Austria. Marine and Petroleum Geology 26, 379–396.

Deines, P., 1980. The isotopic composition of reduced organic carbon. In: Fritz, P., Fontes, J.C. (Eds.), Handbook of Environmental Isotope Geology. The Terrestrial Environment, vol. 1. Elsevier, Amsterdam, pp. 329–406.

De Leo, F.C., Smith, C.R., Rowden, A.A., Bowden, D.A., Clark, M.R., 2010. Submarine canyons: hotspots of benthic biomass and productivity in the deep sea. Proceedings of the Royal Society B: Biological Sciences 277, 2783–2792.

De Ruig, M.J., 2003. Deep Marine Sedimentation and Gas Reservoir Distribution in Upper Austria. Oil Gas European Magazine 29, 64–73.

De Ruig, M.J., Hubbard, S.M., 2006. Seismic facies and reservoir characteristics of a deep marine axial channel belt in the Molasse Basin, Puchkirchen Formation, Upper Austria. AAPG Bulletin 90, 735–752.

Espitalié, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J., Boutefeu, A., 1977. Méthode rapide de caractérisation des roches mères, de leur potentiel pétrolier et de leur degré dévolution. Revue de l'Institut Français du Pérole 32, 23–42.

Espitalié, J., Senga Makadi, K., Trichet, J., 1985. Role of the mineral matrix during kerogen pyrolysis. Organic Geochemistry 6, 365–382.

Faupl, P., Roetzel, R., 1987. Gezeitenbeeinflußte Ablagerungen der Innviertler Gruppe (Ottnangien) in der oberösterreichischen Molassezone. Jahrbuch der Geologischen Bundesanstalt 130, 415–447.

Filipescu, S., Kaminski, M.A., 2008. Paleocene deep-water agglutinated foraminifera in the Transylvanian Basin. In: Kaminski, M.A., Coccioni, R., Marsili, A. (Eds.), Proceedings of the Seventh International Workshop on Agglutinated Foraminifera. Grzybowski Foundation Special Publication, pp. 25–30.

Fornaciari, E., Rio, D., 1996. Latest Oligocene to early middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micropaleontology 42, 1–36.

Frieling, D., Aehnelt, M., Scholz, H., Reichenbacher, M., 2009. Sequence stratigraphy of an alluvial fan-delta in the Upper Marine Molasse (Pfänder area, Late Burdigalian, Miocene). Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 160, 333–357.

Genser, J., Cloetingh, S.A.P.L., Neubauer, F., 2007. Late orogenic rebound and oblique Alpine convergence: new constraints from subsidence analysis of the Austrian Molasse Basin. Global and Planetary Change 58, 214–223.

Gooday, A.J., Levin, L.A., Thomas, C.L., Hecker, B., 1992. The distribution and ecology of *Bathysiphon filiformis* Sars and *B. major* (protista, foraminiferida) on the continental slope off North Carolina. Journal of Foraminiferal Research 22, 129–146.

Gooday, A.J., Shires, R., Jones, A.R., 1997. Large, deep-sea agglutinated Foraminifera; two differing kinds of organization and their possible ecological significance. Journal of Foraminiferal Research 27, 278–291.

Govindan, A., 2004. Miocene deep water agglutinated foraminifera from offshore Krishna-Godavari Basin, India. Micropaleontology 50, 213–252.

Grunert, P., Soliman, A., Ćorić, S., Scholger, R., Harzhauser, M., Piller, W.E., 2010a. Stratigraphic re-evaluation of the stratotype for the regional Ottnangian stage (Central Paratethys, middle Burdigalian). Newsletters on Stratigraphy 44, 1–16.

Grunert, P., Harzhauser, M., Rögl, F., Sachsenhofer, R., Gratzer, R., Soliman, A., Piller, W.E., 2010b. Oceanographic conditions as a trigger for the formation of an Early Miocene (Aquitanian) *Konservat-Lagerstätte* in the Central Paratetyhs Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 292, 425–442.

Grunert, P., Soliman, A., Harzhauser, M., Müllegger, S., Piller, W.E., Roetzel, R., Rögl, F., 2010c. Upwelling conditions in the Early Miocene Central Paratethys sea. Geologica Carpathica 61, 129–145.

Grunert, P., Soliman, A., Ćorić, S., Roetzel, R., Harzhauser, M., Piller, W.E., 2012. Facies development along the tide-influenced shelf of the Burdigalian Seaway: an example from the Ottnangian stratotype (Early Miocene, middle Burdigalian). Marine Micropaleontology 84-85, 14–36.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. Palaeontologia Electronica 4, 1–9.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Society of Economic Paleontologists and Mineralogists, vol. 42, pp. 71–108.

Haq, B.U., Al-Qahtani, A.M., 2005. Phanerozoic cycles of sea-level change on the Arabian Platform. GeoArabia 10, 127–160.

Hart, M.B., 1988. Early Miocene Agglutinated Foraminifera from the Bermuda Abyssal Plain: DSDP Site 603 (NW Atlantic Ocean). Abhandlungen der Geologischen Bundesanstalt 41, 121–131.

Hedberg, H.D., 1976. International Stratigraphic Guide. John Wiley and Sons, New York.

Hertelendi, E., Vetö, I., 1991. The marine photosynthetic carbon isotope fractionation remained constant during the Early Oligocene. Palaeogeography, Palaeoclimatology, Palaeoecology 83, 333–339.

Hinsch, R., 2008. New Insights into the Oligocene to Miocene Geological Evolution of the Molasse Basin of Austria. Oil Gas European Magazine 34, 138–143.

Hoefs, J., 1987. Stable isotope geochemistry, third ed. Springer, Berlin-Heidelberg-New York.

Holcová, K., 2002. Calcareous nannoplankton from the Eggenburgian stratotype and faciostratotypes (Lower Miocene, Central Paratethys). Geologica Carpathica 53, 381–390.

Hubbard, S.M., de Ruig, M.J., Graham, S.A., 2005. Utilizing outcrop analogs to improve subsurface mapping of natural gas-bearing strata in the Puchkirchen Formation, Molasse Basin, Upper Austria. Austrian Journal of Earth Sciences 98, 52–66.

Hubbard, S.M., de Ruig, M.J., Graham, S.A., 2009. Confined channel-levee complex development in an elongate depo-center: deep-water Tertiary strata of the Austria Molasse basin. Marine and Petroleum Geology 26, 85–112.

Jin, J., Aigner, T., Luterbacher, H.P., Bachmann, G.H., Müller, M., 1995. Sequence stratigraphy and depositional history of the south-eastern German Molasse Basin. Marine and Petroleum Geology 12, 929–940.

Jones, R.W., 1999. Fortis Field (North Sea) revisited: a demonstration of the value of historical micropaleontological data. In: Jones, R.W., Simmons, M.D. (Eds.), Biostratigraphy in Production and Development Geology. Geological Society Special Publication 152, London, pp. 185–200.

Jones, R.W., 2006. Applied Palaeontology. Cambridge University Press, Cambridge.

Jones, R.W., Charnock, M.A., 1985. "Morphogroups" of agglutinating foraminifera. Their life positions and feeding habitats and potential applicability in (paleo) ecological studies. Revue de Paleobiologie 4, 311–320.

Jorissen, F.J., Fontanier, C., Thomas, E., 2007. Paleoceanographical proxies based on deep-sea benthic foraminiferal assemblage characteristics. In: Hillaire-Marcel, C., de Vernal, A. (Eds.), Proxies in Late Cenozoic Paleoceanography. Developments in Marine Geology 1, Amsterdam-London, pp. 263–326.

Kaiho, K., 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. Geology 22, 719–722.

Kaminski, M.A., Gradstein, F.M., 2005. Atlas of Paleogene cosmopolitan deep-water agglutinated foraminifera. In: London Grzybowski Foundation. Special Publication, vol. 10, p. 547.

Kaminski, M.A., Gradstein, F.M., Berggren, W.A., Geroch, S., Beckmann, J.P., 1988. Flysch-type agglutinated foraminiferal assemblages from Trinidad: taxonomy, stratigraphy and paleobathymetry. Abhandlungen der Geologischen Bundesanstalt 41, 155–228.

Kaminski, M.A., Silye, L., Kender, S., 2005. Miocene deep-water agglutinated foraminifera from ODP hole 909c: implications from the paleoceanography of the Fram Strait Area, Greenland Sea. Micropaleontology 51, 373–403.

Kender, S., Kaminski, M.A., Cieszkowski, M., 2005. Foraminifera from the Eocene Variegated Shales near Barwinek (Magura Unit, Outer Carpathians), the type locality of Noth (1912) revisited. Annales Societatis Geologorum Poloniae 75, 249–272.

Kender, S., Kaminski, M.A., Jones, R.W., 2008. Early to middle Miocene foraminifera from the deep-sea Congo Fan, offshore Angola. Micropaleontology 54, 477–568.

Koho, K.A., Kouwenhoven, T.J., de Stigter, H.C., van der Zwaan, G.J., 2007. Benthic foraminifera in the Nazaré Canyon, Portuguese continental margin: Sedimentary environments and disturbance. Marine Micropaleontology 66, 27–51.

Kollmann, K., Malzer, O., 1980. Die Molassezone Oberösterreichs und Salzburgs. In: Bachmayer, F. (Ed.), Erdöl und Erdgas in Österreich. Naturhistorisches Museum Wien, pp. 179–201.

Kominz, M.A., Browning, J.V., Miller, K.G., Sugarman, P.J., Mizintseva, S., Scotese, C.R., 2008. Late Cretaceous to Miocene sea-level estimates from the New Jersey and Delaware coastal plain coreholes: an error analysis. Basin Research 20, 211–226.

Krenmayr, H.-G., 1991. Sedimentologische Untersuchungen der Vöcklaschichten (Innviertler Gruppe, Ottnangien) in der oberösterreichischen Molassezone im Gebiet der Vöckla und der Ager. Jahrbuch der Geologischen Bundesanstalt 134, 83–100.

Kuhlemann, J., 2007. Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Global and Planetary Change 58, 224–236.

Kuhlemann, J., Kempf, O., 2002. Post-Eocene evolution of the North Alpine Foreland Basin and its response to Alpine tectonics. Sedimentary Geology 152, 45–78.

Küpper, I., Steininger, F., 1975. Faziostratotypen der Puchkirchener Schichtengruppe. In: Baldi, T., Seneš, J. (Eds.), OM – Egerien. Die Egerer, Pouzdraner, Puchkirchener Schichtengruppe und die Bretkaer Formation. Chronostratigraphie und

Neostratotypen. Miozän der Zentralen Paratethys, vol. 5. Verlag der Slowakischen Akademie der Wissenschaften, pp. 205–220.

Langford, F.F., Blanc-Valleron, M.-M., 1990. Interpreting Rock-Eval Pyrolysis Data Using Graphs of Pyrolizable Hydrocarbons vs. Total Organic Carbon. AAPG Bulletin 74, 799–804.

Lewan, M.D., 1986. Stable carbon isotopes of amorphous kerogens from Phanerozoic sedimentary rocks. Geochimica et Cosmochimica Acta 50, 1583–1591.

Linzer, H.-G., 2001. Cyclic channel systems in the Molasse foreland basin of the Eastern Alps – the effects of Late Oligocene foreland thrusting and Early Miocene lateral escape. AAPG Bulletin 85, 118.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), A Geologic Time Scale 2004. Cambridge University Press, Cambridge, pp. 409–440.

Malzer, O., Rögl, F., Seifert, P., Wagner, L., Wessely, G., Brix, F., 1993. Die Molassezone und deren Untergrund. In: Brix, F., Schultz, O. (Eds.), Erdöl und Erdgas in Österreich, pp. 281–357.

Mandic, O., Steininger, F.F., 2003. Computer-based mollusc stratigraphy - a case study from the Eggenburgian (Early Miocene) type region (NE Austria). Palaeogeography, Palaeoclimatology, Palaeoecology 197, 263–291.

Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Organic Geochemistry 27, 213–250.

Meyers, P.A., 2003. Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. Organic Geochemistry 34, 261–289.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science 310, 1293–1298.

Miller, W., 1988. Giant Bathysiphon (Foraminiferida) from Cretaceous turbidites, northern California. Lethaia 21, 363–374.

Miller, W., 2005. A Bathysiphon (Foraminifera) 'shell bed' from the Cretaceous of northern California, USA: example of a parautochthonous macro-skeletal deposit in deep-ocean turbidites. Palaeogeography, Palaeoclimatology, Palaeoecology 260, 342–346.

Murray, J.W., 2006. Ecology and Applications of Benthic Foraminifera. Cambridge University Press, Cambridge.

Nagy, J., 1992. Environmental significance of foraminiferal morphogroups in Jurassic North sea deltas. Palaeogeography, Palaeoclimatology, Palaeoecology 95, 111–134.

Nagy, J., Berge, S.H., 2008. Micropalaeontological evidence for brackish water conditions during deposition of the Knorringfjellet Formation, Late Triassic-Early Jurassic, Spitsbergen. Polar Research 27, 413–427.

Nagy, J., Gradstein, F.M., Kaminski, M.A., Holbourn, A.E.L., 1995. Foraminiferal morphogroups, paleoenvironments and new taxa from Jurassic and Cretaceous strata of Thakkhola, Nepal. In: Kaminski, M.A., Geroch, S., Gasinski, M.A. (Eds.), Proceedings of the Fourth International Workshop on Agglutinated Foraminifera. Grzybowski Foundation, London, pp. 181–209.

Nagy, J., Hess, S., Alve, E., 2010. Environmental significance of foraminiferal assemblages dominated by small-sized Ammodiscus and Trochammina in Triassic and Jurassic delta-influenced deposits. Earth-Science Reviews 99, 31–49.

Nagy, J., Johansen, H.O., 1991. Delta-influenced foraminiferal assemblages from the Jurassic (Toarcian-Bajocian) of the northern North Sea. Micropaleontology 37, 1–40.

Papp, A., 1960. Das Vorkommen von Miogypsina in Mitteleuropa und dessen Bedeutung für die Tertiärstratigraphie. Mitteilungen der Geologischen Gesellschaft in Wien 51, 219.

Papp, A., 1968. Nomenclature of the Neogene of Austria. Verhandlungen der Geologischen Bundesanstalt 1968, 19–27.

Papp, A., 1975. Die Großforaminiferen des Egerien: In: Baldí, T., Seneš, J. (Eds.), OM — Egerien. Die Egerer, Pouzdraner, Puchkirchener Schichtengruppe und die Bretkaer Formation. Chronostratigraphie und Neostratotypen. Miozän der Zentralen Paratethys, vol. 5. Verlag der Slowakischen Akademie der Wissenschaften, pp. 289–307.

Peña, F.A.C., 2007. The Early Miocene Upper Marine Molasse of the German Part of the Molasse Basin – a Subsurface Study. Sequence Stratigraphy, Depositional Environment and Architecture, 3D Basin Modeling. Ph.D. thesis, Eberhard-Karls-Universität Tübingen, Germany. 133 pages.

Petters, V., 1936. Geologische und mikropaläontologische Untersuchungen der Eurogasco im Schlier Oberösterreichs. Petroleum Zeitschrift 32, 3.

Piller, W.E., Harzhauser, M., Mandic, O., 2007. Miocene Central Paratethys stratigraphy – current status and future directions. Stratigraphy 4, 151–168.

Piller, W.E., Egger, H., Erhart, C., Gross, M., Harzhauser, M., Hubmann, B., van Husen, D., Krenmayr, H.-G., Krystyn, L., Lein, R., Lukeneder, A., Mandl, G., Rögl, F., Roetzel, R., Rupp, C., Schnabel, W., Schönlaub, H.P., Summesberger, H., Wagreich, M., 2004. Die Stratigraphische Tabelle von Österreich 2004 (sedimentäre Schichtfolgen). Österreichische stratigraphische Kommission und Kommission für die paläontologische und stratigraphische Erforschung Österreichs.

Pippèrr, M., 2011. Characterisation of Ottnangian (middle Burdigalian) palaeoenvironments in the North Alpine Foreland Basin using benthic foraminifera – a review of the Upper Marine Molasse of southern Germany. Marine Micropaleontology 79, 80–99.

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.

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.

Pratt, L.M., 1984. Influence of paleoenvironmental factors on preservation of organic matter in Middle Cretaceous Greenhorn Formation, Pueblo, Colorado. AAPG Bulletin 68, 1146–1159.

Rögl, F., Hochuli, P., Mueller, C., 1979. Oligocene-Early Miocene stratigraphic correlations in the Molasse Basin of Austria. Annales Geologiques des Pays Helleniques, Tome hors series, 1045–1050.

Rupp, C., Haunold-Jenke, Y., 2003. Untermiozäne Foraminiferenfaunen aus dem oberösterreichischen Zentralraum. Jahrbuch der Geologischen Bundesanstalt 143, 227–302.

Rupp, C., Hofmann, T., Jochum, B., Pfleiderer, S., Schedl, A., Schindlbauer, G., Schubert, G., Slapansky, P., Tilch, N., van Husen, D., Wagner, L., Wimmer-Frey, I., 2008. Geologische Karte der Republik Österreich 1:50.000, Blatt 47 Ried im Innkreis. Erläuterungen zu Blatt 47 Ried im Innkreis. Geological Survey of Austria, Vienna.

Rupp, C., van Husen, D., 2007. Zur Geologie des Kartenblattes Ried im Innkreis. In: Egger, H., Rupp, C. (Eds.), Beiträge zur Geologie Oberösterreichs, Arbeitstagung der Geologischen Bundesanstalt 2007. Geological Survey of Austria, Vienna, pp. 73–112.

Schlunegger, F., Leu, W., Matter, A., 1997. Sedimentary Sequences, Seismic Facies, Subsidence Analysis, and Evolution of the Burdigalian Upper Marine Molasse Group, Central Switzerland. AAPG Bulletin 81, 1185–1207.

Steel, R.J., Carvajal, C., Petter, A.L., Uroza, C., 2008. Shelf and shelf-margin growth in scenarios of rising and falling sea level. In: Hampson, G.J., Steel, R.J., Burgess, P.M., Dalrymple, R.W. (Eds.), Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy. SEPM, Special Publication, vol. 90, pp. 47–71.

Van den Akker, T.J.H.A., Kaminski, M.A., Gradstein, F.M., Wood, J., 2000. Campanian to Palaeocene biostratigraphy and paleoenvironments in the Foula Sub-basin, west of the Shetland Islands, UK. Journal of Micropalaeontology 19, 23–43.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. In: American Association of Petroleum Geologists, Methods in Exploration Series 7. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Wagner, L.R., 1996. Stratigraphy and hydrocarbons in the Upper Austrian Molasse Foredeep (active margin). In: Wessely, G., Liebl, W. (Eds.), Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. European Association of Geoscientists and Engineers Special Publications 5, pp. 217–235.

Wagner, L.R., 1998. Tectono-stratigraphy and hydrocarbons in the Molasse Foredeep of Salzburg, Upper and Lower Austria. In: Mascle, A., Puigdefábregas, C., Luterbacher, H.P., Fernández, M. (Eds.), Cenozoic Foreland Basins of Western Europe. Geological Society Special Publications, vol. 134. Geological Society, London, pp. 339–369.

Wenger, W.F., 1987. Die Foraminiferen des Miozäns der bayerischen Molasse und ihre stratigraphische sowie paläogeographische Auswertung. Zitteliana 16, 173–340.

Zweigel, J., 1998. Eustatic versus tectonic control on foreland basin fill. Contributions to Sedimentary Geology 20. Schweizerbart, Stuttgart.