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EARLY BADENIAN PALEOENVIRONMENT IN THE LAVANTTAL BASIN (MÜHLDORF FORMATION; AUSTRIA): EVIDENCE FROM GEOCHEMISTRY AND PALEONTOLOGY.

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Organic petrography
Organic matter
Foraminifera
Ostracoda
Badenian

ABSTRACT

Early Badenian transgressions affected wide areas in the Central Paratethys and caused marine/brackish deposition even within the Alps (Lavanttal Basin, Fohnsdorf Basin). Lithology, bulk geochemistry, and fossil content (foraminifera, calcareous nannoplankton, ostracoda, otoliths) of the Mühldorf Formation were investigated to reconstruct environmental changes in the Lavanttal Basin during Early Badenian times.

The Mühldorf Formation overlies fluvial deposits (Granitztal Formation) and consists of a lacustrine lower and a marine upper part. The latter has been dated as late Early Badenian (uppermost M5b, lower part of NN5).

The lacustrine part (“fish shale”) records deposition in a quiet anoxic environment. High sulfur contents suggest a brackish influence. Organic carbon contents up to 10% result from algal blooms. Silty material with low organic matter contents and varying amounts of land plant detritus was deposited during times of enhanced river runoff.

The marine part of the Mühldorf Formation contains tuff layers and displays an upward shallowing and coarsening trend. Accumulation of the marine succession commenced in a relatively stable offshore zone (probably >100 m water depth). Suboxic/low oxic conditions near the sediment/water interface resulted in poor living conditions for benthic foraminifera. Low organic matter productivity in the water column is indicated by very low numbers of planktonic foraminifera, low organic matter contents (<1% TOC), and a dominance of land plant material. Two events with enhanced river runoff interrupted the stable environment and resulted in a temporary subtle decrease in salinity, water column stratification, decrease in oxygen contents at the sediment/water interface, decrease in biodiversity, and enhanced organic matter preservation.

More frequent environmental changes occurred during deposition of the middle part of the marine Mühldorf Formation when water depth decreased approx. to 50 to 100 m. Oxygenation levels near the sediment/water interface decreased further and reached the suboxic/dysoxic boundary. Inflow of nutrient-rich cold freshwater resulted in a drastic increase in plankton productivity and, consequently, in increased organic matter flux to the sediment surface promoting the growth of infauna. Thereafter, plankton productivity decreased, followed by a decrease in abundance of infauna shortly afterwards. Calcareous nannoplankton dominated by small reticulofenestrids and helicosphaerids is abundant in the fine-grained lower part.

The sandy upper part of the marine Mühldorf Formation records a change to a marginal marine, higher-energy environment (deltaic-estuarine offshore transition, shoreface, and lagoon). Foraminiferal assemblages suggest suboxic conditions in the top layer of fine-grained sediments, and oxic conditions in the water column. Total foraminiferal number dropped to a minimum and biodiversity was relatively low. Nannoflora is rare in the uppermost part of the Mühldorf Formation. Non-marine sediments with sapropelic shale near their base overlie the Mühldorf Formation.

Maximum water depth occurred during deposition of the lower part of the marine Mühldorf Formation. Probably, this part represents a maximum flooding surface (interval). The lower lacustrine part is interpreted as the Transgressive Systems Tract and the upper part as the Highstand Systems Tract of a sequence, which is coeval with TB 2.4. Maximum flooding even influenced the central part of the Alps and established brackish conditions in the nearby Fohnsdorf Basin.

Weite Bereiche der Zentralen Paratethys wurden während des frühen Badeniums von Transgressionen erfasst. Diese erzeugten inmitten der Alpen marin/brackische Bedingungen (Lavanttal Becken, Fohnsdorf Becken). In vorliegender Arbeit werden Lithologie, Geochemie und Fossilführung (Foraminiferen, kalkiges Nannoplankton, Ostrakoden, Otolithen) der Mühldorf-Formation untersucht. Ziel der Arbeit ist es, Veränderungen des Ablagerungsraumes im Lavanttal während des frühen Badenium zu rekonstruieren.

Die Mühldorf-Formation überlagert fluviatile Ablagerungen (Granitztal-Formation) und setzt sich aus einem liegenden lakustrinen und einem hangenden marinen Teil zusammen. Letzterer wurde mit spätem frühen Badenium datiert (oberste M5b, unterer Teil der NN5).

Der lakustrine Teil ("Fischschiefer") wurde in einem ruhigen, anoxischen Bereich abgelagert. Hohe Schwefelgehalte indizieren einen brackischen Einfluss. Hohe Gehalte an organischem Material (bis 10% TOC) sind eine Folge von Algenblüten. Siltige Gesteine mit geringen Gehalten an (Landpflanzen-dominiertem) organischem Material wurden während Zeiten erhöhten Flusswassereintrages abgelagert.

Der marine Teil der Mühldorf-Formation beinhaltet Tufflagen und zeigt einen Trend zur Verflachung und Kornvergröberung ins Hangende. Die Ablagerung begann in einem relativ stabilen Bereich mit vermutlich mehr als 100 m Wassertiefe. Suboxische/gering oxische Verhältnisse an der Wasser/Sedimentgrenzfläche bedingten schlechte Lebensbedingungen für benthische Foraminiferen. Geringe Produktivität in der Wassersäule wird durch eine geringe Anzahl planktischer Foraminiferen, geringe Gehalte an organischem Kohlenstoff (<1%) und organischem, von Landpflanzen dominierendem Material angezeigt. Zwei Ereignisse mit verstärktem Süßwassereintrag unterbrachen die stabilen Verhältnisse und führten zu geringerer Salinität, Stratifizierung des Wasserkörpers, Abnahme des Sauerstoffgehaltes im Bodenwasser, Abnahme der Biodiversität und verbesserter Erhaltung des organischen Materials.

Änderungen der Milieubedingungen waren während der Ablagerung des mittleren Teils der marinen Mühldorf-Formation häufiger. Gleichzeitig nahm die Wassertiefe auf 50 bis 100 m ab. Der Sauerstoffgehalt an der Wasser/Sedimentgrenzfläche sank weiter und erreichte die Grenze zwischen suboxischem und dysoxischem Bereich. Der Eintrag nährstoffreichen kalten Süßwassers bedingte eine drastische Zunahme der Planktonproduktivität und als Folge dessen einen vermehrten Fluss von organischem Material auf die Sedimentoberfläche. Dieser förderte das Gedeihen von Infauna. Später nahmen zuerst die Planktonproduktivität und danach die Häufigkeit der Infauna wieder ab. Kalkiges Nannoplankton tritt im tieferen feinkörnigen Teil der marinen Mühldorf-Formation häufig auf und wird durch kleine Reticulofenestriden und Helicosphaeriden dominiert.

Der sandige obere Teil der marinen Mühldorf-Formation zeigt den Wechsel zu einem randnahen, höherenergetischen Milieu an (Delta-Ästuar Übergangsbereich, Strand, Lagune). Foraminiferengesellschaften indizieren suboxische Verhltnisse in den obersten Schichten der feinkörnigen Sedimente. Die Anzahl der Foraminiferen fiel auf ein Minimum und die Biodiversität war relativ gering. Im obersten Teil der Mühldorf-Formation ist Nannoflora selten. Die Mühldorf-Formation wird von Süßwasserablagerungen überlagert, die an ihrer Basis einen Sapropelithorizont aufweisen.

Die maximale Wassertiefe wurde während der Ablagerung des tieferen Teils der marinen Mühldorf-Formation erreicht. Wahrscheinlich repräsentiert dieser eine Maximum Flooding Surface (Interval). Der lakustrine Teil wird als Transgressive Systems Tract interpretiert und der hangende Teil als Highstand Systems Tract einer Sequenz, die zeitlich mit der Sequenz TB 2.4 korreliert. Die maximale Überflutung erreichte sogar die Zentralalpen und führte zu brackischen Verhältnissen im nahen Fohnsdorf Becken.

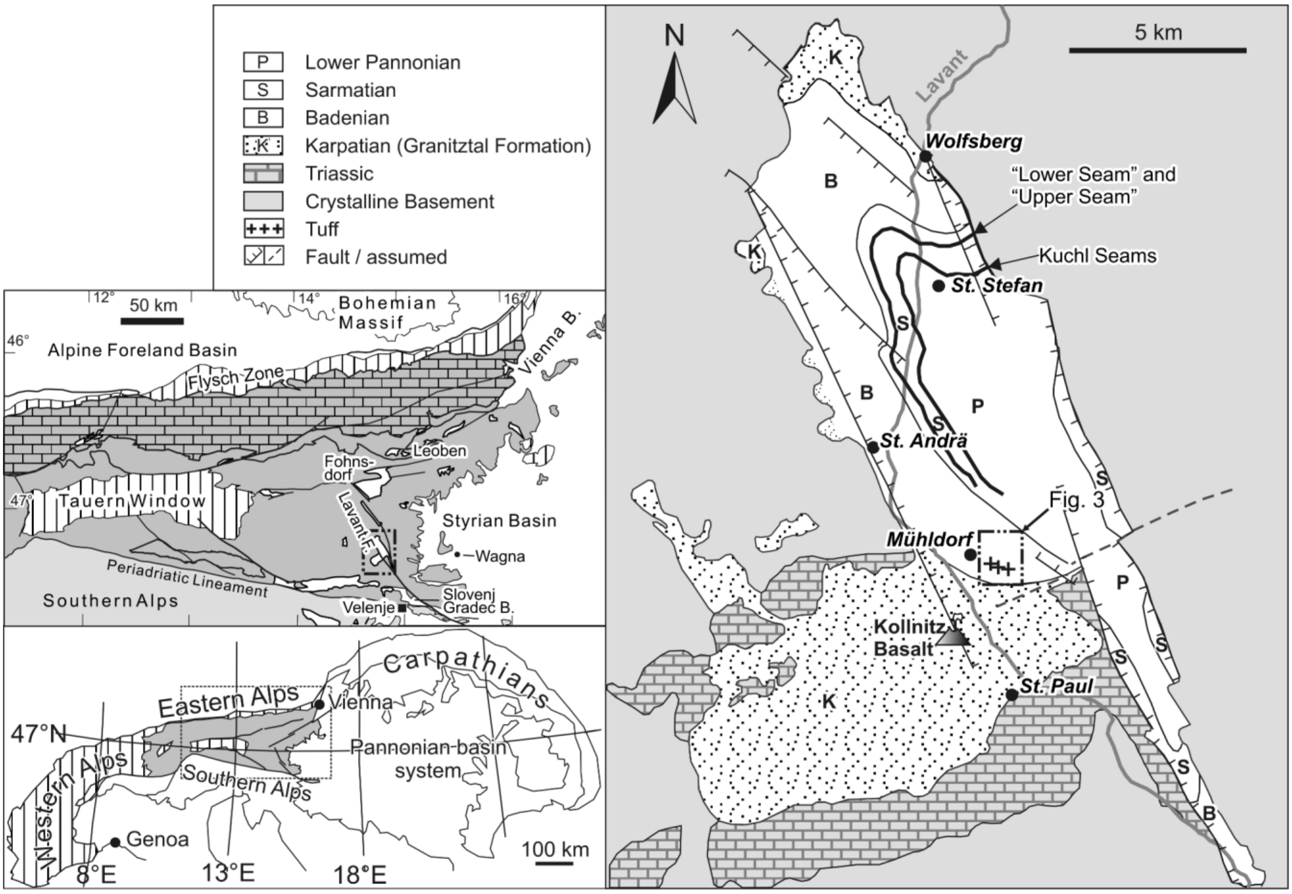


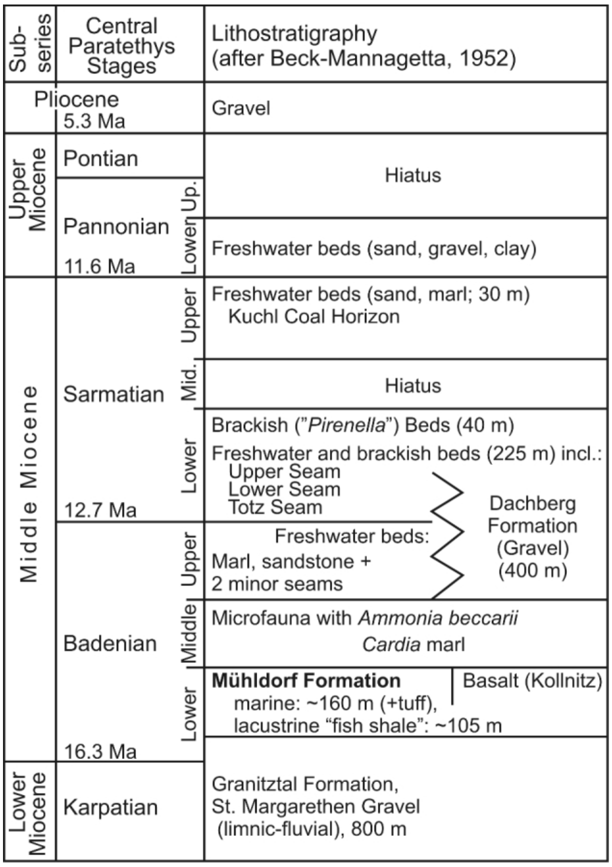
Figure 1: Location map of the study area and geological map of the Lavanttal Basin.

1. INTRODUCTION

Extensive parts of the Central Paratethys were affected by marine transgressions during the Early Badenian (Middle Miocene). These transgressions caused brackish influence even within the Central Alps (e.g. Fohnsdorf Basin; Sachsenhofer et al., 2003). Most probably, the brackish influence of lacustrine systems in the Alps resulted from tectonic movements along major strike-slip faults, which established a connection with the Paratethys through the Lavanttal Basin (Strauss et al., 2001; Fig. 1). Marine Lower Badenian sediments in the latter basin (Mühldorf Formation; Fig. 2), therefore, are of prime importance for the understanding of Badenian paleogeography in the Alpine realm.

Sediments of the Mühldorf Formation were drilled by the Eisenbahn-HL-AG within the frame of exploratory work for the Koralm rail tunnel connecting the Styrian and Lavanttal basins. For the present project a total of ten boreholes, up to 50 m deep, were selected (see Fig. 3a for position of boreholes). It was planned to investigate a continuous profile from the uppermost Granitztal Formation underlying the Mühldorf Formation to non-marine rocks overlying them. However, during construction of an exploratory tunnel, it became evident that some intervals were missed by the boreholes (see Fig. 3b).

The aim of the study is to establish the stratigraphy and paleoenvironment of the Lower Badenian in the Lavanttal Basin. To reach this aim, we apply a multi-disciplinary approach including core descriptions, determination of bulk organic (organic carbon, RockEval pyrolysis) and inorganic geochemical parameters (inorganic carbon, sulphur), and of organic petrological and paleontological data (foraminifera, ostracoda, calcareous nannoplankton, fish remains).



Sub-series	Central Paratethys Stages		Lithostratigraphy (after Beck-Mannagetta, 1952)	
Pliocene 5.3 Ma			Gravel	
Upper Miocene	Pontian		Hiatus	
	Pannonian	Up.		
	11.6 Ma	Lower	Freshwater beds (sand, gravel, clay)	
Middle Miocene	Sarmatian	Upper	Freshwater beds (sand, marl; 30 m) Kuchl Coal Horizon	
		Mid.	Hiatus	
	12.7 Ma	Lower	Brackish ("*Pirenella*") Beds (40 m) Freshwater and brackish beds (225 m) incl.: Upper Seam Lower Seam Totz Seam	Dachberg Formation (Gravel) (400 m)
	Badenian	Upper	Freshwater beds: Marl, sandstone + 2 minor seams	
		Middle	Microfauna with *Ammonia beccarii* *Cardia* marl	
	16.3 Ma	Lower	**Mühldorf Formation** marine: ~160 m (+tuff), lacustrine "fish shale": ~105 m	Basalt (Kollnitz)
Lower Miocene	Karpatian		Granitztal Formation, St. Margarethen Gravel (limnic-fluvial), 800 m	

FIGURE 2: Stratigraphy of the Neogene of the Lavanttal Basin (modified from Beck-Mannagetta, 1952).

2. GEOLOGICAL SETTING

The evolution of the Eastern Alps in Early and Middle Miocene times was controlled by large-scale extension and lateral tectonic extrusion (e.g. Ratschbacher et al., 1991; Frisch et al., 2000). The sinistral northern border of the extruding wedge was located in the Northern Calcareous Alps, whereas the dextral Periadriatic Lineament acted as its southern border. The still active NW-SE trending Lavant fault system dextrally offsets the Periadriatic Lineament for 10 to 14 km (Vrabec et al., 2006). Several Miocene basins, including the main Lavanttal Basin, formed along the Lavant fault system and prove its activity during Miocene times.

The lithostratigraphic subdivision of the Lavanttal Basin is based on Beck-Mannagetta (1952). The basin fill starts with Lower Miocene (Karpatian) deposits overlying crystalline rocks and Mesozoic sediments (Figs. 1, 2). These fluvial deposits (Granitztal Formation; "Granitztal Beds" of Beck-Mannagetta 1952, pp. 82-90; St. Margarethen Gravel) are overlain by the Mühldorf Formation ("Mühldorf Beds" of Beck-Mannagetta 1952, pp. 44-48), which traditionally is subdivided into a lacustrine lower part ("fish shale") and a marine upper part (Beck-Mannagetta, 1952). Various macro- and microfossils including plant fossils have been described from the Mühldorf Formation (e.g. Grill in Beck-Mannagetta, 1952; Weinfurter, 1952; Berger, 1955; Kühn, 1963; Schmid, 1974). Coeval magmatic activity is proven by tuffs in the Mühldorf Formation and by the Kollnitz basalt (14.9 ± 0.9 my; Lippolt et al., 1975). During Middle Badenian time, the salinity decreased and freshwater conditions prevailed during the Late Badenian. Fluvial gravels of the Dachberg Formation ("Dachberg Gravel" of Beck-Mannagetta, 1952, pp. 48-51) were transported into the basin from the south and from the northwest, whereas marls and thin coal seams were deposited in lacustrine settings.

Brackish sediments at the base of the Sarmatian succession mark another transgression. In the central basin the brackish sediments are overlain by freshwater deposits with three coal seams, the lowermost "Totz Seam", up to 1 m thick, the "Lower Seam" (up to 2.9 m) and the "Upper Seam" (up to 3.3 m; Bechtel et al., 2007). Towards the south, the coal-bearing succession interfingers with the Dachberg Gravel. Sapropelic rocks, up to 4 m thick, overlie the Upper Seam and grade upwards into brackish sediments (80-190 m thick; Beck-Mannagetta, 1952). Upper Sarmatian freshwater deposits of 30 m thickness follow above an unconformity. The shaly-sandymarly rocks contain the lower Kuchl seam at their base and the upper Kuchl seam at their top.

A thick sandy succession with subordinate shales and gravels was deposited during Late Miocene (?Pannonian) time (Fig. 2). Fossils are missing. Coarse grained (?Pliocene) gravels overlie the sandy succession.

3. Samples and Analytical Methods

Ten boreholes (see Fig. 3 for position of boreholes) were selected for the study and sampled using a high resolution approach. Two additional samples were collected in an excavation pit. Most of the samples are fine-grained, but some fine- to medium-grained sandstones were also considered.

Portions of 153 shaly samples were powdered for analyses of bulk geochemical parameters. Total carbon (TC) and sulfur (S) contents were determined using a LECO 300 CS™ analyzer. The organic carbon (TOC) content was measured using the same instrument on decarbonated samples. The difference between TC and TOC is the inorganic carbon (TIC) content. Calcite equivalent percentages have been calculated using the formula TIC*8.34.

Rock Eval pyrolysis (Espitalié et al., 1977) was carried out in duplicate using a RE II+ instrument. The amount of hydrocarbons released from kerogen during gradual heating (S2 in mgHC/g rock) has been normalized to TOC to give the Hydro-

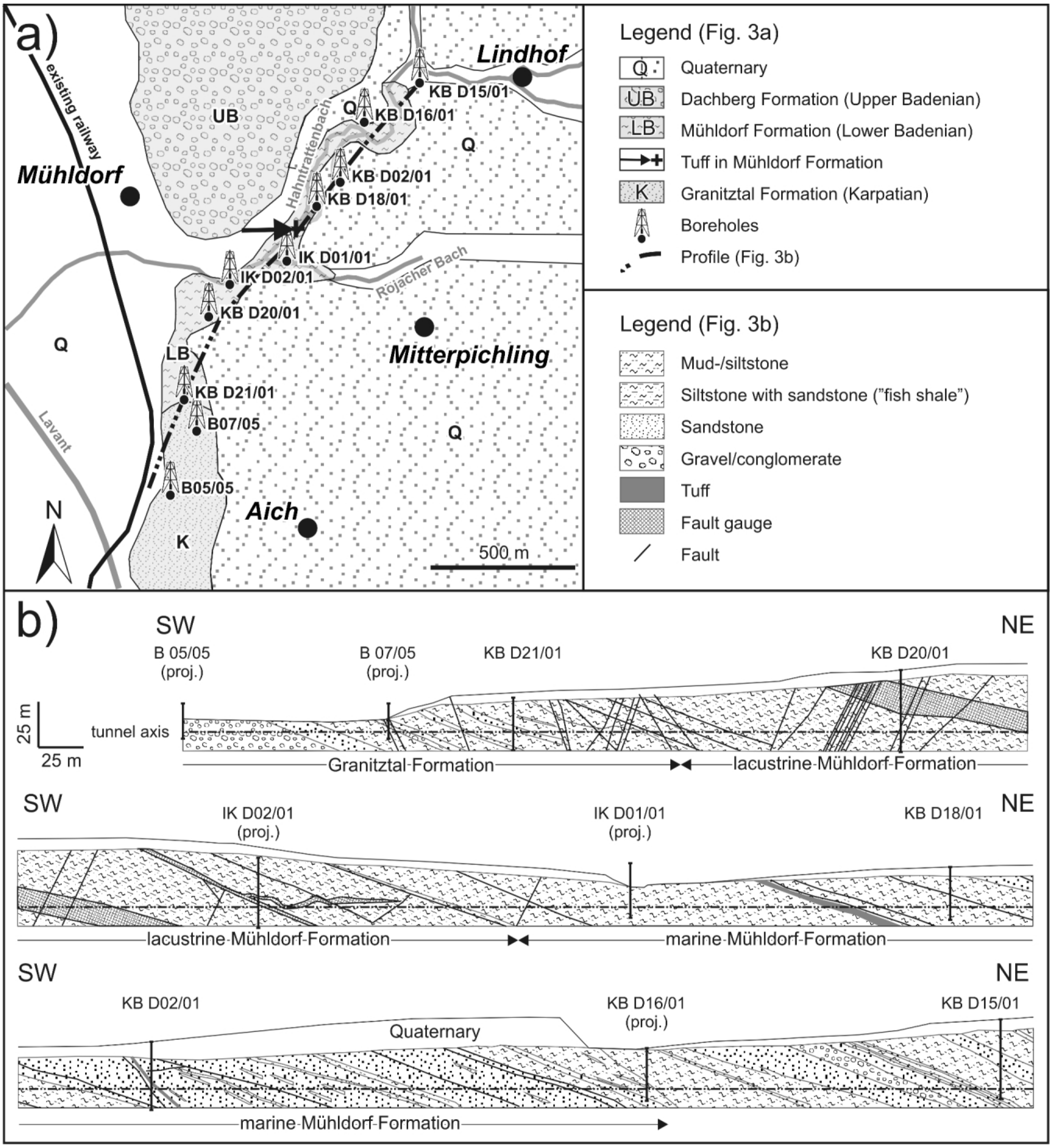


Figure 3: a) Position of studied wells in the Lavanttal Basin. b) Lithostratigraphic profile along the axis of the exploratory tunnel (provided by R. Otto; company 3G).

gen Index (HI). As a maturation indicator, the temperature of maximum hydrocarbon generation (Tmax) was determined.

For maceral anaylsis polished blocks of 19 core samples representing different facies zones within the Mühldorf Formation and their overburden were prepared. Depending on the amount of organic matter, up to 3000 points were counted in reflected white and fluorescent light using a Leitz microscope (Taylor et al., 1998). Even so, in organic-poor sediments (<1.5% TOC) the number of counted macerals has been less than 50. The microscopic results of these rocks, therefore, have to be regarded as semi-quantitative. Maceral percentages are given in vol.% normalized to 100% organic matter.

96 samples were selected for micropaleontological studies. Samples were treated in saturated Na_2SO_4 x 10 H_2O until they completely disintegrated and washed over sieves with 63 µm, 125 µm, 250 µm and 500 µm meshes. The dried fractions were weighed and checked for fossils. The ≥125 µm fractions of those samples that contain more than 300 foraminiferal specimens were mixed and split into subsamples. About 300 specimens were counted on species level. Only samples adjacent to a tuff level in borehole KB D02/01 contained fewer specimens. For paleoenvironmental studies, total (TFN), benthic (BFN), planktonic (PFN), epifauna (EPIFN) and infauna (INFN) foraminiferal numbers have been determined in number of specimens per gram sediments. Vertical trends of these numbers were interpreted as an indication of environmental changes through time. However, limiting taphonomic factors and sedimentation rate affect these indices. Whereas PFN provides information on the upper water column (esp. bioproductivity, water temperature), EPIFN and INFN provide insight into environmental conditions (e.g. organic matter flux, oxygenation, disturbance) at the sea floor. Thus, PFN, EPIFN and INFN trends give information on the bentho-pelagic linkage. However, one has to be aware that at the times of high food availability some infauna becomes epifauna. Moreover, organic carbon flux to the sea floor is not reflected accurately in dysoxic environments and on the continental margins (Naidu and Malmgren, 1995; Schmiedl and Mackensen, 1997). Diversity was measured using the Shannon H index (Buzas and Gibson, 1969) and the dominance D (den Dulk, 2000). The benthic foraminifera oxygen index (BFOI; Kaiho, 1994) was calculated to estimate the oxygen levels for bottom water. However, there is no straightforward relationship between the benthic foraminifera assemblages of paleontological samples and the oxygen level. BFOI calculated from paleontological samples measures an average value of a mixture of different paleomicroenvironments (Murray, 2001). Further information on the paleoenvironment is derived from the proportion of foraminifera with different wall structures and the first three dominant genera (TDG).

Samples used for analysis of bulk parameters were investigated with some additional (sandy) samples for calcareous nannoplankton. Standard smear slides were analysed using a light microscope (1000x magnification) at normal and crossed nicols. Abundance and preservation of nannoplankton assemblages, as well as abundances of detected taxa are described semiquantitatively.

4. Results

4.1 Lithology, bulk geochemical parameters and organic petrography

A lithostratigraphic column from the upper part of the Granitztal Formation to the cap rocks of the Mühldorf Formation is presented in Fig. 4. The sketch is based on data from boreholes and an exploratory tunnel (Fig 3b). Photographs of some typical lithotypes are presented in Figs. 4a-k. Stratigraphic columns of the Miocene section in the studied boreholes are shown in Fig. 5 together with bulk geochemical data. Note that Quaternary rocks, up to 10 m thick, cover the Miocene section in all boreholes, but are not shown in Fig. 5. Typical macerals for different stratigraphic units are displayed in Fig. 6. Tmax values (423 ± 6°C) and vitrinite reflectance (0.30-0.32%Rr) show that the sediments are thermally immature.

Lithology and geochemical data are described from bottom to top. This implies that the description starts with the southwestern borehole B05/05 (see Fig. 3).

4.1.1 Upper part of the Granitztal Formation

The upper part of the Granitztal Formation (boreholes B05/05, B07/05, KB D21/01) displays a distinct fining upward trend (Fig. 4). B05/05 comprises mainly conglomerates (Fig. 4a), gravels and sandy layers. B07/05 contains silt- and mudstones with coarser grained layers (Fig. 4b). KB D21/01 is dominated by mud- and siltstones with frequent sandy layers. The mud- and siltstones are largely carbonate-free and contain very little organic matter (<0.35%TOC). A higher TOC content in a single sample from borehole B07/05 results from detrital land plants. Sulfur contents are generally low (<0.2%), but vary between 15 and 20 m depth in KB D21/01, where they reach a maximum of 1.7%. TOC/S ratios are generally >2.8, but some samples from the depth interval between 10 and 20 m in borehole KB D21/01 are characterized by values <2.8. The hydrogen index (HI) does not exceed 35 mgHC/gTOC.

4.1.2 Lacustrine part of the Mühldorf Formation (“fish shale”)

The boundary between the Granitztal Formation and the Mühldorf Formation has not been drilled. In the exploratory tunnel the contact between the two units was faulted (R. Otto, personal comm.). Although the contact is shown as an erosional surface in Fig. 3b, a (rapid) gradual transition cannot be excluded.

The “fish shale” was studied in boreholes KB D20/01 and IK D02/01. Based on information from these boreholes and the exploratory tunnel, a thickness of about 105 m is estimated. However, because of frequent fault zones, the thickness might be overestimated. The “fish shale” comprises laminated mud-

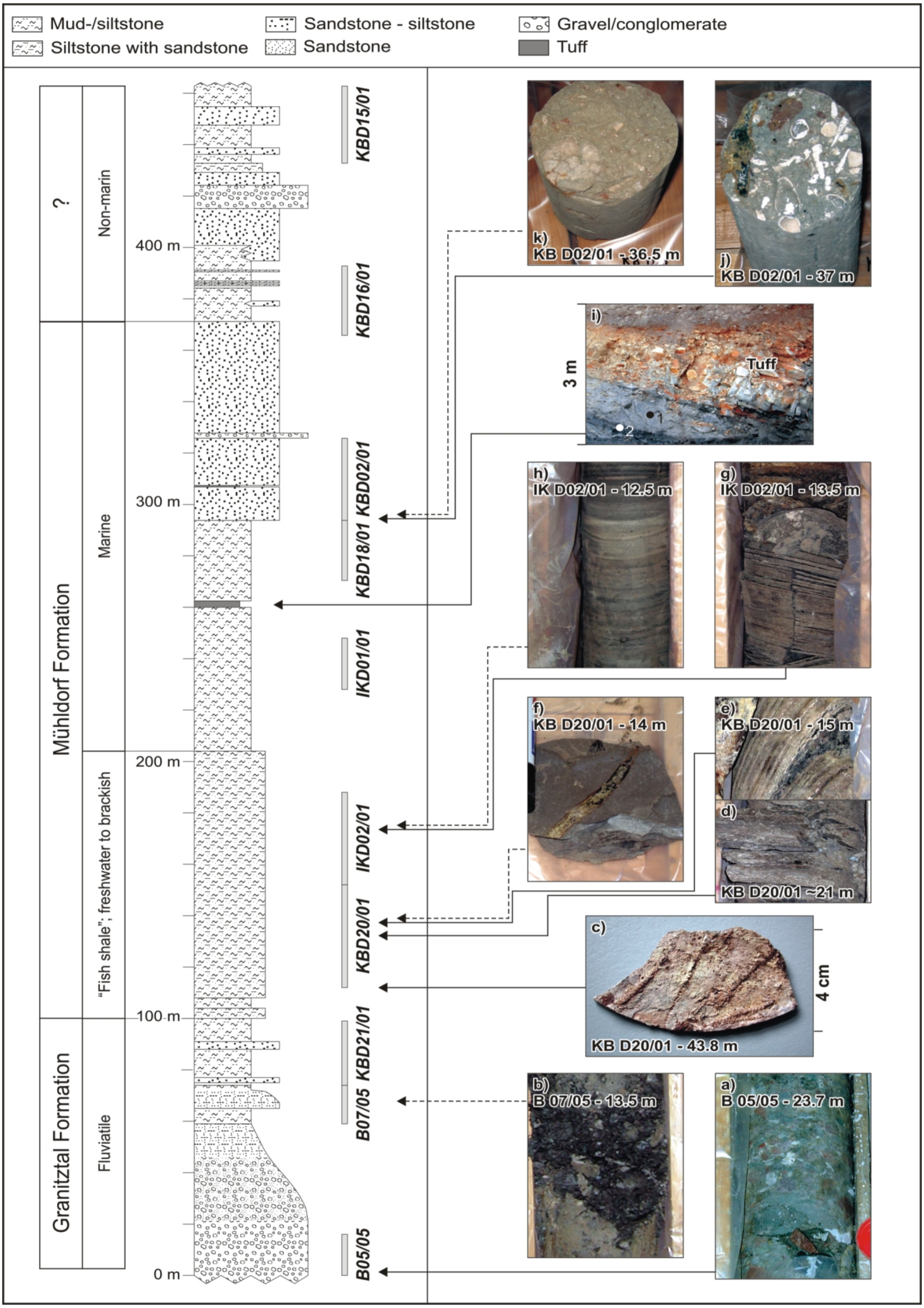


FIGURE 4: Lithostratigraphic column of the Mühldorf Formation. The position of studied boreholes is indicated. The diameter of cores shown in photographs is 10 cm.

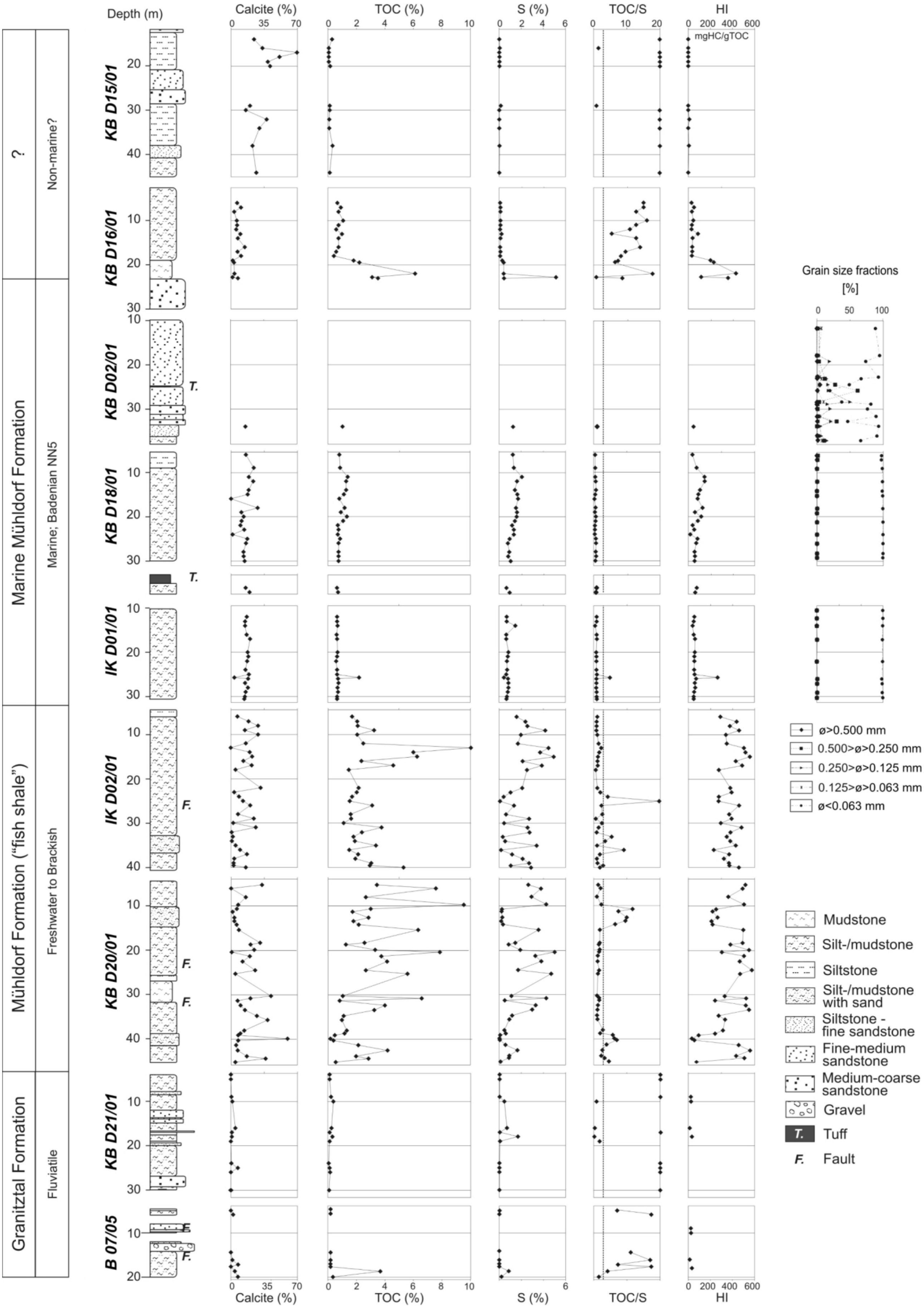


Figure 5: Lithology of studied boreholes. Bulk geochemical data are shown for all boreholes. TOC – total organic carbon, S – total sulfur, HI – hydrogen index.

stones and shaly marls with silty and fine-grained sandy layers (Fig. 4c-h). Small whitish nodules and crusts are abundant in shaly lithologies and consist at least partly of Ca-phosphate (Fig. 4d). Strongly inclined sediments were drilled in KB D20/01 at 15 m depth (Fig. 4e). Probably the tilting of rocks in this depth interval is due to faulting, but slumping cannot be excluded. Fish remains are common (e.g. Figs. 4c; 6d). In some samples coal fragments and ostracods are present. Coalified plant material is especially abundant in silty and fine-grained sandy layers (Fig. 4f). Otoliths were found in a sample from the lower part of borehole KB D20/01 (see section on otoliths).

Carbonate (0-60%) and TOC contents (0.2-10.1%) vary considerably. Average values are 14.2% carbonate and 2.9% TOC. Sulfur contents up to 5% result in low TOC/S ratios (<2.8). Organic matter contents in silty and sandy layers (KB D20/01: 41-38 m; 15-10.5 m; IK D02/01: 37-32 m) are relatively low and TOC/S ratios are high (>2.8). High TOC/S ratios also occur in a thin shaly interval in IK D02/01 (25-24 m).

HI values in the lacustrine part of the Mühldorf Formation typically vary between 250 and 600 mgHC/gTOC and range from 400 and 600 mgHC/gTOC in organic-rich intervals. This classifies the organic matter as kerogen type II.

Seven samples with TOC/S ratios <2.8, TOC contents ranging from 2 to 10%, and HI values >400 mgHC/gTOC have been studied microscopically. Their maceral composition is dominated by liptinite (75-90%). Lamalginite, often enriched in disctinct layers, is the most important liptinite maceral (60-85%; Fig. 6a). Telalginite is rare (<3%), whereas the percentage of landplant-derived liptinite (mainly sporinite) varies significantly and can reach 20%. Vitrinite (10-25%) and inertinite (≤1%) macerals are rare. Lamalginite percentages are positively correlated with TOC contents (correlation coefficient r^2=0.58).

Maceral percentages from a shaly and a silty sample with TOC/S ratios >2.8 have been studied. These samples contain 1.7 and 1.8% TOC, respectively. Their organic matter is composed of similar percentages of liptinite and vitrinite macerals (Fig. 6b). Lamalginite is not as dominant as in samples with TOC/S ratios <2.8 (~20%). This maceral composition is reflected by relatively low HI values. This applies for both, the shaly interval in IK D02/01 (~275 mgHC/gTOC) and silty and sandy layers in boreholes KB D20/01 and IK D02/01 (~250 mgHC/gTOC). HI in silty layers near the base of the "fish shale" is even <50 mgHC/gTOC.

4.1.3 Marine part of the Mühldorf Formation

The marine upper part of the Mühldorf Formation is about 165 m thick and is represented by boreholes IK D01/01, KB D18/01, KB D02/01, and the sandstone package at the base of KB D16/01. The lower boundary was not drilled, but exposures in the exploratory tunnel suggest a conformable contact between the lacustrine and the marine parts of the Mühldorf Formation (R. Otto, personal comm.; Fig. 3b). The marine rocks comprise grey mudstones and shaly marls, as well as silty and sandy layers. Number and grain-size of sandstone beds increase upwards defining a distinct coarsening upward trend. Carbonate contents in fine-grained rocks are about 15 to 20%. A tuff layer, 20 cm thick, was drilled within the sandy part in borehole KB D02/01, but tuffitic material can be observed up to 4.8 m above this layer. Another tuff layer, about 2.5 m thick, has been exposed in an excavation pit and overlies silty mudstones (Fig. 4i). Its stratigraphic position between boreholes IK D01/01 and KB D18/01 is shown in Figs. 3b and 4. Frequently present are macrofossils including sea urchins and molluscs (Figs. 4j-k). Fish remains, otoliths and ostracods occur in all three boreholes. Some bryozoan remains are present in IK D01/01.

TOC contents are often between 0.6 and 0.8% and HI values typically range from 40 to 70 mgHC/gTOC. Terrestrial macerals (vitrinite: ~60%; inertinite: ~15%) predominate in these organic-poor rocks. Liptinite is generally rare (~25%), but some dinoflagellate cysts (counted as telalginite) are present (Fig. 6e).

Higher TOC contents up to 1.4% occur in KB D18/01 between 21 and 11 m depth. In this depth interval HI ranges up to 150 mgHC/gTOC. Three samples from this depth interval (1.10-1.37% TOC) have been studied petrographically and yield similar maceral percentages than organic-poor rocks (vitrinite: 50%, inertinite: 25%; liptinite: 25%). Foraminifera tests are important constituents of this sample (Fig. 6g).

A single sample in borehole IK D01/01 (25.7 m) holds a significantly higher TOC content of 2.2% and is characterized by a HI value of 265 mgHC/gTOC. Maceral analysis reveals a high percentage of terrestrial macerals (65% vitrinite, 20% sporinite and cutinite). At least part of the vitrinite is phyllovitrinite indicating the presence of leaves (Fig. 6f). Apart from the allochthonous, terrestrial macerals, telalginite (~5%) and liptodetrinite (~10%) contribute to the organic matter of this sample.

Sulfur contents range from 0.4 to 2.0%. A maximum is observed in borehole KB D18/01 at 11 m depth. Above the maximum, sulfur contents decrease upwards. TOC/S ratios are very low (<1) in IK D01/01, and even lower in borehole KB D18/01. The organic-rich sample in borehole IK D01/01 (25.7 m) is a remarkable exception with a TOC/S ratio >2.8.

4.1.4 Rocks overlying the Mühldorf Formation

The sandstone package at the base of borehole KB D16/01 forms the top of the Mühldorf Formation. The overburden succession, which has no lithostratigraphic designation yet, starts with mudstone and siltstone. The colour of these fine-grained rocks changes in an upward direction from dark brown to grey and light blue. Coal fragments, some ostracods and few remains of fishes and molluscs occur in KB D16/01. Borehole KB D15/01 comprises blue coloured marls and pelitic marls, as well as siltstone and sandstone. Carbonate contents in pelitic rocks from this borehole are significanlty higher (16-70%) than in borehole KB D16/01 (1-14%).

TOC contents (1.5-6.0%) and HI values (120-430 mgHC/gTOC) are high in the lower part of borehole KB D16/01 (23-19 m depth). A single sample contains a very high sulfur content. Maceral composition (82% liptinite incl. 67% lamalginite; 18% vitrinite) of a sapropelic shale at 22 m depth (6%TOC; 430 mgHC/gTOC) is similar to that of the “fish shale” (Fig. 6h). Significantly lower pyrite content is the main petrographic difference.

Above 19 m depth, TOC (<1.2%), HI (<100 mgHC/gTOC) and sulfur values are low and decrease to even lower values in KB D15/01. HI values reflect a change from kerogen type II to kerogen type III-IV. This is supported by the maceral composition of a sample from KB D15/01 (16 m depth), which is dominated by 75% vitrinite. TOC/S ratios are generally >2.8 indicating a non-marine environment.

4.2 Fossil content

4.2.1 Foraminifera

Foraminifera were detected exclusively in the marine part of the Mühldorf Formation (IK D01/01, KB D18/01, KB D02/01). An alphabetical list of all detected foraminifera is given in Table 1. The first three dominant genera are listed for each sample in Table 2. Vertical trends of indices used for paleoenvironmental interpretations as well as the distribution of paleoenvironmentally most indicative taxa (*Oridorsalis umbonatus*, *Melonis pompilioides*, *Spirorutilus carinatus*, *Uvigerina* spp., *Bolivina* spp., *Bulimina* spp., *Fursenkoina acuta*, *Nonion communis*, *Ammonia viennensis*, keeled *Elphidium* spp., *Asterigerinata planorbis*) are presented in Fig. 7. The ecospace preference of these taxa is summarized in the Appendix.

The total foraminiferal number (TFN) is moderate in IK D01/01 and the lower half of KB D18/01 (c. 50 specimens per g) and reaches a maximum in the upper part of KB D18/01 (c. 300 specimens per g). In contrast, foraminifera are rare in the sandy rocks of borehole KB D02/01. In general, benthic foraminifera are more frequent than planktonic foraminifera, but relatively high percentages of planktonic formanifera occur in the upper portions of boreholes IK D01/01 and KB D18/01, and the middle and upper part of borehole KB D02/01. The maximum in numbers of planktonic formanifera (PFN) occurs in borehole KB D18/01 at a depth of 12.0-11.9 m. Above this horizon, the abundance of plankton decreases dramatically.

The abundance of infauna and epifauna is strongly varying, but similar in the lower part of the marine Mühldorf Formation (IK D01/01). Between the upper part of IK D01/01 and the top of the marine Mühldorf Formation benthic foraminifera associations are dominated by infauna. In IK D01/01 the abundance of infauna and epifauna covariate negatively except in the uppermost sample where the absolute frequency starts to covariate positively. This trend of positive covariation continues in borehole KB D18/01, where the abundance of infauna (INFN) reaches a maximum at 9.1-9.0 m depth (i.e. 1.9 m above the PFN maximum). The change from negative to positive covariation between infauna and epifauna coincides with the first appearance of keeled *Elphidium* spp. (Fig. 7). Whereas the abundance of epifauna shows a relatively smooth vertical trend, the abundance of infauna varies considerably. Because of the dominance of infauna in borehole KB D18/01, the benthos-plankton relationship is essentially an infauna-plankton relationship in this borehole.

The Shannon diversity index H ranges from 1 to 3.2 and exhibits an upward decreasing trend. In contrast, the dominance D increases in the same direction.

The Benthic Foraminifera Oxygen Index (BFOI) varies between -40 (dysoxic/suboxic boundary) and 0 (suboxic/low oxic boundary). Most values are slightly below 0. In borehole KB D18/01 BFOI increases upwards from -30 to -5. This upward increasing trend is disturbed only by a sample at 26.0-25.9 m depth, which shows the most negative value (-40).

Variations in abundance of a few ecologically important taxa are described in the following (see also Fig. 7). *Oridorsalis umbonatus* is present in IK D01/01 in considerable amounts and in the middle of KB D18/01 in negligible amounts. In IK D01/01, its abundance correlates positively with that of epifauna. *Melonis pompilioides* is present in borehole IK D01/01 in small amounts and in the upper part of borehole KB D18/01, where PFN is the highest, in negligible quantity. *Ammonia viennensis* appears at the bottom of borehole KB D18/01 and is very rare until the upper part of the borehole. Its abundance increases significantly in the depth interval with a high PFN and remains important throughout borehole KB D02/01. *Elphidium* spp. appears first in negligible amounts in the uppermost sample of borehole IK D01/01. It is absent in KB D18/01 and reappears in the lowermost sample of borehole KB D02/01, where its quantity increases upwards. *Asterigerinata planorbis* has its first appearance in the lowermost sample of borehole KB D02/01, where it is present in most samples.

4.2.2 Nannoplankton

Abundances of calcareous nannoplankton are listed in Tables 3 and 4. Selected representatives are displayed in Fig. 8. As expected, samples from the Granitztal Formation (KB D21/01) are barren with respect to calcareous nannoplankton.

Samples from the lacustrine part of the Mühldorf Formation (“fish shale”; KB D20/01, IK D02/01) contain scarce, moderately to well preserved assemblages with *Isolithus semenenko* and few forms, which belong to Genus *Isolithus*.

In contrast, the marine part of the Mühldorf Formation is very rich in well preserved calcareous nannoplankton. Assembla-ges in boreholes IK D01/01, KB D18/01 and the lower part of KB D02/01 (38-29 m) contain high percentages of *Reticulofenestra minuta* and *Helicosphaera carteri*. These two forms dominate the nannoplankton associations with more than 80%. Regularly occur: *Braarudosphaera bigelowii*, *Coccolithus miopelagicus*, *C. pelagicus*, *Cyclicargolithus floridanus*, *Pontosphaera multipora*, *Sphenolithus heteromorphus*, *Umbilicosphaera jafarii*, Reticulofenestrids (*Reticulofenestra gelida*, *R. haqii*, *R. pseudoumbilica*), Helicoliths (*Helicosphaera walbersdor-*

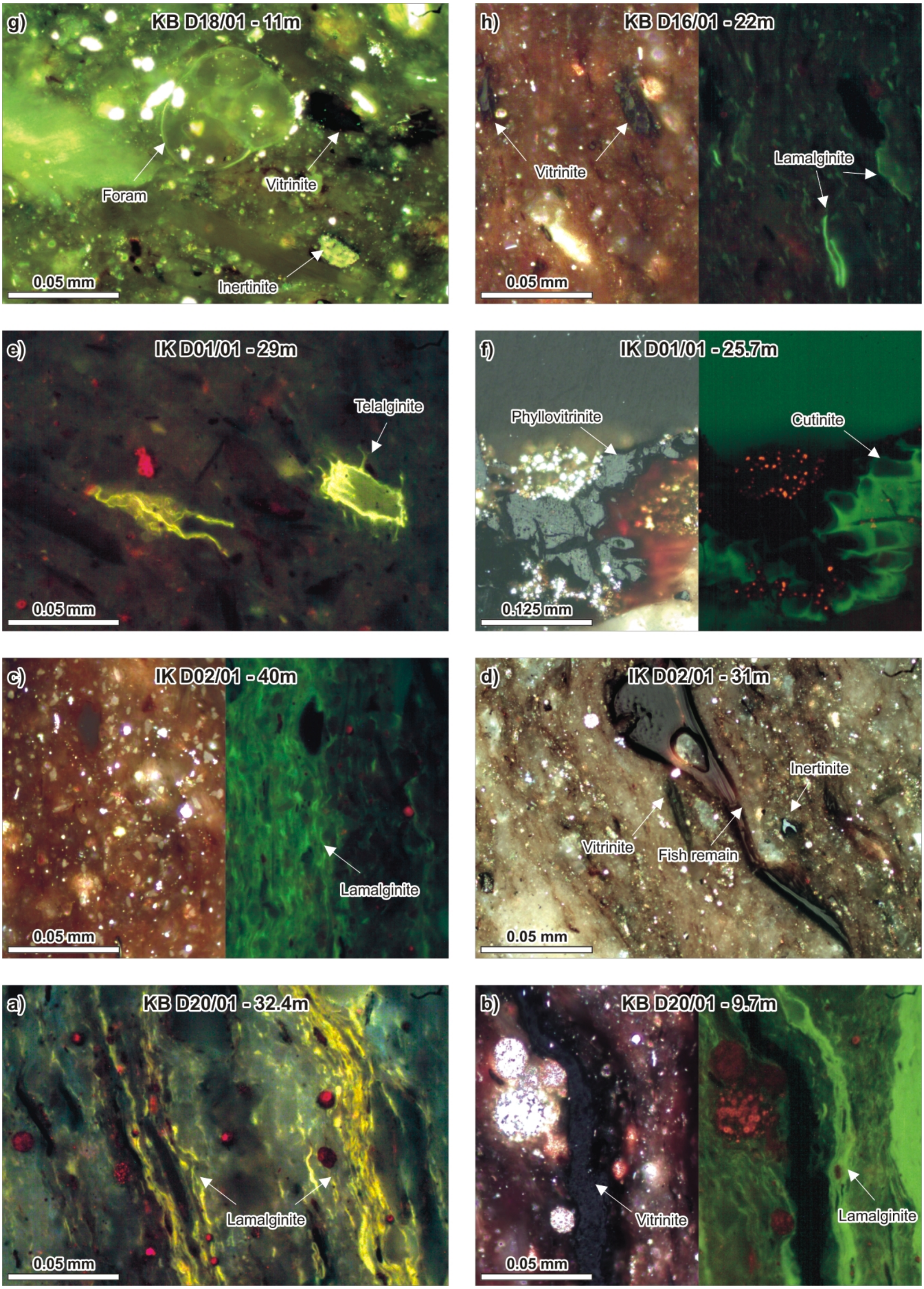


Figure 6: Photomicrographs of characteristic macerals from the lacustrine (a-d) and the marine part of the Mühldorf Formation (e-g), and sapropelic shale overlying Mühldorf Formation (h). b, c, f, and g are taken using normal white light, all other figures are in normal white light and in fluorescence mode.

fensis, *H. wallichi*, *H. waltrans*, *H. wederii*). Rare are: *Coronocyclus nitescens*, *Discoaster variabilis*, *Holodiscolithus macroporus*, *Rhabdosphaera sicca*, *Sphenolithus moriformis*, *Syracosphaera pulchra*, *Thoracosphaera saxea*, *Th. heimii*. In some samples (e.g. uppermost sample in KB D18/01 at 6 m depth) a higher percentage of discoasterids was observed. The upper part of KB D02/01 (28-10 m) is barren or contains only very rare calcareous nannoplankton. The lowermost sample from borehole KB D16/01 (30 m) contains *Sphenolithus heteromorphus* in very low amounts. The presence of this marker suggests that the lowermost sandstone layer from KB D16/01 forms part of the marine Mühldorf Formation. Slight reworking from Upper Paleocene/Lower Eocene (*Discoaster multiradiatus*, *D. lodoensis*, *Sphenolithus radians* etc.) and Cretaceous (*Biscutum ellipticum*, *Cribrosphaerella ehrenbergii*, *Watznaueria barnesae* etc.) horizons were observed.

With the exception of the sample at 30 m depth in borehole KB D16/01, all samples from boreholes KB D16/01 and KB D15/01 are barren, suggesting that they represent rocks overlying the Mühldorf Formation.

4.2.3 OSTRACODA

Ostracods occur in the Mühldorf Formation and in rocks overlying them. Table 5 provides a list with studied samples and detected taxa.

The ostracod fauna in the lacustrine part of the Mühldorf Formation (KB D20/01, IK D02/01) is impoverished and badly preserved. Only *Fabaeformiscandona pokornyi* could be identified with adult (female) and juvenile valves at species level. Determination of two other taxa (cf. *Cypria* sp., *Herpetocypris*? sp.) is left in open nomenclature because of scarce and fragmentary valves (Fig. 9).

The ostracode faunas from the lower part of the marine Mühldorf Formation (IK D01/01) are strongly dominated by Cytherellids (*Cytherella* aff. *compressa*, *Cytherella* aff. *vandenboldi*, *Cytherelloidea* sp.).

	IK D01/01	*KB D18/01*	*KB D02/01*
Benthic foraminifera			
Adelosina longirostra (d`Orbigny)		X	
Adelosina schreibersi (d`Orbigny)	x	x	x
Alveophragmium obliquicameratum (Marks)	X		
Ammodiscus sp.	X		
Ammonia viennensis (d`Orbigny)		x	x
Amphicoryna badenensis (d`Orbigny)	x		
Amphistegina mammilla (Fichtel & Moll)	x		x
Angulogerina angulosa (Williamson)	x	x	x
Astacolus crepidulus (Fichtel & Moll)	X	X	
Asterigerinata planorbis (d`Orbigny)			x
Astrononion stelligerum (d`Orbigny)	x	x	x
Bathysiphon filiformis Sars M.	x		
Bolivina antiqua d`Orbigny		x	
Bolivina digitalis (d`Orbigny)	x	x	x
Bolivina dilatata Reuss	x	x	x
Bolivina hebes Macfadyen	x	x	
Bolivina plicatella Cushman	x	x	
Bolivina pokorny Cicha & Zapletalova	X	x	
Bolivina sp.			x
Bucnerina sp.	x		
Budashevaella wilsoni (Smith)	X	x	
Bulimina elongata d`Orbigny		x	
Bulimina striata d`Orbigny	x	x	
Bulimina subulata Cushman & Parker	x	x	x
Cancris auriculus (Fichtel & Moll)	x		x
Cassidulina laevigata d`Orbigny	x		
Ceratocancris haueri (d`Orbigny)	x	x	x
Chilostomella ovoidea Reuss		X	
Cibicides sp.			x
Cibicidoides pachyderma (Rzehak)	x	x	x
Cibicidoides ungerianus (d`Orbigny)	x	x	
Cornuspira angigyra (Reuss)	X		
Cribrostomoides columbiensis moravica Cicha & Zaplet.	X		
Cribrostomoides subglobosus (Cushman)	x	x	
Cycloforina badenensis (d`Orbigny)	x		x
Cycloforina boueana (d`Orbigny)	X	X	
Cycloforina contorta (d`Orbigny)	x		
Dentalina acuta d`Orbigny	X	x	
Dimorphina akneriana (Neugeboren)	X	X	
Elphidiella minuta (Reuss)	x		x
Elphidium spp.			x
Elphidium cf. *fichtelianum* (d`Orbigny)	x		
Elphidium crispum (Linné)			X
Elphidium reussi Marks			X
Elphidium sp.			X
Eponides sp.		x	
Fursenkoina acuta (d`Orbigny)	x	x	x
Glandulina ovula d`Orbigny		x	
Globocassidulina globosa (Hantken)	x		x
Globocassidulina oblonga (Reuss)	x	x	X
Globulina gibba d`Orbigny	x	x	x
Globulina punctata d`Orbigny	x		
Globulina spinosa d`Orbigny	x	x	
Grigelis pyrula (d`Orbigny)	X	X	
Guttulina communis (d`Orbigny)	x	x	x
Gyroidinoides umbonatus (Silvestri)	x	x	
Hansenisca soldanii (d`Orbigny)	x	x	
Hanzawaia boueana (d`Orbigny)	x	x	x
Haplophragmoides spp.	x	x	
Haplophragmoides carinatus Cushman & Renz	X	X	
Haplophragmoides vasiceki Cicha & Zapletalova	x		
Heterolepa spp.	x	x	
Heterolepa dutemplei (d`Orbigny)	X	X	X
Heterolepa praecincta Franzenau	X	X	X
Hoeglundina elegans (d`Orbigny)		X	
Laevidentalina elegans (d`Orbigny)	X	X	X
Lagena haidingeri (Czjzek)	x		
Lapugyina schmidi Popescu	X	x	x
Lenticulina spp.	x	x	x
Lenticulina austriaca (d`Orbigny)	X		
Lenticulina calcar (Linné)	X	X	X
Lenticulina echinata (Soldani)	x		
Lenticulina inornata (d`Orbigny)	X	X	X
Lenticulina orbicularis (d`Orbigny)	X		
Lenticulina reniformis (d`Orbigny)	X		
Lenticulina similis (d`Orbigny)	X	X	
Benthic foraminifera			
Lenticulina vortex (Fichtel & Moll)	X	X	
Marginulina hirsuta d`Orbigny	x	x	
Martinottiella communis (d`Orbigny)	x		
Martinottiella karreri (Cushman)	x	x	
Melonis pompilioides (Fichtel & Moll)	x	x	x
Neoeponides schreibersi (d`Orbigny)	x	x	x
Nodosaria guttifera (d`Orbigny)	X		
Nodosaria ? hispida (Soldani)	X		
Nonion commune (d`Orbigny)	x	x	x
Nonionella turgida (Williamson)		x	
Nummoloculina contraria (d`Orbigny)	x	x	
Oridorsalis umbonatus (Reuss)	x	x	
Pappina parkeri (Karrer)	X	x	x
Pappina primiformis (Papp & Turnovsky)	x	x	
Planularia dentata (Karrer)	x		
Planostegina costata (d`Orbigny)		X	x
Polymorphina complanata d`Orbigny	X		
Porosononion granosum (d`Orbigny)		x	x
Praeglobobulimina pupoides (d`Orbigny)	x	x	x
Pseudogaudryina mayeriana (d`Orbigny)	x	x	
Pseudonodosaria brevis (d`Orbigny)		X	
Pseudotriloculina consobrina (d`Orbigny)	x		x
Pullenia bulloides (d`Orbigny)	x	x	x
Pullenia quinqueloba (Reuss)		X	
Pyramidulina raphanistrum (Linné)	X		x
Pyrgo lunula (d`Orbigny)		X	
Pyrgo simplex (d`Orbigny)	x	x	
Quinqueloculina spp.			x
Quinqueloculina akneriana d`Orbigny	x		
Quinqueloculina buchiana d`Orbigny	x	x	X
Quinnqueloculina haidingeri d`Orbigny	x	X	X
Reticulophragmium cf. *karpaticum* Cicha & Zapletalova	X		
Reussella spinulosa (Reuss)	x	x	x
Riminopsis boueanus (d`Orbigny)	x	x	x
Rosalina obtusa d`Orbigny			x
Semivulvulina deperdita (d`Orbigny)	X	X	
Semivulvulina pectinata (Reuss)	x	x	
Sigmoilinita tenuis (Czjzek)	x	x	x
Sigmoilopsis spp.	x	x	x
Sigmoilopsis coelata (Costa)	X	X	X
Sigmoilopsis foeda (Reuss)	X	X	X
Siphonina reticulata (Czjzek)	x	x	x
Spiroloculina canaliculata d`Orbigny	x	x	
Spiroloculina excavata d`Orbigny	x		
Spirorutilus carinatus (d`Orbigny)	x	x	x
Stilostomella adolphina (d`Orbigny)	x		
Textularia spp.			x
Textularia gramen d`Orbigny	x	x	X
Textularia laevigata d`Orbigny	x	x	X
Textularia mariae d`Orbigny	x	x	
Triloculina gibba d`Orbigny			x
Trifarina bradyi Cushman	x		
Uvigerina spp.			x
Uvigerina acuminata Hosius	x		
Uvigerina cf. *bulbacea* Galloway & Heminway	x	x	X
Uvigerina pygmoides Papp & Turnovsky	x	x	X
Valvulineria complanata (d`Orbigny)	x	x	x
Varidentella rotunda (Gherke)	x		x
Virgulinella pertusa (Reuss)		x	
Virgulopsis tuberculatus (Egger)		x	x
Planktonic foraminifera			
Globigerina bulloides d`Orbigny	X		
Globigerina praebulloides Blow	X		
Globigerina subcretacea Lomnicki	X		
Globigerina tarchanensis Subbotina & Chutzieva	X		
Globigerinella regularis (d`Orbigny)	X		
Globigerinoides bisphericus Todd	X	X	X
Globigerinoides quadrilobatus (d`Orbigny)	X		
Globigerinoides cf. *sacculifer* (Brady)			X
Globigerinoides trilobus (Reuss)	X	X	
Praeorbulina circularis (Blow)	X	X	
Praeorbulina curva (Blow)		X	
Praeorbulina cf. *sicana* (De Stefani)		X	
Taxa present in splitted samples	x		
Taxa present in the whole sample	X		

TABLE 1: List of recorded foraminifera.

Other common species are *Acanthocythereis hystrix*, *Buntonia brunensis*, *Buntonia subulata*, *Bosquetina carinella*, *Henryhowella asperrima* and *Parakrithe dactylomorpha*. Less frequent taxa are *Argilloecia* sp., *Carinovalva* sp., *Krithe* sp., *Occultocythereis bituberculata*, *Paracypris polita*, *Paracytheridea triquetra*, *Pterygocythereis calcarata*. In contrast to IK D01/01, Cytherellids do not dominate the associations in borehole KB D18/01. In this borehole ostracod faunas from samples 29.2-29.1 to 14.1-14.0 are impoverished (common: *Acanthocythereis hystrix*, *Buntonia subulata*, *Paracypris polita*, subordinate: *Cytherelloidea* sp., *Cytheridea acuminata*, *Xestoleberis* ex gr. *communis*, *Cytherella* aff. *compressa*, *Pterygocythereis calcarata*, *Bosquetina carinella*, *Carinovalva* sp., *Henryhowella asperrima*, *Parakrithe dactylomorpha*). The depth interval between 12 and 6 m yielded rather rich faunas with frequent *C. acuminata* (esp. in 9.1-9.0, 7.1-7.0), X. ex gr. *communis*, *A. hystrix*, *B. subulata*, *P. polita*, *P. calcarata*, *B. carinella* and *P. dactylomorpha*.

In borehole KB D16/01 the sample 22.2-22.0 contains fragmented valves of juvenile *Candona* s.l. and a few specimens

Borehole	Sample	*Oridorsalis umbonatus*	*Sigmoilinita tenuis*	*Cassidulina laevigata*	*Angulogerina angulosa*	*Spirorutilus carinatus*	*Bulimina striata*	*Bulimina elongata*	*Bulimina subulata*	*Bolivina spp.*	*Reussella spinulosa*	*Heterolepa spp.*	*Neoeponides schreibersi*	*Hanzawaia boueana*	*Fursenkoina acuta*	*Nonion commune*	*Ammonia viennensis*	*Elphidium spp.*	*Asterigerinata planorbis*
KB D02/01	11.8-11.9																40-50	20-30	10-20
	17.9-18.0															10-20	30-40	10-20	
	19.2-19.8															10-20	30-40	10-20	
	22.7-22.8													10-20		20-30	30-40		
	23.1-23.2															20-30	20-30	10-20	
	24.5-24.6												20-30				10-20	10-20	
	25.8-25.9																		
	28.4-28.5																40-50	10-20	10-20
	28.9-29.0														5-10	30-40	10-20		
	29.9-30.0					10-20										30-40	10-20		
	31.7-31.8					10-20									10-20	30-40			
	32.8-32.9																70-80	5-10	5-10
	33.9-34.0									5-10						30-40	5-10		
	36.0-36.1											10-20				10-20	20-30		
	37.1-37.2											50-60				10-20	10-20		
KB D18/01	6.0-6.1					20-30					10-20					10-20			
	7.0-7.1					20-30										20-30			
	9.0-9.1					10-20										30-40	10-20		
	11.9-12.0					10-20			30-40							20-30			
	14.0-14.1								10-20	50-60						5-10			
	15.1-15.2					10-20			30-40							10-20			
	18.0-18.1					20-30		10-20								10-20			
	19.0-19.1				5-10	10-20				30-40									
	21.0-21.2					5-10				40-50						10-20			
	23.8-24.0								10-20	20-30									
	25.9-26.0								10-20	30-40						10-20			
	28.1-28.2				10-20				10-20	30-40									
	29.1-29.2								10-20	30-40						10-20			
IK D01/01	10.4-10.5			10-20		10-20			10-20										
	12.25-12.35					10-20	20-30		10-20										
	13.9-14.0					10-20	10-20		5-10										
	17.0-17.1	10-20				10-20			5-10										
	21.9-22.0					20-30			10-20			10-20							
	25.9-26.0		10-20			30-40			10-20										
	27.0-27.1		10-20			10-20						10-20							
	29.0-29.1			10-20					10-20					5-10					
	30.1-30.2			10-20					10-20			5-10							

Table 2: List of three dominant foraminiferal genera/species in the samples. Their ecology and paleocology (see Appendix) provide important information for paleoenvironmental considerations.

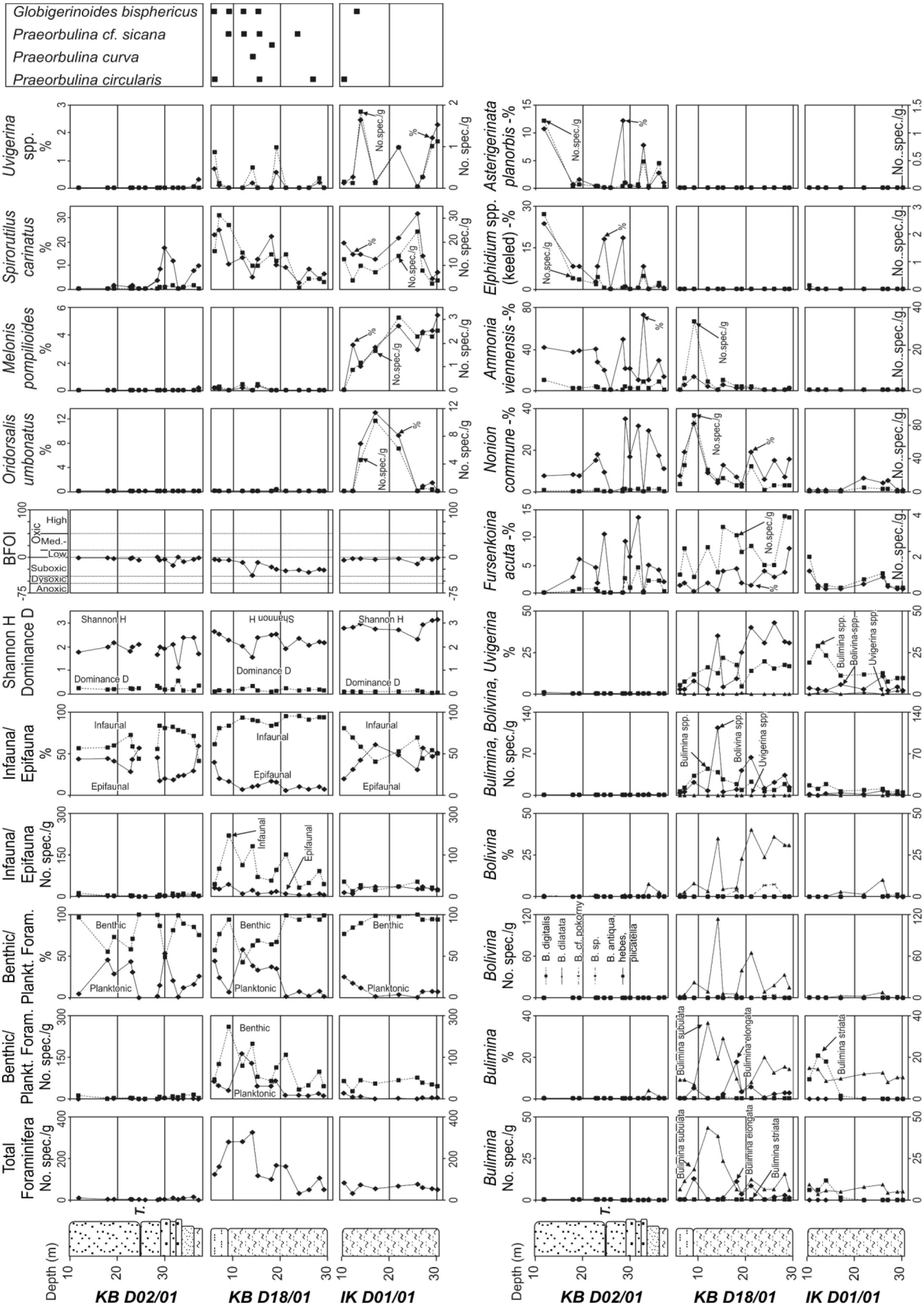


Figure 7: Vertical variation of foraminifera-based indices used for paleoenvironmental interpretations and of the abundance of paleoenvironmentally most indicative taxa. BFOI-Benthic Foraminifera Oxygen Index.

of broken *Pseudocandona* sp. shells.

4.2.4 Otoliths

(Few) otoliths occur in most samples from the upper part of the Mühldorf Formation, but only in a single sample from its lower part. Eight sagittae of adult or subadult specimens from this sample (KB D20/01: 38.8-38.7 m) were identified (Fig. 10).

Order Perciformes
Family Gobiidae Bonaparte 1832
Genus Gobius Linnaeus 1758
Gobius (n.) sp.

Five juvenile sagittae from the same sample probably also belong to *Gobius* (n.) sp. The investigated otoliths (length 1.12-1.80 mm, height 0.97-1.50 mm) differ from *Gobius multipinnatus* (H. von Mayer 1852) and "*Gobius praetiosus*" (Prochazka 1893) due to their more rectangular and symmetrical shape, the higher anterior rim and the presence of a well developed anterodorsal edge. They resemble *Gobius* aff. *multipinnatus*, which is known from the Ottnangian and Early Karpatian of the Western Paratethys (Reichenbacher et al., 2004), but differ from it because of their relatively longer form (length/height index of 1.2 versus 1.0-1.1 in *G.* aff. *multipinnatus*) and the asymmetrically curving outer face.

Weinfurter (1952) described from the locality Weinzettel near Ober-Aigen, which is also situated in the Lavanttal, the new species *Gobius noricus* and *Gobius carinthiacus*. However, *Gobius carinthiacus*, which has a length of not more than 0.65 mm, probably is the juvenile morphotype of *Gobius noricus*. According to Weinfurter (1952), the otoliths-bearing sediments from Weinzettel can be dated as Sarmatian. *G. noricus* and „*G. carinthiacus*" differ from the herein described *Gobius* (n.) sp. because of their higher general shape (length/height index about 1.0 or less) and the absence of a posterodorsal projection.

5. Discussion

5.1 Biostratigraphy and dating

5.1.1 Lacustrine part of the Mühldorf Formation ("fish shale")

Although it is difficult to date lacustrine sediments, otoliths and ostracods provide some age information on the lower part of the Mühldorf Formation.

An endemic *Gobius* speciation happened during the Karpatian in the Western Paratethys, when the marine-brackish conditions changed to freshwater. Similarities between the otoliths of *Gobius multipinnatus*, *Gobius* aff. *multipinnatus* and *Gobius latiformis* (Reichenbacher, 1993) indicate that the latter two species have evolved gradually from *Gobius multipinnatus* (see Reichenbacher, 1993). The intermediate position of *Gobius* (n.) sp. with regard to *G. multipinnatus* and *G.* aff. *multipinnatus* from the Western Paratethys may point to a Late Ottnangian or Early Karpatian age of the sediments. However, one should take into consideration that the speciation of *G. multipinnatus* into new forms may have happened independently in the Styrian Basin and the Lavanttal area. Consequently, the age of *Gobius* (n.) sp. cannot be stated with certainty.

Ostracod species left in open nomenclature (cf. *Cypria* sp. and *Herpetocypris*? sp.) cannot be used for biostratigraphical dating. *Fabaeformiscandona pokornyi*, which occurs in the

borehole	sample (m)	abundance	preservation	*Isolithus semenenko*	*Isolithus* spp.
KB D20/01	5.3	barren			
	6.1	F	G	x	x
	8	F	G	x	
	9.7	barren			
	10.7	R	M	x	x
	11.9	barren			
	12.6	F	G	x	x
	13.4	F	G	x	
	14.2	F	G	x	
	15.4	R	M	x	x
	18.3	C	G	c	r
	18.7	F	G	x	x
	19.9	F	G	x	
	20.4	barren			
	21.3	C	G	a	r
	22.5	F	G	c	f
	24.5	F	G	c	f
	25.3	R	G	x	
	25.7	F	G	x	
	30.3	F	G	x	
	30.8	F	G	x	
	31.3	F	G	x	
	32.4	R	G	x	
	33.4	R	G	x	
	34.7	R	G	x	
	35.6	F	G	x	x
	38	R	G	x	x
	38.7	F	G	x	x
	39.1	R	G	x	
	39.9	barren			
	40.2	barren			
	41.3	barren			
	42.5	barren			
	43.8	barren			
	44.3	R	G	x	
	45.1	barren			

borehole	sample (m)	abundance	preservation	*Isolithus semenenko*	*Isolithus* spp.
IK D02/01	6	barren			
	7	barren			
	8	F	M	x	
	9	R	M	x	
	10	R	M	x	
	11				
	12	R	M	x	
	13	R	M	x	
	14	C	G	x	
	15	C	G	x	
	16	F	G	x	x
	17	F	G	x	
	18	R	G	x	
	19				
	22	R	G	x	
	23	R	G	x	
	24	barren			
	26	barren			
	28	R	M	x	
	29	barren			
	30	barren			
	31	F	G	x	
	32	barren			
	33	barren			
	34	barren			
	35	R	M	x	
	36	barren			
	37	C	G	x	
	38	R	G	x	
	39	R	G	x	
	39.5	barren			
	40	R	G	x	
	40.7	R	G	x	

Table 3: Abundance of calcareous nannofossils in the lacustrine Mühldorf Formation (A= abundant, dominant species with more than 50% of an assemblage; C=common, 10-50%; F=few, <10% of an assemblage; R=rare, only a few specimens were found; B=barren. The preservation of the calcareous nannoplankton assemblage is characterized by the following terms: G=good, no evidence of etching or overgrowth; M=moderate; P=poor, significant etching or overgrowth.

lower part of the Mühldorf Formation, is known from Lower Miocene to Pleistocene deposits of Switzerland, S-Germany, the Czech Republic and Turkey; maybe from S-France (Witt, 1998, cum lit.). Because *F. pokornyi* is noticed especially from the Karpatian and Badenian in the Central Paratethys (see Witt, 1998, 2000), it gives hints to these stages.

An attribution to the (Karpatian or) Lower Badenian is therefore most likely and is also supported by the superposition of evidently Lower Badenian sediments (see next section).

Calcareous nannoplankton assemblages contain *Isolithus semenenko* and *Isolithus* spp. *Isolithus semenenko* was originally described from Upper Miocene sediments of the Eastern Paratethys. It also occurs in Pannonian brackish sediments from Croatia (Ćorić, 2004). If the attribution of the sediments to the Middle Miocene is correct, this implies that *Isolithus semenenko* is a good facies, but not a good time indicator.

5.1.2 MARINE PART OF THE MÜHLDORF FORMATION

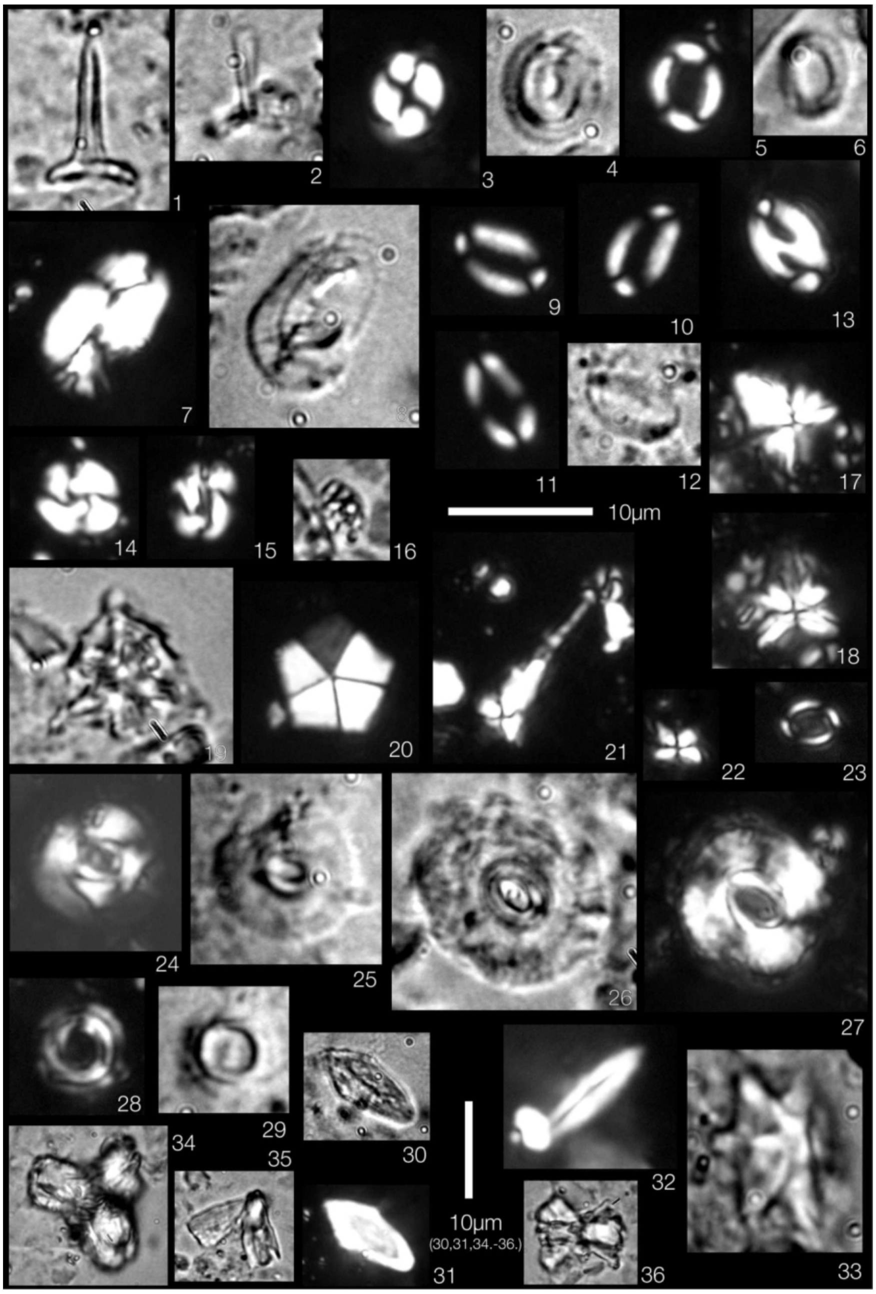
Foraminifera: In the assembla-ges of boreholes IK D01/01 and KB D18/01, the planktonic chronostratigraphic marker *Praeorbulina* cf. *sicana*, *Praeorbulina curva* and *Praeorbulina circularis* were found (Fig. 7), whereas *Orbulina suturalis* is missing. This finding supports the result of Rögl et al. (2002) and shows that the marine part of the Mühldorf Formation falls within the upper part of the biozone M5b (Fig. 11).

Calcareous nannoplankton: Sediments of the marine part of the Mühldorf Formation contain the zonal marker *Sphenolithus heteromorphus*. This form has a stratigraphical range from NN2 to NN5. Its last occurrence (LO) defines the Nn5/NN6 boundary.

Helicosphaera waltrans is present in most samples. This short-range form, described by Theodoridis (1984) from Gozo (Italy), is used for the subdivision of the Middle Miocene in the Mediterranean (Theodoridis, 1984, Fornaciari et al., 1996) and Paratethyan bioprovinces. Occurrences of this stratigraphically important form were described from the Austrian and Czech parts of the Alpine-Carpathian Foredeep (Ćorić and Rögl, 2004; Ćorić and Švabenická, 2004; Švabenická, 2002), and the Styrian Basin (Rögl et al., 2002). Recently, the stratigraphic range of *H. waltrans* (upper part of NN4 and lower part of NN5) has been defined from 15.476 Ma (first common occurrence; FCO) to 14.357 Ma (last commom occurrence; LCO) by Di Stefano et al. (subm.) and Abdul Aziz et al. (in press).

Helicosphaera ampliaperta is largely absent. The LO of this zonal marker defines the NN4/NN5 boundary. (Very sporadic occurrences at 14 and 29 m depth in IK D01/01 result from reworking of older strata).

Therefore, based on the co-occurrence of *S. heteromorphus* and *H. waltrans* and the absence of *H. ampliaperta*, sediments from IK D01/01, KB D18/01, KB D02/01, and the lowermost sample from KB D16/01 (30 m) can be attributed to the lower part of nannoplankton zone NN5 (*Sphenolithus heteromorphus*



Zone, Martini, 1971). Rich nannoplankton assemblages with Reticulofenestrids (*Reticulofenestra gelida*, *R. minuta*, *R. haqii*, *R. pseudoumbilica*), Helicoliths (*Helicosphaera carteri*, *H. walbersdorfensis*, *H. wallichi* etc.), Discoasterids (*Discoaster adamanteus*, *D. musicus*, *D. exilis*, *D. variabilis* etc.) confirm this stratigraphic attribution.

Ostracoda: *Buntonia subulata*, *Costa punctatissima*, *Henryhowella asperrima*, *Olimfalunia plicatula*, *Paracytheridea triquetra*, *Parakrithe dactylomorpha*, *Pterygocythereis calcarata* in boreholes IK D01/01 and KB D18/01 are recorded from Badenian and older (mainly Karpatian) sediments in the Central Paratethys. Biostratigraphically not indicative are *Argilloecia* sp., *Carinovalva* sp., *Cytherelloidea* sp., *Krithe* sp., *Loxo-concha* sp., *Xestoleberis* ex gr. *communis*. Restricted to the Badenian of the Central Paratethys are: *Acanthocythereis hystrix*, *Bosquetina carinella*, *Buntonia brunensis*, *Cytheridea acuminata*, *Occultocythereis bituberculata*, *Paracypris polita* and questionably *Cytherella* aff. *compressa*, *Cytherella* ex gr. *postdenticulata*, *Cytherella* aff. *vandenboldi* (cf. Brestenska and Jiricek, 1978; Zorn, 2004; Gross, 2006). Although *A. hystrix* is scarcely reported from the Middle and Upper Badenian (Szczechura, 1987; Paruch-Kulczycka and Szczechura, 1996), it is one of the best ostracodologic markers for the Lower Badenian (see Jiricek and Riha, 1991). This species is found from the base to the top of boreholes IK D01/01 and KB D18/01. For this reason both rock columns are attributed to the ostracod zone NO7 sensu Jiricek and Riha (1991), which is correlated to the Lagenidae Zone of the Lower Badenian.

Summarizing the results of all fossil groups and considering the latest chronostratigraphic table (Rögl et al., 2007; Fig. 11), a late Early Badenian age (14.91-14.74 Ma) results for the marine part of the Mühldorf Formation. The marine part of the Mühldorf Formation is thus tentatively correlatable with the uppermost part (sandstone layers with mollusc casts overlain discordantly by corallinacean limestone) of the lithological section exposed in the Wagna quarry in the Styrian Basin (Rögl et al. 2002, 2005; see Fig. 1 for location of Wagna). However, because marly layers in the corallinacean limestone contain *Orbulina suturalis* beside *Praeorbulina circularis*, the limestone should be slightly younger than the Mühldorf Formation and a correlation between its marine part with the sandstone beds seems most likely. Coeval stratigraphic successions in the neighbouring Mura-Zala Basin in Slovenia comprise from bottom to top of silty marlstone, coarse clastics, and corallinacean limestone (Žnidarcic and Mioc, 1987). The first occurrences of *Orbulina suturalis* and accompanying *Praeorbulina circularis* is in the corallinacean limestone (Rifelj, unpubl.). So far, in the silty marlstone only Early Badenian marker species *Uvigerina macrocarinata* has been found (Rögl and Rifelj, unpubl.). These data suggest a correlation of the marine part of the Mühldorf Beds with the silty marlstone. A poorly known stratigraphy of the Slovenj Gradec Basin along the Lavanttal Fault in Slovenia prevents biostratigraphic correlation between the two.

5.2 PALEOENVIRONMENT

5.2.1 UPPER PART OF THE GRANITZTAL FORMATION

Boreholes B 05/07, B 07/07 and KB D21/01 (Figs. 4, 5) represent the uppermost part of the Granitztal Formation. Coarse- to fine-grained, fluvial sediments occur in these boreholes. A general upward fining trend indicates decreasing energy levels. Moderately high sulfur contents and low TOC/S ratios in KB D21/01 might inidicate stagnant conditions. No fossil remains were found in the studied part of the Granitztal Formation.

FIGURE 8: Light microscope photographs of calcareous nannofossils.
1. *Rhabdosphara* sicca Stradner 1963 (KB D18/01: 29 m).
2. *Rhabdosphaera clavigera* Murray & Blackman 1898 (IK D01/01: 22 m).
3-4. *Coccolithus pelagicus* (Wallich 1871) Schiller 1930 (KB D18/01: 29 m).
5-6. *Coccolithus* sp. (KB D18/01: 29 m).
7-8. *Helicosphaera carteri* (Wallich 1877) Kamptner 1954 (KB D18/01: 29 m).
9-12. *Helicosphaera carteri* (Wallich 1877) Kamptner 1954, Early growth stage (KB D18/01: 29 m).
13. *Helicosphaera waltrans* Theodoridis 1984 (IK D01/01: 22 m).
14. *Cyclicargolithus floridanus* (Roth & Hay 1967) Bukry 1971 (IK D01/01: 22 m).
15. *Reticulofenestra pseudoumbilica* (Gartner 1967) Gartner 1969 (IK D01/01: 22 m).
16. *Holodiscolithus macroporus* (Deflandre 1954) Roth 1970 (KB D18/01: 7 m).
17-18. *Sphenolithus heteromorphus* Deflandre 1953 (IK D01/01: 22 m).
19. *Lithostromation perdurum* Deflandre 1942 (IK D01/01: 18 m).
20. *Braarudosphaera bigelowii* (Gran & Braarud 1935) Deflandre 1947 (IK D01/01: 14 m).
21-22. *Sphenolithus heteromorphus* Deflandre 1953 (KB D18/01: 28 m).
23. *Coronosphera mediterranea* (Lohmann 1902) Gaarder 1977 (KB D18/01: 16 m).
24-25. *Calcidiscus tropicus* Kamptner 1956 (KB D18/01: 22 m).
26-27. *Calcidiscus premacintyrei* Theodoridis 1984 (KB D18/01: 22 m).
28-29. *Geminilithella rotula* Kamptner 1956 (KB D18/01: 22 m).
30-31. Ascidian spicule - *Perforocalcinella fusiformis* Bona 1964 (KB D18/01: 7 m).
32. *Triquetrorhabdulus milowii* Bukry 1971 (KB D18/01: 9 m).
33. *Discoaster adamanteus* Bramlette & Wilcoxon 1967 (KB D18/01: 11 m).
34. *Isolithus semenenko* Ljuljeva 1989 (KB D20/01: 21.3 m).
35. *Isolithus* sp. 1 (KB D20/01: 21.3 m).
36. *Isolithus* sp. 2 (KB D20/01: 21.3 m).

5.2.2 LACUSTRINE MÜHLDORF FORMATION (“FISH SHALE”)

Laminated mudstones and pelitic marls with frequent fish remains follow above the Granitztal Formation in boreholes KB D20/01 and IK D02/01. Strictly anoxic conditions during deposition of the main part of this unit are proven by a lack of bioturbation and TOC/S ratios significantly below 2.8. Very high sulfur contents suggest a brackish influence. In contrast, low sulfur contents and high TOC/S ratios (>2.8) mainly in silty/sandy intervals (KB D20/01: 41.6-38.9 m and 14.7-10.1 m; IK D02/ 01: 36.9-32.5 m; 25-24 m) suggest short events with freshwater influx due to enhanced fluvial activity.

Ostracods and nannoplankton provide additional evidence for paleosalinity. The ostracod fauna is dominated by *Fabaeformiscandona pokornyi*, which is close to the living freshwater ostracod *F. balatonica* (Daday 1894). This recent taxon prefers shallow pools and the swampy shore-zone of lakes that can dry up in the summer. But it is also recorded from the littoral of lakes and from rivers. Probably oligohaline waters are tolerated (see Meisch, 2000; Gross, 2004). *Cypria* is a frequent limnic ostracod, which can occur in oligo- to mesohaline settings too (see van Morkhoven, 1963; Hartmann, 1989). Recent species of *Herpetocypris* prefer shallow, often rich vegetated freshwater environments, but can tolerate oligohaline conditions (see Meisch, 2000). All three taxa are thin-shelled. From *F. pokornyi*, that is recorded from all studied samples, different life stages are found. At least, if not all, the latter species is considered to be an autochthonous element, which indicates shallow, quiet, freshwater environments (pools, shore-zone of lakes, slow running rivers). Slightly oligohaline (<5 ‰) waters cannot be excluded, as these taxa are able to tolerate such conditions. A low salinity paleoenvironment is also supported by monospecific assemblages of calcareous nannofossils with *Isolithus semenenko* and *Isolithus* spp.

High amounts of organic matter (up to 10%TOC) were deposited in the shallow, oxygen-depleted lake. The positive correlation between lamalginite and TOC percentages implies that variations in organic matter are mainly a result of variation in lamalginite abundance. The enrichment of lamalginite in layers suggests that high TOC contents are due to algal blooms. HI classifies the organic matter as type II kerogen.

Intervals with silty/sandy rocks contain relatively little organic matter with reduced HI values (type III (-II) kerogen). The latter results from a predominance of vitrinite, which indicates, together with the coarser grain-size, enhanced terrestrial input. Probably, also the conditions for production and preservation of aquatic organic matter became worse during periods with enhanced fluvial activity.

5.2.3 MARINE MÜHLDORF FORMATION

The marine upper part of the Mühldorf Formation consists of a fine-grained lower part (IK D01/01, KB D18/01) and a coarse-grained upper part (KB D02/01, base of KB D16/01). Magmatic activity is evidenced by tuff layers. The most detailed information on paleoenvironment is provided by foraminifers and geochemical proxies.

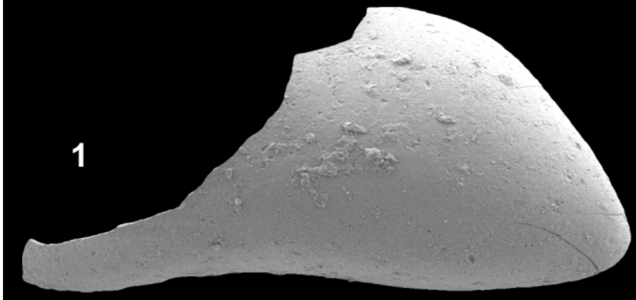
Fine-grained part: Borehole IK D01/01 represents the lower part of the marine Mühldorf Formation. Offshore conditions are suggested by the presence of *Oridorsalis umbonatus* (Fig. 7), indicative for outer shelf to lower bathyal environments (Murray, 1991). The presence of *Bathysiphon filiformis*, *Pullenia bulloides*, *Melonis pompilioides*, *Spirorutilus carinatus*, *Adelosina scheibersi*, *Cancris auriculus*, *Lenticulina* and *Uvigerina* fauna indicate mid to outer shelf water depth. Further evidence for offshore conditions is provided by the ternary foraminifera diagram based on Murray (1973) and Armstrong and Brasier (2005; Fig. 12). Most samples from IK D01/01 plot into the offshore field, although some samples plot close to the marginal, brackish field (Fig. 12). In IK D01/01 the Shannon diversity index H shows the highest and the dominance index D the lowest values (Fig. 7). This is an additional argument for offshore conditions characterized by a relatively stable ecospace.

Most BFOI values are slightly below the 0 value, which is the boundary between low oxic and suboxic conditions. Oxygen-depleted conditions are also indicated by TOC/S ratios significantly below 2.8 (Fig. 5). Nevertheless, TOC contents (0.6-0.75%) and HI values (40-70 mgHC/gTOC) are low. In view of the oxygen-depleted environment, the low TOC content results rather from low organic matter production, than from poor preservation. HI values and maceral composition indicate a dominance of allochthonous landplants. Dinoflagellate cysts are a minor, but significant contributor to the organic matter.

Compared with higher intervals within the marine Mühldorf Formation, and in agreement with the postulated stable offshore environment, vertical variations of inorganic and organic carbon, sulfur and foraminifera-based indices are minor (Figs. 5, 7). Nonetheless, two events with environmental stress are recorded by disturbances of the vertical trends:

1) BFOI reaches a minimum in the lower part of the borehole (26.0-25.9 m depth) indicating enhanced oxygen deficiency. A coeval significant increase in TOC/S ratio suggests a decrease in salinity due to freshwater influx. Thus, the decrease in oxygenation is probably associated with stronger water column stratification. Enhanced river runoff is also indicated by a (subtle) increase in grain size and the predominance of terrestrial macerals (85%). Diversity indices H, D as well as distribution trends of *Bolivina* spp., *Spirorutilus carinatus*, *Fursenkoina acuta*, *Nonion commune*, and *Oridorsalis umbonatus* are affected by the decrease

FIGURE 9: Ostracoda (l = length, h = height, w = width)
1-10. *Fabaeformiscandona pokornyi* (Kheil 1964); Lavanttal, KB-D20/01 (44.90–45.00 m).
1. left valve, female, lateral view: l >1.13 mm, h = 0.52 mm
2. right valve, female, lateral view: l >1.11 mm, h = 0.51 mm
3. left valve, female, internal view: l >0.98 mm, h = 0.50 mm
4. left valve, juvenile, dorsal view: l = 0.67 mm, w = 0.15 mm
5. right valve, juvenile, dorsal view: l = 0.70 mm, w = 0.13 mm
6 = 3. left valve, female, dorsal view: l >0.98 mm, w >0.25 mm
7 = 2. right valve, female, dorsal view: l >1.11 mm, w = 0.20 mm
8: right valve, juvenile, lateral view: l = 0.69 mm, h = 0.32 mm
9. right valve, juvenile, lateral view: l = 0.63 mm, h = 0.29 mm
10 = 8. right valve, internal view: l = 0.69 mm, h = 0.32 mm
11. cf. *Cypria* sp.; Lavanttal, KB-D20/01 (44.90–45.00 m). Carapace, left valve, lateral view: l = 0.53 mm, h = 0.36 mm.
12-15. *Herpetocypris*? sp.; Lavanttal, KB-D20/01 (44.90–45.00 m).
12. left valve, lateral view: l >0.99 mm, h >0.50 mm
13. right valve, lateral view: l >0.87 mm, h >0.45 mm
14. left valve, internal view: l >0.85 mm, h >0.42 mm
15 = 14. left valve, dorsal view: l >0.85 mm, w >0.15 mm
16 = 13. right valve, internal view: l >0.87 mm, h >0.45 m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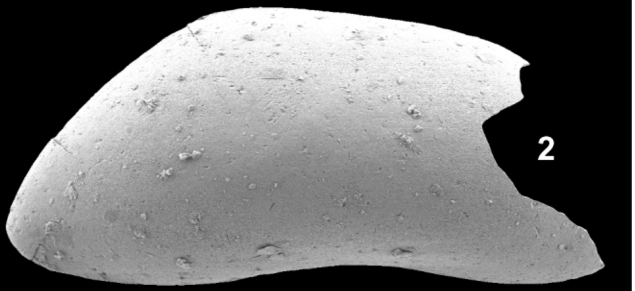
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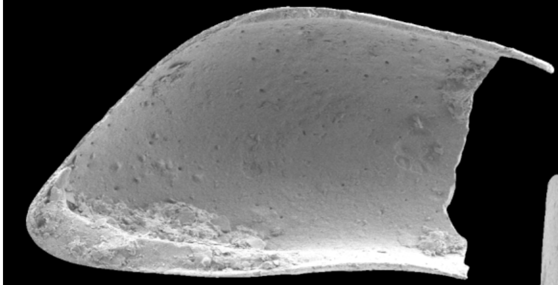
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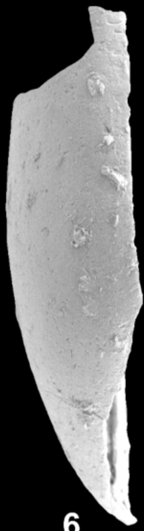
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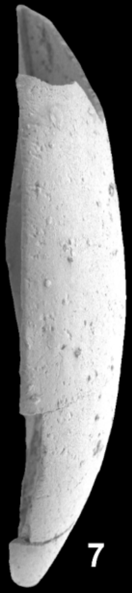
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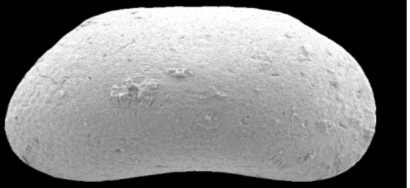
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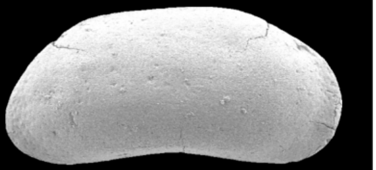
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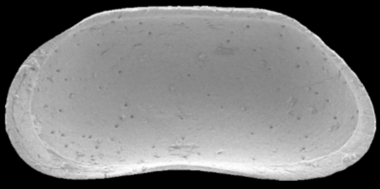
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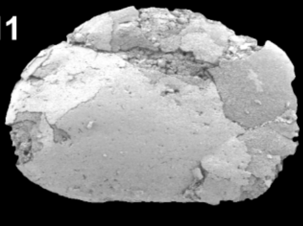
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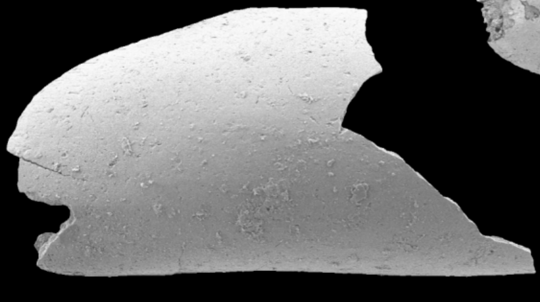
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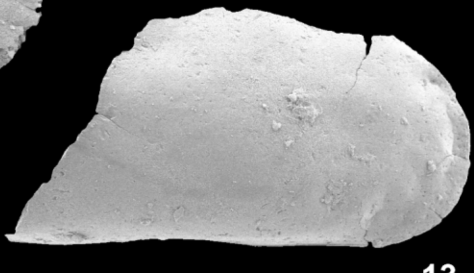
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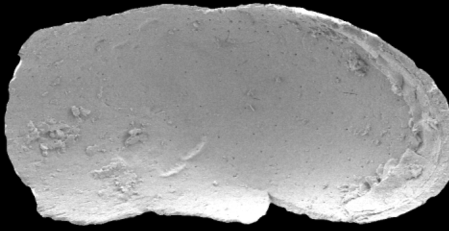
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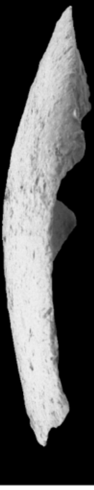
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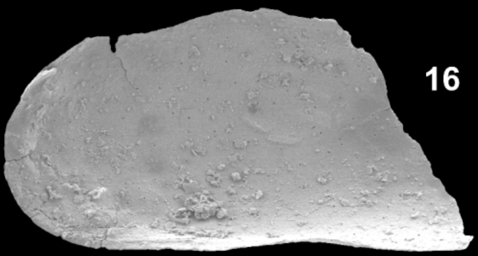
16

borehole	**KB D16/01**																			**KB D02/01**																			
sample (m)	6	7	8	10	11	12	13	14	16	17	18	19	19.5	22	22.8	23	24.3	25	30	10	11	12	16	17	18	19	20	22	23	24	28	29	30	32	33	34	36	37	38
abundance XXX	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	barren	R	barren	barren	barren	R	barren	barren	R	barren	barren	R	F	R	A	R	C	R	C	F	F	C
preservation XXX																			G				G			G			G	M	P	G	G	G	G	G	G	G	G
Braarudosphaera bigelowii																														r		r				r	r		r
Calcidiscus macintyrei																																							
Calciosollenia murray																																							
C. premacintyrei																																							
C. tropicus																																							
Catinaster sp.																																						r	
Coccolithus miopelagicus																																r							r
C. pelagicus																							x			x			x	a	x	f	c	c	x	f	c	f/c	f
Coccolithus sp.																																							
Coronocyclus nitescens																																		r				r	
Coronosphaera mediterranea																																				r	r		
Cyclicargolithus floridanus																																							
Discoaster adamanteus																																							
D. deflandrei																																							
D.exilis																																							
D. cf. *germanicus*																																							
D. variabilis																																					r	r	r
D. musicus																																							
D. sanmiguelensis																																							
Discoster sp.																																							
Geminilithella rotula																																r		r	x		r		
Helicosphaera ampliaperta																																							
H. carteri																																f	f	f		f	r	r	r
H. euphratis																																							
H. granulata																																							
H. minuta																																r		r		r	r		
H. obliqua																																							
H. sellii																																							
H. vallichi																																r				r			
H. vedderi																																							
H. walbersdorfensis																																r				r	r	r	r
H. waltrans																																r					r		r
H. vedderi																																							r
Helicosphaera sp.																																							
Holodiscolithus macroporus																																							
Lithostromation perdurum																																r							
Micrantolothus vesper																																							
Pontosphaera discopora																																					r		
Pontosphaera multipora																													x			r		r		r	r		
Reticulofenestra gelida																														r			r	r	x		r	r	f
R. haqi																														r		r				f	f	f	f
R. minuta																							x						x	r		c	r	f	x	c	f	f/c	c
R. pseudoumbilica 5-7µm																																				r			
R. pseudoumbilica > 7µm																																							
Rhabdosphaera clavigera																																							
R. pannonica																																							
R. sicca																																		r		r	r	r	r
R. sp.																																							
Scyphosphaera sp.																																							
Sphenolithus abies																																		r					
S. heteromorphus																			x											r		r	r	f		f	f	r	r
S. moriformis																														r		r		r			r	r	
Syracosphaera pulchra																																r					r	r	
Syracosphaera sp.																																							
Thoracosphaera heimii																																							
Thoracosphaera saxea																																							r
Triquetrorehabdulus chalengeri																																							
T. milowii																																							
Triqutrorhabdulus sp.																																r							
Umbilicosphaera jafarii																																r		r		r	f	f	f
rew. Paleog. & L.-Miocene																																							
Chiasmolithus sp.																																r							
Cyclicargolithus luminis																																							
Discoaster lodoensis																																							
Discoaster multiradiatus																																							
Pontosphaera lata																																							
Lanternithus minutus																														r									
Sphenolithus pseudoradians																																							
Sphenolithus radians																																							
Toweius sp.																																							
Zygrhablithus bijugatus																																							
reworked Cretaceous																																							
Arkhangelskiella cymbiformis																																							
Biscutum ellipticum																																							
Cribrosphorella ehrenbergii																																							
Eiffellithus gorkae																																							r
Micula decussata																																							
Prediscosphaera cretacea																																							
Retecapsa crenulata																																							
Watznaueria barnesae																														r				r		r			
Zeugrhabdotus diplogramus																																							

TABLE 4: Abundance of calcareous nannofossils in the marine Mühldorf Formation and in borehole KB D16/01 (A= abundant, dominant species with more than 50% of an assemblage; C=common, 10-50%; F=few, <10% of an assemblage; R=rare, only a few specimens were found; B=barren.

borehole		**KB D18/01**																						**IKD01/01**																	
sample (m)		6	7	8	9	10	11	12	14	15	16	18	19	20	21	22	23	24	25	26	28	29	30	11	12	13	14	16	17	18	20	21	22	24	25	26	27	28	29	30	30.6
abundance		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	barren	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	C	A	A	A	A	A	A	A
preservation		G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G		G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Braarudosphaera bigelowii		r	r	r	r	r	r	r	r	r	r	r	r	r	r		r		r	r	r	r		r	r	r	r/f	r	r	r	r	r	r	r	r	r	r	r	r	r	r
Calcidiscus macintyrei		r																																							
Calciosollenia murray																																						r			
C. premacintyrei		r														r																									
C. tropicus		r											r			r																									
Catinaster sp.																																									
Coccolithus miopelagicus														r			r			r	r							r	r	r		r	r		r	r	r	r	r		
C. pelagicus		f	f	f	f	f	f	f	f	f	f	f	r	r	r	r	r		r	r	r	r	f	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	f	r
Coccolithus sp.																						r																			
Coronocyclus nitescens					r			r		r	r										r		r	r						r											r
Coronosphaera mediterranea							r				r																														
Cyclicargolithus floridanus																					r					r	r	r	r	r	r	r	r		r	r			r		
Discoaster adamanteus		r		r			r																																		
D. deflandrei		r												r																											
D.exilis		r	r																																						
D. cf. *germanicus*		r																																							
D. variabilis		r/f	r			r	r			r		r	r	r							r							r									r				
D. musicus		r																																							
D. sanmiguelensis		r	r				r																																		
Discoster sp.		r	r																r	r													r		r	r					
Geminilithella rotula		r	r			r	r	r	r	r	r		r			r																									
Helicosphaera ampliaperta																											r												r		
H. carteri		f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f		f	f	f	f	f	a	f	f	f/c	f/c	f/c	c	c	f/c	f	f/c	f/c	f	f	f	f	f	f
H. euphratis										r																															
H. granulata									r																																
H. minuta						r								r												r			r					r	r	r			r		
H. obliqua																																	r						r		r
H. sellii											r																														
H. vallichi		f	f	f	f	f	f	f	f	f	f	f	f	f	f	f	f		f	f	f	f	f			r	r	r	r	r	r	f	f	f	r	f	f	f	f	f	f
H. vedderi		r				r		r		r			r	r	r								r																		
H. walbersdorfensis		r				r				r				r					r			r				r		r	r	r	r	r	r	r	r		r	r	r	r	r
H. waltrans		r	r	r	r	r	r	r	r	r	r	r	r	r					f		r				r	r	r			r	r	r	r						r		
H. vedderi																													r												
Helicosphaera sp.																																						r			
Holodiscolithus macroporus			r																																		r		r		
Lithostromation perdurum		r												r											r							r									
Micrantolothus vesper		r												r																											
Pontosphaera discopora										r																															
Pontosphaera multipora		r							r	r	r		r											r	r	r	r	r	r	r	r	r	r	r	r	f	f	f	f	f	r
Reticulofenestra gelida		r		r	r	r	r	r	r	r	r	r	r	r	r	r	r		r					r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r
R. haqi		r	r	r	r	r	r	r	r	r	r	r	r	f	f	f	r		r	r	r	r	r		r	r	f	r	r	r	r	r	r	r	r	r	r	r	r	r	r
R. minuta		c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c		c	c	c	c	c	r	c	c	c	f/c	f/c	f/c	f/c	c	c	f/c	c	c	c	c	c	c	c
R. pseudoumbilica 5-7µm		r	r	r	r	r	r	r	f	r	r	r	r	r	f	f	r		r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r
R. pseudoumbilica > 7µm															r									r						r										r	
Rhabdosphaera clavigera		r																															r								
R. pannonica										r				r																										r	
R. sicca		r	f	f	r	r	r	r	r	r	r	r	r	r	r	r	r		r	r	f	r	r		r				r					f	r	r	r		r	r	
R. sp.						r																																			
Scyphosphaera sp.		r				r				r																															
Sphenolithus abies		r																																							
S. heteromorphus		f	f	r				r	f	f	f	r	r	r	r	f	f		f	r	r	r		r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r
S. moriformis		r				r				r						f	f		r	r	r			r		r	r	r	r											r	
Syracosphaera pulchra		r			r	r				r		r		r	r		r					r	r			r															
Syracosphaera sp.																										r															
Thoracosphaera heimii																													r												
Thoracosphaera saxea		r				r								r	r														r			r		r	r	r				r	
Triquetrorehabdulus chalengeri		r				r				r													r																		
T. milowii					r																																				
Triqutrorhabdulus sp.		r								r				r			r			r															r						
Umbilicosphaera jafarii		r	f	f	f	r	f	f	f	r	f	f	f	f	f	r	r		r	r	r	r		r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r
Chiasmolithus sp.	rew. Paleog. & L.-Miocene	r																									r	r	r	r			r								r
Cyclicargolithus luminis														r																											
Discoaster lodoensis																			r						r													r			
Discoaster multiradiatus																				r									r												
Pontosphaera lata																																			r						
Lanternithus minutus																													r												
Sphenolithus pseudoradians																							r																		
Sphenolithus radians																													r	r											
Toweius sp.																								r		r	r		r			r	r								
Zygrhablithus bijugatus																																		r							
Arkhangelskiella cymbiformis	reworked Cretaceous				r																																				
Biscutum ellipticum																														r											
Cribrosphorella ehrenbergii					r																									r											
Eiffellithus gorkae																																									
Micula decusata						r															r		r											r							
Prediscosphaera cretacea														r		r																r					r				
Retecapsa crenulata																				r																					
Watznaueria barnesae					r						r										r		r					r	r		r	r	r	r	r		r				
Zeugrhabdotus diplogramus																						r																			

The preservation of the calcareous nannoplankton assemblage is characterized by the following terms: G=good, no evidence of etching or overgrowth; M=moderate; P=poor, significant etching or overgrowth.

in oxygen level. High organic matter content (2.2%TOC) results mainly from allochthonous plant material, but also from autochthonous organic matter production (15% telalginite + liptodetrinite). The relatively high HI value (265 mgHC/gTOC) indicates enhanced organic matter preservation. Furthermore, the freshwater influx resulted in a decrease in carbonate content.

2) INFN, EPIFN, *Oridorsalis umbonatus*, *Melonis pompilioides*, *Bulimina* spp., *Fursenkoina acuta* and *Elphidium* spp. indicate another change in environmental factors in the upper part of IK D01/01 (10.5-10.4 m depth; just below the boundary between siltstone and fine-grained sandstone). We speculate that this is also a result of enhanced freshwater inflow. However, geochemical and petrographic data are not available from this horizon.

Calcareous nannoplankton provides information on the conditions within the photic zone. Generally, coccolithophores flourish in warm, stratified, oligotrophic ocean environments. Calcareous nannoplankton in borehole IK D01/01 is abundant and well preserved. Dominating forms are small reticulofenestrids (*R. minuta* and *R. haqii*) and *Helicosphaera carteri*. The bloom of small reticulofenestrids, which characterizes Badenian sediments in the Styrian, Vienna and Molasse Basins, points to a well stratified, oligotrophic water column. Common occurrences of *Helicosphaera* are typical for hemipelagic sediments deposited at shorter distances from landmasses (Perch-Nielsen, 1985). Scarce presence of discoasterids, forms typical for warm open ocean paleoenvironments, and common helicosphaerids point to a near shore environment. Regular, but low presence of *B. bigelowii* is a signal for a weak freshwater input (Perch-Nielsen, 1985).

The ostracod faunas of borehole IK D01/01 are dominated by Cytherellids. These are eurybathic filter feeders with some preference for the circalittoral, which are able to survive areas/periods with reduced dissolved oxygen (see Boomer and Whatley, 1992). Other common and less frequent species point to an inner-/middle circalittoral, fully marine setting. The lack of epineritic forms (e.g. Hemicytherids are completely missing) shows bathyneritc facies (see Liebau, 1980). *Loxoconcha* sp. and *Xestoleberis* ex gr. *communis* maybe tolerate these conditions or are allochthonous elements. *A. hystrix* and *O. bituberculata* refer to warm waters (see Montenegro et al., 1998). Subsuming these data, a warm-temperate, sometimes oxygen-depleted sea with depths ranging from 50-150 m (most probably around 100 m) is signalized by ostracods.

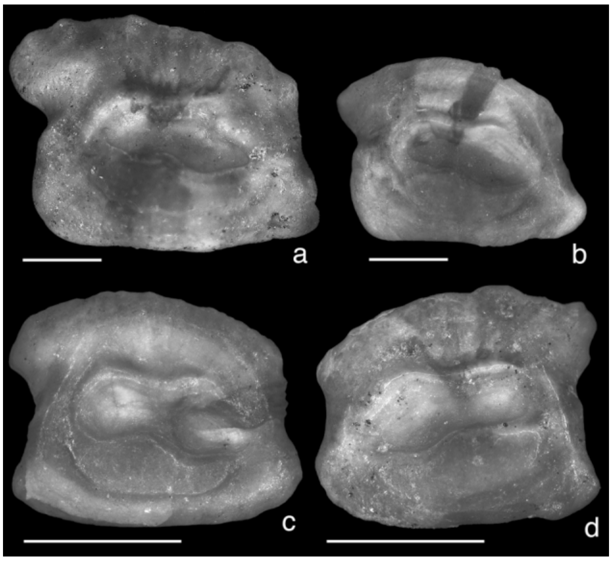

Figure 10: Otoliths (sagittae) of *Gobius* (n). sp., KB D20/01 (38.8-38.7 m); a-c = left sagittae; d = right sagitta, Scale bar = 1 mm.

In borehole KB D18/01 from the uppermost 25 m of the fine-grained part of the marine Mühldorf Formation, most indices exhibit more prominent and more frequent fluctuations than in IK D01/01 (Fig. 7). This indicates an environmental shift from borehole IK D01/01 to borehole KB D18/01. We associate it with more frequent inflows of continental water. This is supported by a shift of data points in the wall structures diagram towards the brackish field (Fig. 12), a well developed *Ammonia-Nonion* association (Fig. 7) and an increase in grain size (Fig. 5). The increase in grain size and in *Ammonia viennensis* are positively related (comp. Figs. 5, 7).

Low BFOI values, reduced biodiversity (i.e. low H and high D values), a clear dominance of infauna over epifauna, and an increase in the abundance of *Bulimina* spp., *Bolivina* spp. and *Fursenkoina acuta* (Fig. 7), which are characteristic low oxygen tolerant infaunal dwellers, point to significant environmental stress due to low oxygen contents at the sediment/water interface. Strong oxygen depletion is also supported by very low TOC/S ratios (0.5-0.9), which are even lower than in IK D01/01.

A drastic increase in PFN above 20 m depth (Fig. 7) suggests higher plankton productivity. High productivity in the upper water column is further supported by abundant telalginite. Since PFN as well as INFN and TOC increase above 20 m depth, it is concluded that the drastic increase in plankton production resulted in an increase in organic matter (i.e. food) supply into the sediment (Figs. 5, 7). Maxima in *Bolivina* spp.-*Bulimina* spp. abundance and a decrease in EPIFN prove oxygen-depleted conditions in the uppermost sediment layer and the bottom water. The increase in plankton productivity may result from mixing of warm marine and cold nutrient-rich continental waters. Thus, we presume that freshwater influx influenced the geochemistry at the sediment/water interface by establishing density stratification in the water column and by higher organic matter export. Both of them result in a reduction of oxygen levels in the sediment and in the bottom water.

PFN decreases abruptly above the PFN maximum (12.0-11.9 m). This shows that during deposition of the uppermost part of borehole KB D18/01 environmental factors must have reached a critical threshold for plankton to survive. The decrease in plankton productivity is also reflected by a decrease in TOC between 11 and 9 m depth from 1.37 to 0.88%.

The INFN maximum (9.1-9.0 m) postdates the PFN maximum (Fig. 7). In sample 9.1-9.0 m the abundant *Bolivina*

Bulimina infauna is replaced for the first time by a *Nonion-Ammonia* infauna (Fig. 7, Table 2), which also depends on a rather organic-rich, suboxic ecospace, but can tolerate salinity fluctuations. Between 9 and 6 m depth, a drastic decrease in infauna follows the decrease in plankton productivity (Fig. 7). Relatively high BFOI values in samples at 7 and 6 m depth show that this decrease is associated with an increase in the oxygenation level.

The changes recorded by foraminifera and geochemical proxies are not visible in the calcareous nannoplankton. Sediments from borehole KB D18/01 contain a similar rich nannoflora (with dominance of small reticulofenestrids and helicosphaerids) like samples from IK D01/01. The uppermost samples (7-6 m) from KB D18/01 contain higher percentage of discoasterids (*Discoaster adamanteus*, *D. variabilis*, *D. sanmiguelensis*). An enrichment in these forms points to an increase in water temperature.

In borehole KB D18/01, Cytherellids do not predominate ostracod associations, like in IKD01/01. Ostracod faunas from samples 14.0-14.1 to 29.1-29.2 m are impoverished. The few ostracod remains most probably refer to an inner circalittoral, warm water situation. Typical epineritic elements are missing. Overall, the ostracods indicate a warm-temperate, inner circalittoral (depth approximately 50-100 m) depositional area.

Coarse-grained part: The coarse-grained upper part of the marine Mühldorf Formation is nearly 80 m thick. Borehole KB D02/01 represents its lower part; the lowermost sandstone layer in borehole KB D16/01 represents its top. The lithology suggests a marginal marine setting with a higher energy level. This interpretation is supported by the position of samples from borehole KB D02/01 in the wall structure diagram (Fig 12). In this environment suboxic conditions persist in the top layer of fine-grained sediments, whereas oxic conditions prevail in the water column (compare abundance of *Nonion-Ammonia* infauna with abundance of *Elphidium* spp. and *Asterigerinata planorbis*; Fig. 7; Table 2).

The BFOI is in the same value range as in borehole IK D01/01 (Fig. 7), but biodiversity is lower (i.e. low H, high D) than in the fine-grained part of the marine Mühldorf Formation (Fig. 7). Furthermore, the TFN drops to a minimum (Fig. 7).

Foraminifera associations are dominated by *Fursenkoina acuta*, *Nonion commune*, *Ammonia viennensis*, *Elphidium* spp. and *Asterigerinata planorbis* (Fig. 7, Table 2). The abundance of *Fursenkoina acuta* is negatively correlated with BFOI and disappears when BFOI is close to 0. *Spirorutilus carinatus* shows a similar relation, whereas the oxic taxa keeled *Elphidium* spp. and *Asterigerinata planorbis* are abundant when BFOI is close to 0.

Unstable paleoenvironmental conditions created nannoplankton assemblages with different abundance, but generally well preserved nannoplankton in the lower part of borehole KB D02/01 (38-23 m). In contrast only samples from 16 and 19 m depth contain rare well preserved nannoflora in its upper part. Normal marine conditions in the lowermost part of borehole KB D16/01 at 30 m depth are proven by (very rare) *S. heteromorphus*.

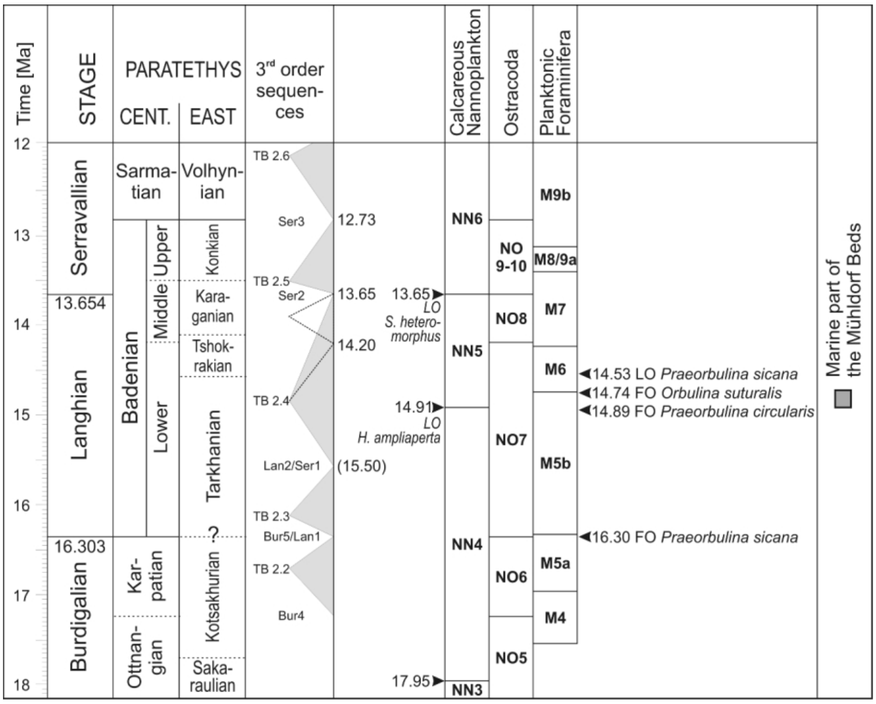

Figure 11: Stratigraphy of the late Lower Miocene and Middle Miocene. Standard geologic time scale, Central Paratethyan stages, nannoplankton zonations, and global 3rd order sequences follow Rögl et al. (2007). An additional 3rd order sequence in the Vienna Basin (Strauss et al., 2006), which has been re-dated by Rögl et al. (2007: 14.2-13.65), is indicated by a solid line. Planktonic foraminiferal zonations follow Lourens et al. (2004). Ostracod zonations follow Jiricek and Riha (1991). The established time span of the marine part of the Mühldorf Formation is indicated.

5.2.4 ROCKS OVERLYING THE MÜHLDORF FORMATION

Sediments overlying the basal sandstone in borehole KB D16/01 are barren of nannofossils. With the exception of a single sample, TOC/S ratios are >2.8 suggesting a freshwater environment. This is supported by the presence of *Candona* s.l. and *Pseudocandona* sp. at 22.2-22.0 m depth. A sapropelic shale was deposited near the base of the non-marine sequence. Its organic matter (kerogen type II) is similar to that of the lacustrine part of the Mühldorf Formation ("fish shale"), but its sulfur content is significantly lower. The easternmost borehole KB D15/01 comprises organic-poor, fossil-free, pelitic rocks, which are interpreted as sediments of a well-oxygenated freshwater lake.

5.3. SEQUENCE STRATIGRAPHY AND CORRELATION

The evolution of the fill in sedimentary basins is controlled by various factors including tectonic activity creating accommodation space and by global sea level variations. It is likely that the Lavanttal Fault has been active during Early Badenian times (e.g. Strauss et al., 2001). Nevertheless, the Lower Badenian succession might record an Early Badenian eustatic cycle.

The fluvial Granitztal Formation is interpreted as sediments of a Lowstand Systems Tract. The lacustrine (brackish) part and the lowermost marine part include sediments of the Transgressive Systems Tract. Foraminiferal assemblages suggest that maximum water depth occurred during deposition of the lower part of the marine Mühldorf Formation (IK D01/01). Therefore, we speculate that this interval corresponds to a maximum flooding surface. The shallowing and coarsening upward trend above borehole IK D01/01 (KB D18/01; KB D02/01) is interpreted as the Highstand Systems Tract.

We suspect that the investigated interval is a representative of the global 3rd order sequence TB 2.4 of Haq et al. (1988) and Hardenbol et al. (1998; see Fig. 11).

Although the sedimentary sequence in the neighboring Fohnsdorf Basin is clearly controlled by variable subsidence rates in a pull-apart (Sachsenhofer et al., 2003), its basin fill is influenced by the Early Badenian sea level rise. Whereas the rise in level established fully marine environments in the Lavanttal Basin, it caused a brackish environment in the Fohnsdorf Basin. A tuff layer, which was deposited in the Fohnsdorf Basin during the vanishing stages of the brackish influence, was dated at 14.9 ± 0.8 Ma. (Ebner et al., 2002). The maximum flooding event, therefore, should be slightly older. Despite of all uncertainties related to biostratigraphy and absolute age dating, the age estimate for the maximum flooding surface in both basins agree reasonable well.

Remarkably, the age of the tuff in the Fohnsdorf Basin is identical with that of the Kollnitz volcano in the Lavanttal Basin (14.9 ± 0.9 my; Lippolt et al., 1975). Unfortunately the tuff in the Mühldorf Formation has not yet been dated.

6. CONCLUSIONS

The marine part of the Mühldorf Formation is dated with planktonic foraminifera *Praeorbulina cf. sicana*, *P. curva* and *P. circularis* into the upper part of biozone M5b. Nannoplankton assemblages with *Sphenolithus heteromorphus* and *Helicosphaera waltrans*, but without *H. ampliaperta* enable an attribution to the lower part of nannoplankton zone NN5. The presence of *Acanthocythereis hystrix* argues for the ostracod zone NO7. This proves a late Early Badenian age (14.91-14.74 Ma). No reliable age data exist for the lacustrine part of the Mühldorf Formation, but a (Karpatian to) Early Badenian age is most likely.

The Mühldorf Formation overlies fluvial deposits of the Granitztal Formation. The lower part of the Mühldorf Formation has been deposited in a shallow, quiet lake with prevailing anoxic conditions. High sulfur contents suggest a brackish influence. Organic carbon contents up to 10% result from algal blooms. Silty material with low organic matter contents and varying amounts of detrital landplants was deposited during times of enhaced river runoff.

The marine part of the Mühldorf Formation shows an upward shallowing and coarsening trend. Oxygen contents in the bottom water varied, but suboxic conditions prevailed during deposition. Calcareous nannoplankton and ostracods indicate warm-(temperate) conditions. In contrast, small planktonic foraminifera, and benthic foramini-fera *Oridorsalis umbonatus*, *Bathysifon filiformis*, *Pullenia bulloides* may indicate colder surface and bottom waters.

Accumulation of the marine succession started in an offshore setting characterized by a relatively stable mid to outer shelf setting. Water depth probably exceeded 100 m. Despite of oxygen-depleted conditions, TOC contents are low (<1%) and organic matter is dominated by land plants. This indicates low organic matter productivity in the water column. Two events interrupting the stable environment are recorded in the lower part of the marine succession (IK D01/01).

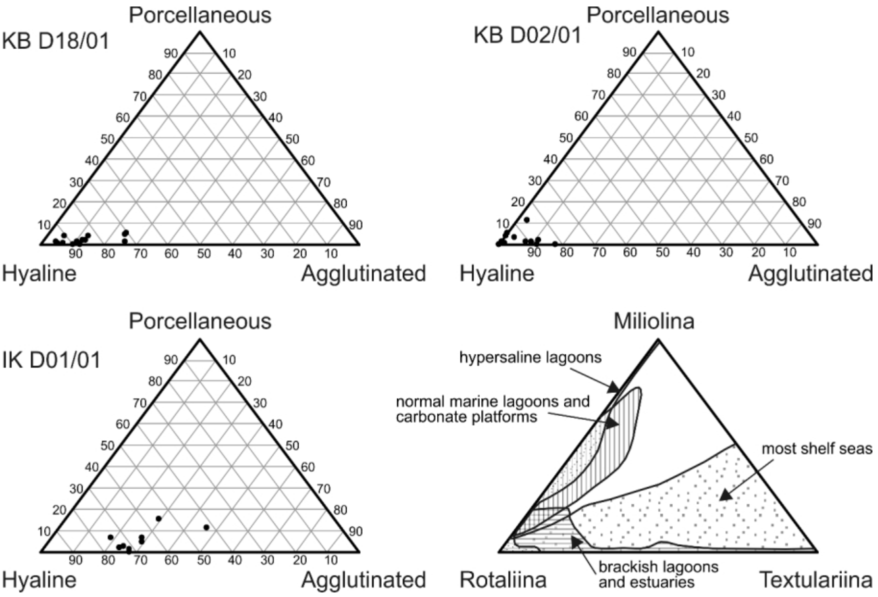

FIGURE 12: Ternary plot of agglutinated, porcellaneous and hyaline foraminifera. The relation with water depth and salinity is shown after Armstrong and Brasier (2005; cum lit).

These events are attributed to enhanced river runoffs, which resulted in a slight and temporary decrease in salinity, water column stratification, decrease in oxygenation level at the sediment/water interface and in the top layer of the sediment, decrease in biodiversity, and enhanced organic matter preservation.

Environmental factors changed more frequently during deposition of the middle part of the marine Mühldorf Formation (KB D18/01) and oxygen contents at the sediment/water interface decreased to a minimum (reaching the suboxic/ dysoxic boundary). Foraminiferal and ostracod assemblages indicate a decrease in water depth (approx. 50-100 m). Plankton productivity increased dramatically during deposition of the upper part of borehole KB D18/01, probably a result from inflow of nutrient-rich cold freshwater,. High plankton productivity increased the organic matter flux to the sediment surface. Because of the reduced oxygen level in the bottom water, the epifauna remained subordinate, whereas infauna was able to exploit the increased food supply and flourished. During deposition of the uppermost part of the drilled section, plankton productivity decreased first, and the number of foraminifera living within the sediment slightly later. An increase in the abundance of discoasterids in the uppermost part of KB D18/01 indicates a short increase in water temperature.

The sandy upper part of the marine Mühldorf Formation (KB D02/01 and base of KB D16/01) records the change to a marginal marine, higher-energy environment (deltaic-estuarine offshore transition, shoreface, and lagoon). Foraminiferal assemblages suggest suboxic conditions in the top layer of fine-grained sediments, and oxic conditions in the water column. Faunal diversity during deposition of the upper part of the Mühldorf Formation was relatively low. Furthermore, the total foraminiferal number dropped to a minimum. Unstable paleoenvironmental conditions created nannoplankton assemblages with different abundance, but generally well preserved nannoplankton in the lower part of borehole KB D02/01 (38-23 m). In contrast, only few samples contain rare well preserved nannoflora in its upper part. Tuff layers in the fine-grained part and in the sandy part of the marine Mühldorf Formation record magmatic events. Nonmarine sediments, which comprise sapropelic shale near their base, follow above the Mühldorf Formation.

Maximum water depth occurred during deposition of the lower part of the marine Mühldorf Formation. We speculate that this part represents a maximum flooding surface (interval). The lower lacustrine part is interpreted as the Transgressive Systems Tract and the upper part as the Highstand Systems

Ecology		freshwater (?oligohaline)					infra- to circalittoral												eurybathic				circalittoral to (epi-)bathyal					
							infra- to inner circalittoral												inf.	circalitt.								
Logs	Taxa / Samples	*Candona* s.l. (juvenile)	cf. *Cypria* sp.	*Fabaeformiscandona pokornyi* (Kheil, 1964)	*Herpetocypris*? sp.	*Pseudocandona* sp.	*Costa punctatissima* Ruggieri, 1962	*Cytherella* aff. *vandenboldi* Sissingh, 1972	*Cytherelloidea* sp.	*Cytheridea acuminata* Bosquet, 1852	*Loxoconcha* sp.	*Occultocythereis bituberculata* (Reuss, 1850)	*Paracytheridea triquetra* (Reuss, 1850)	*Xestoleberis* ex gr. *communis* Müller, 1894	*Acanthocythereis hystrix* (Reuss, 1850)	*Buntonia brunensis* Riha, 1985	*Buntonia subulata* (Ruggieri, 1954)	*Paracypris polita* Sars, 1866	*Olimfalunia plicatula* (Reuss, 1850)	*Cytherella* aff. *compressa* (Münster, 1830)	*Cytherella* ex gr. *postdenticulata* Oertli, 1961	*Pterygocythereis calcarata* (Bosquet, 1852)	*Argilloecia* sp.	*Bosquetina carinella* (Reuss, 1850)	*Carinovalva* sp.	*Henryhowella asperrima* (Reuss, 1850)	*Krithe* sp.	*Parakrithe dactylomorpha* Ruggieri, 1962
KBD16/01	22.00-22.20	x				x																						
KBD18/01	6.00-6.10								x	x				x	x		x	x							x			x
	7.00-7.10								x	x	x			x	x		x	x		x	x	x	x	x	x		x	x
	9.00-9.10									x				x	x		x	x	x	x		x		x				x
	11.90-12.00						x			x				x	x		x	x				x		x				x
	14.00-14.10													x	x		x	x		x				x		x		x
	15.10-15.20														x		x	x		x				x				x
	18.10-18.20								x						x		x	x		x					x			
	19.00-19.10													x	x		x					x						x
	21.00-21.20									x				x	x			x				x		x				
	23.80-24.00																	x										
	25.90-26.00									x														x				
	28.10-28.20														x		x	x		x								
	29.10-29.20														x			x										
IKD01/01	10.40-10.50										x		x	x	x	x	x	x		x		x		x		x		x
	12.25.12.35							x			x	x		x		x	x			x			x	x		x		x
	13.90-14.00								x					x		x	x			x			x			x		x
	17.00-17.10								x						x	x	x			x							x	x
	21.90-22.00								x					x	x	x	x			x				x		x		x
	25.90-26.00								x					x	x	x	x			x			x	x		x		x
	27.00-27.10														x	x	x			x				x		x		x
	29.00-29.10								x					x	x	x	x			x			x	x	x	x	x	x
	30.10-30.20							x						x	x	x				x					x		x	
IKD02/01	17.70-17.80			x																								
KBD20/01	11.35-11.45			x																								
	38.70-38.80		x	x																								
	44.90-45.90			x	x																							

Table 5: Distribution of ostracods in the investigated samples and proposed paleoecological preferences.

Tract of a sequence, which corresponds to TB 2.4 of Haq et al. (1988) and Hardenbol et al. (1998). Maximum flooding during TB 2.4 even influenced the central part of the Alps and established brackish conditions in the Fohnsdorf Basin.

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REFERENCES

Abdul Aziz, H., Di Stefano, A., Foresi, L.M., Hilgen, F.J., Iaccarino, S. M., Kuiper, K.F., Lirer, F., Salvatorini, G. and Turco, E., in press. Integrated stratigraphy and 40Ar/39Ar chronology of early Middle Miocene sediments from DSDP Leg 42A (Western Mediterranean). Paleogeography, Paleoclimatology, Paleoecology.

Armstrong, H.A. and Brasier, M.D., 2005. Microsfossils, 2nd ed., Blackwell Publishing, Oxford, 296 pp.

Bechtel A., Reischenbacher D., Sachsenhofer, R.F., Gratzer R., Lücke A. and Püttmann W., 2007. Relations of petrographical and geochemical parameters in the Middle Miocene Lavanttal lignite (Austria). International Journal of Coal Geology, 70, 325-349.

Beck-Mannagetta, P., 1952. Zur Geologie und Paläontologie des Tertiärs des unteren Lavanttales. Jahrbuch der Geologischen Bundesanstalt, 95, 1-102.

Berger, W., 1955. Jungtertiäre Pflanzenreste aus dem unteren Lavanttal in Ostkärnten. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 100, 402-430.

Boomer, I. and Whatley, R., 1992. Ostracoda and dysaerobia in the Lower Jurassic of Wales: the reconstruction of past oxygen levels. Palaeogeography, Palaeoclimatology, Palaeoecology, 99, 373-379.

Brestenska, E. and Jiricek, R., 1978. Ostrakoden des Badenien der Zentralen Paratehtys. In: Brestenska, E. (ed.), Chronostratigraphie und Neostratotypen Miozän der Zentralen Paratethys. 6 (M4) Badenium. Verlag der Slowakischen Akademie der Wissenschaften, Bratislava, pp. 405-439.

Buzas, M. A. and Gibson, T.G., 1969. Species diversity: Benthonic foraminifera in Western North Atlantic. Science, 163, 72-75.

Ćorić, S., 2004. Occurences of endemical calcareous nannoplankton genus Isolithus Luljeva, 1989 in the Central Paratethys. Scripta Facultatis Scientiarum Naturalium Universitatis Masarykianae Brunensis, 31-32, (2001-2002), Geology, 19-22.

Ćorić, S. and Rögl, F., 2004. Roggendorf-1 borehole, a key section for Lower Badenian transgressions and the stratigraphic position of the Grund Formation (Molasse Basin, Lower Austria). Geologica Carpathica, 55/2, 165-178.

Ćorić, S. and Švabenická, L., 2004. Calcareous nannofossil biostratigraphy of the Grund Formation (Molasse Basin, Lower Austria). Geologica Carpathica, 55/2, 147-153.

den Dulk, M., 2000. Benthic foraminiferal response to Late Quaternary Variations in Surface Water Productivity and Oxygenation in the Northern Arabian Sea. Geologica Ultraiectina, 188, 205 pp.

Di Stefano, A., Foresi, L.M., Iaccarino, S.M., Turco, E., Amore, F. O., Mazzei, R., Morabito, S., Salvatorini, G. and Abdul Aziz, H., submitted. Calcareous plankton high resolution biomagnetostratigraphy for the Langhian of the Mediterranean area. Rivista Italiana di Stratigrafia e Paleontologia.

Ebner, F., Dunkl, I., Mali H. and Sachsenhofer R. F., 2002. Stratigraphic evidence of pyroclastic layers in Miocene basins of the Eastern Alps (Austria). Geologica Carpathica 53 (Spec. Issue), Proceedings of XVII. Congress of Carpathian-Balkan Geological Association Bratislava, September 1st – 4th 2002.

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

Fornaciari, E., Di Stefano, A., Rio, D. and Negri, A., 1996. Middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region. Micropaleontology, 42, 1, 37-63.

Frisch, W., Dunkl, I. and Kuhlemann, J., 2000. Post-collisional orogen-parallel large-scale extension in the Eastern Alps. Tectonophysics, 327, 239-265.

Gross, M., 2004. Zur Ostracodenfauna (Crustacea), Paläoökologie und Stratigrafie der Tongrube Mataschen (Unter-Pannonium, Steirisches Becken, Österreich). Joannea Geologie und Paläontologie, 5, 49-129.

Gross, M., 2006. Mittelmiozäne Ostracoden aus dem Wiener Becken (Badenium/Sarmatium, Österreich). Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, Sonderband, 1, 1-224.

Haq, B.U., Hardenbol, J. and, Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea level changes. SEPM Special Publication, 42, 71-108.

Hardenbol, J., Thierry, J., Farley, M.B., Jaquin, T., Graciansky, P.-C. and Vail, P.R., 1998. Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins. SEPM Special Publication, 60, 3-13.

Hartmann, G., 1989. Ostracoda. Dr. H.G. Bronns Klassen und Ordnungen des Tierreichs, 5/1/2/4/5 (1989). VEB Gustav Fischer Verlag, Jena, 787-1067.

Jiricek, R. and Riha, J., 1991. Correlation of Ostracod Zones in the Paratethys and Tethys. Saito Ho-on Kai Special Publications (Proceedings of Shallow Tethys), 3, 435-457.

Jones, R.W., Brady, B.H. and Natural History Museum, 1994. The Challenger Foraminifera. Oxford University Press, Oxford, 416 pp.

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

Kühn, O., 1963. Korallen aus dem Miozän des Lavant-Tales. Senckenbergiana Lethaea, 44, 85-107.

Liebau, A., 1980. Paläobathymetrie und Ökofaktoren: Flachmeer-Zonierungen. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, 160/2, 173-216.

Lippolt, H.J., Baranyi, I. and Todt, W., 1975. Das Kalium-Argon Alter des Basaltes von Kollnitz im Lavanttal. Der Aufschluß, 26, 238-242.

Loubere, P. and Fariduddin, M., 1999. Benthic Foraminifera and the flux of organic carbon to the seabed. In: Sen Gupta, K.B. (ed.), Modern Foraminifera, Kluwer Academic Publishers, 181-199.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J. and Wilson, D., 2004. The Neogene Period. In: Gradstein, F.M., Ogg, J. and Smith, A. (eds.), A geologic time scale 2004. Cambridge University Press, Cambridge, 409-440.

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. and Edizioni Tecnoscienza (eds.), Proceedings of the II Planktonic Conference Roma 1970, 739-785.

Meisch, C., 2000. Freshwater Ostracoda of Western and Central Europe. In: Schwoerbel, J. and Zwick, P. (eds.), Süßwasserfauna von Mitteleuropa, 8/3. Spektrum Akademischer Verlag, Heidelberg/Berlin, 522 pp.

Montenegro, M.E., Pugliese, N. and Bonaduce, G., 1998. Shelf Ostracods distribution in the Italian seas. Bulletin du Centres de Recherches Elf Exploration-Production, Memoires, 20, 91-101.

Murray, J.W., 1971. An Atlas of British Recent Foraminiferids, Heinemann, London, 244 pp.

Murray, J.W., 1973. Distribution and Ecology of Benthic Foraminiferids, Heinemann, London, 274 pp.

Murray, J.W., 1991. Ecology and Palaeoecology of Benthic Foraminifera, Longman, Harlow, 397 pp.

Murray, J.W., 2001. The niche of benthic foraminifera, critical thresholds and proxies. Marine Micropaleontology, 41, 1-7.

Murray, J.W., 2006. Ecology and Applications of Benthic Foraminifera. Cambridge University Press, Cambridge, 438 pp.

Naidu, P. D. and Malmgren, B.A., 1995. Do benthic foraminifer records represent a productivity index in oxigen minimum zone areas? An evaluation from the Oman Margin, Arabian Sea. Marine Micropaleontology, 26, 1-4, 49-55.

Paruch-Kulczycka, J. and Szczechura, J., 1996. Ostracoda. In: Malinowska, L. and Piwocki, M. (eds.), Budowa geologiczna Polski, 3. Polska Agencja Ekologiczna, Warszawa, 727-742.

Perch-Nielsen, K., 1985. Cenozoic calcareous nannofossils. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (eds), Plankton Stratigraphy. Cambridge University Press, 427-554.

Ratschbacher, L., Frisch, W., Linzer, H.-G. and Merle, O., 1991. Lateral extrusion in the Eastern Alps, 2. Structural analysis. Tectonics, 10, 257-271.

Reichenbacher, B., 1993. Mikrofauna, Paläobiogeographie und Biostratigraphie der miozänen Brack- und Süßwassermolasse in der westlichen Paratethys unter besonderer Berücksichtigung der Fisch-Otolithen. Senckenbergiana lethaea, 73, 277-374.

Reichenbacher, B., Böhme, M., Heissig, K., Prieto, J. and Kossler, A., 2004. New approach to assess biostratigraphy, palaeoecology and past climate in the South German Molasse Basin during the Early Miocene (Ottnangian, Karpatian). Courier Forschungsinstitut Senckenberg, 249, 71-89.

Rögl, F., Spezzaferri, S. and Ćorić, S., 2002. Micropaleontology and biostratigraphy of the Karpatian-Badenian transition (Early-Middle Miocene boundary) in Austria (Central Paratethys). Courier Forschungsinstitut Senckenberg, 237, 47-67.

Rögl, F., Ćorić, S., Hohenegger, J., Pervesler, P., Roetzel, R., Scholger, R., Spezzaferri, S. and Stingl, K., 2005. The Styrian Tectonic Phase – A series of events at the Early/Middle Miocene boundary revised and stratified (Styrian Basin, Central Paratethys). 12th Congress R.C.M.N.S., Abstracts Book, Vienna, 191-192.

Rögl, F., Ćorić, S., Hohenegger, J., Pervesler, P., Roetzel, R., Scholger, R., Spezzaferri, S. and Stingl, K., 2007. Cyclostratigraphy and Transgressions at the Early/Middle Miocene (Karpatian/Badenian) Boundary in the Austrian Neogene Basins (Central Paratethys). Scripta Facultatis Scientiarum Naturalium Universitatis Masarykianae Brunensis, ser. Geology, submitted.

Sachsenhofer, R.F., Bechtel, A., Reischenbacher, D. and Weiss A., 2003. Evolution of lacustrine systems along the Miocene Mur-Mürz fault system (Eastern Alps) and implications on source rocks in pull-apart basins. Marine and Petroleum Geology, 20, 83-110.

Scherbacher, M., Schmiedl, G. and Hemleben, Ch., 2001. Early Oligocene benthic foraminifera from the Lower Inn Valley: Implications for the paleoenvironmental evolution of the western Paratethys. In: Piller, W.E. and Rasser, M.W. (eds.), Paleogene of the Eastern Alps. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 14, 611-640.

Schmid, M., 1974. Bericht über Untersuchungen im Tertiär des Lavanttales. Verhandlungen der Geologischen Bundesanstalt, 122-123.

Schmiedl, G. and Mackensen, A., 1997. Late Quaternary paleoproductivity and deep water circulation in the eastern South Atlantic Ocean: Evidence from benthic foraminifera. Palaeogeography, Palaeoclimatology, Palaeoecology, 130, 43-80.

Strauss, P.H., Wagreich, M., Decker, K. and Sachsenhofer, R.F., 2001. Tectonics and sedimentation in the Fohnsdorf-Seckau Basin (Miocene, Austria): From a pull-apart basin to a half-graben. International Journal of Earth Sciences, 90, 549-559.

Strauss, P., Harzhauser, M., Hinsch, R. and Wagreich., 2006. Sequence stratigraphy in a classic pull-apart basin (Neogene, Vienna Basin). A 3D seismic based integrated approach. Geologica Carpathica, 57, 185-197.

Švabenická, L., 2002. Calcareous nannofossils of the Upper Karpatian and Lower Badenian deposits in the Carpathian Foredeep, Moravia (Czech Republic). Geologica Carpathica, 53, 3, 197-210.

Szczechura, J., 1987. A new ostracode species, Neomonoceratina chomentovensis sp. n., from the Korytnica Basin (Middle Miocene; Holy Cross Mountains, Central Poland). Acta Geologica Polonica, 37/3-4, 105-111.

Taylor, G.H., Teichmüller, M., Davis, A., Diessel, C.F.K., Littke R. and Robert P., 1998. Organic Petrology, Gebrüder Borntraeger, Berlin, 704 pp.

Theodoridis, S., 1984. Calcareous nannofossil biozonation of the Miocene and revision of the helicoliths and discoasterids. Utrecht Micropalentological Bulletin, 32, 1-271.

Van der Zwan, G.J., 1982. Paleoecology of Late Miocene foraminifera. Utrecht Micropalentological Bulletin, 25, 202 pp.

van Morkhoven, F.P.C.M., 1963. Post-Palaeozoic Ostracoda, their Morphology, Taxonomy, and Economic Use. Volume 2, Generic descriptions. Elsevier Publishing Company, Amsterdam/London/New York, 478 pp.

van Morkhoven, F.P.C.M., Berggren, W.A. and Edwards, A.S., 1986. Cenozoic cosmopolitan deep-water benthic foraminifera. Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine, Mem., 11, 1-412.

Vrabec, M., Pavlovcic Preseren, P. and Stopar, B., 2006. GPS study (1996–2002) of active deformation along the Periadriatic fault system in northeastern Slovenia: tectonic model. Geologica Carpathica, 57, 57-65.

Weinfurter, E., 1952. Otolithen aus miozänen Brack- und Süßwasserschichten des Lavanttales in Kärnten. Sitzungsberichte der Österreichischen Akademie der Wissenschaften, Mathematisch-naturwissenschaftliche Klasse, I/161, 141-148.

Witt, W., 1998. Die miozäne Fossil-Lagerstätte Sandelzhausen 14. Ostracoden. Mitteilungen der Bayerischen Staatssammlung für Paläontologie und historische Geologie, 38, 135-165.

Witt, W., 2000. Süßwasserostracoden der miozänen Vorlandmolasse Süddeutschlands. Mitteilungen der Bayerischen Staatssammlung für Paläontologie und historische Geologie, 40, 109-151.

Žnidarcic, M. and Mioc, P., 1987. Osnovna geološka karta SFRJ 1:100.000, List Maribor in Leibnitz (Basic Geological Map of SFRJ 1:100.000, Sheet Maribor and Leibnitz). Zvezni geološki zavod, Beograd.

Zorn, I., 2004. Ostracoda from the Lower Badenian (Middle Miocene) Grund Formation (Molasse Basin, Lower Austria). Geologica Carpatica, 55/2, 179-189.

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APPENDIX: ECOLOGY AND PALEOECOLOGY OF SELECTED TAXA

Ammonia viennensis (*Ammonia beccarii* group): Infauna, inner shelf (Murray, 1991, 2006), most abundant between 0-50 m, wide tolerance to salinity fluctuations (brackish to hyperhaline) in river inlets and lagoons.

Asterigerinata planorbis: Epifauna, epiphytic – prefer algal covered bottom, 0-100 m, normal marine to increased salinity (Murray, 1991, 2006; Van der Zwan, 1982).

Bolivina species: Mainly infauna, rarely epifauna, inner shelf to bathyal (Murray, 1991, 2006), some species tolerant to high oxygen depletion (Murray, 2006), dysoxic (Kaiho, 1994).

Bolivina dilatata: inner shelf to bathyal, abundant between 50-200 m water depth (Murray, 1971; Van der Zwan, 1982 cum lit.), tolerant for oxygen depletion, maximum abundance coincides with maximum concentration of organic matter (Murray, 1991; Van der Zwan, 1982).

Bulimina striata: Infauna, outer shelf to bathyal (Murray, 1991), from 30 m to 800 m (Jones, Brady B. H. and Natural History Museum, 1994), suboxic (Kaiho, 1994), oxygen-depleted and organic matter rich ecospaces (Van der Zwan, 1982; Murray, 1991).

Bulimina elongata: Infauna, inner to outer shelf (Murray, 1991), abundant above 100 m in river mouths (Murray, 1971), high organic matter flux, low oxygen ecospaces (Van der Zwan, 1982), associated with laminated sediments (Van der Zwan, 1982; cum lit.).

Bulimina subulata: Infauna, inner shelf to bathyal (Murray, 1991; 2006), tolerant to high oxygen depletion, associated with laminated sediments (Van der Zwan, 1982; cum lit.).

Elphidium spp., keeled: Epifauna, 0-50 m (Murray, 1991, 2006), wide tolerance to salinity fluctuations (brackish to hyperhaline), oxic, preference to coarser-grained sediments.

Fursenkoina acuta: Infauna, inner shelf to upper bathyal (Murray, 1991, 2006), prefer 0-100 m, great survivor and opportunist in perturbative environments (Murray, 2001), tolerate salinity fluctuation 30-35 ‰ (Murray, 1991), tolerate oxygen level down to anoxia and excess of organic matter flux.

Melonis species: Infauna, shelf to bathyal (Murray, 1991, 2006), some species tolerate dysoxia (Murray, 2006), suboxic (Kaiho, 1994).

Melonis pompilioides: outer shelf to middle bathyal (van Morkhoven et al., 1986), preference to higher organic mater flux (Loubere and Fariduddin, 1999).

Nonion commune: Infauna to epifauna, 0-100 m (Murray, 1991), tolerate salinity fluctuation 30-35 ‰, suboxic (Kaiho, 1994).

Oridorsalis umbonatus: Epifauna, outer shelf to lower bathyal (>100 m water depth) (Murray, 1991), 50-1000 m (Jones, Brady B. H. and Natural History Museum, 1994), without tolerance to oxygen deficience (Van der Zwaan, 1982), suboxic (Kaiho, 1994), preference to low organic matter content (Murray, 2006).

Spirorutilus carinatus: Infauna (Scherbacher et al., 2001; cum. lit.), middle shelf to bathyal (Murray, 1991), slight increase of organic matter flux and seasonally slightly oxygen-depleted bottom waters (Scherbacher et al., 2001).

Uvigerina species: Mainly shallow infauna rarely epifauna, shelf to abyssal (Murray, 2006), suboxic (Kaiho, 1994), prefer high organic matter flux (Murray, 1991).