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The Lower - Middle Miocene transition (Karpatian – Badenian) in the Krems Embayment (Central Paratethys, Lower Austria): a multistratigraphic approach and the role of the Diendorf-Boskovice Fault System.

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Abstract

The Krems Embayment contains the westernmost fully marine depositional environments of the Karpatian and Badenian transgressions in the Central Paratethys. Four drill cores were investigated to analyse the bio- and lithostratigraphic, and tectonic relations. The investigated core sections cover the Karpatian Laa Formation (bio-zones M4, NN4) and the Badenian Gaindorf Formation (M5b-M6, NN4-NN5). Important biostratigraphic indicators identified are *Praeorbulina glomerosa glomerosa, Praeorbulina glomerosa circularis* and *Orbulina suturalis* for the Gaindorf Formation. The Laa Formation is indicated by the absence of *Praeorbulina*, *Orbulina* and *Globigerina falconensis*, low numbers of *Globorotalia bykovae*, and a prominent peak in *Helicosphaera ampliaperta* abundance at the end of the Karpatian. *Cibicidoides lopjanicus* and *Cassigerinella* spp. occur with high percentages in Badenian samples and show much longer stratigraphic ranges than known from literature data. The depositional gap at the Karpatian-Badenian boundary has a minimum duration of 0.41 My in the Krems Embayment. The combination of bio- and lithostratigraphic data allows the correlation across major faults. The Diendorf-Boskovice Fault System played an important role during basin formation and was identified as very active during the early to middle Badenian Stage. The results of this study show the complex interaction of sedimentation, tectonic activity and paleobiological developments in this peripheral part of a marginal sea.

1. Introduction

The study area in Lower Austria in the vicinity of Krems an der Donau (Fig. 1), is a peripheral northern part of the Alpine-Carpathian Foredeep, adjacent to the southeastern margin of the Bohemian Massif. The prominent NE-SW trending Diendorf-Boskovice Fault System extends from Diendorf in Lower Austria to the Boskovice trench in Moravia (Roštínský et al., 2013) and roughly divides the crystalline rocks of the Bohemian Massif from the Cenozoic sediments of the foreland basin. Along the well known southwestern segment of the Diendorf Fault, left-lateral displacement of Moldanubian granulite, paragneiss and granite gneiss reaches between 25 km and 40 km (e.g., Figdor and Scheidegger, 1977; Lenhardt et al., 2007). The offset was generated from Upper Carboniferous/Permian onward, with reactivations in Mesozoic and Cenozoic times. This is documented by sedimentary infill of tectonic basins and grabens along the Diendorf-Boskovice Fault System and related subparallel or conjugate fault systems in the Bohemian Massif (e.g., Fuchs and Matura, 1976; Stackebrandt and Franzke, 1989; Brandmayr et al., 1995; Decker and Peresson, 1996; Nehyba et al., 2012 and references therein). On the southeastern margin of the Bohemian Massif, the subparallel faults of the Diendorf-Boskovice Fault System (e.g., Diendorf Fault, Sitzendorf Fault, Falkenberg Fault) are often linked by approximately N-S trending secondary faults, as interpreted in the study area for instance by Schnabel et al. (2002).

The Badenian Stage is the last stage in the Central Paratethys with a fully marine development even at its western limit: the Krems Embayment (e.g., Rögl, 1998; de Leeuw et al., 2010; Kováč et al., 2017a, b). It is furthermore the last period that shows significant connections between the Mediterranean and the Paratethys (Kováč et al., 2017a, b). During the preceding Karpatian Stage, fully marine depositional environments developed in this area and a distinct sea level lowstand at the Karpatian-Badenian transition was reported by many authors, e.g., Kováč et al. (2018a) or Hohenegger et al. (2014). This lowstand may be correlated to a major tectonic phase during the early Badenian (Kováč et al., 2018b). The highest probability to encounter a complete sedimentary succession across the Karpatian-Badenian boundary is in the deepest part of the basin. Therefore we have chosen four available drill cores that presumably cover depositional environments from near-coast to local deep waters (Fig. 1).

The definition of the base of the Badenian Stage in the Central Paratethys is still under discussion. Traditionally, the beginning of the Badenian Stage was set more or less equal to the (also controversial) beginning of the Langhian Stage (Fig. 2, 15.97 Ma, Raffi et al., 2020). Papp and Cicha (1978) define the base of the Badenian with the appearance of the planktic foraminifera genus *Praeorbulina*. This corresponds to the base of Zone M5a (first appearance of *Praeorbulina sicana* at 16.39 Ma, Wade et al., 2011). In a revision of the timing of the Badenian Stage, Hohenegger et al. (2014) placed the Karpatian-Badenian boundary at the top of the paleomagnetic chron C5Cn.2n (16.303 Ma). This is near the base of *P. sicana* and correlates well with a paleoenvironmental change caused by a significant Alpine tectonic event (Styrian Tectonic Phase). Furthermore, *P. sicana* occurs only sporadically in the sediments. However, the datum at 15.97 Ma is widely accepted since several publications rely on this date (e.g., Harzhauser et al., 2020; Kranner et al., 2021a, b; Piller et al., 2022). Figure 2 shows stratigraphical events relevant for the topic dealt within this contribution together with the formations found. Unfortunately, no complete sedimentary succession from the Karpatian to the Badenian Stage in the western Central Paratethys in surface outcrops is known until now (e.g., Rögl et al., 2002; Hohenegger et al., 2014). The Karpatian-Badenian boundaries were identified as erosional discontinuities, e.g., at Wagna and Retznei in the Styrian Basin (e.g., Hohenegger et al., 2009). Reported drill cores may reveal a more continuous record, but still show significant gaps (Ćorić and Rögl, 2004; Hohenegger et al., 2009). In particular, the basal Badenian planktic foraminiferal Zone M5a has not been verified. Nevertheless, drill cores provide a much higher chance to trace this interval.

Marginal marine basins such as the Central Paratethys are characterized by small scale lateral facies changes and frequent shallow water environments that inhibit the full development of suitable habitats for planktic deep-water species (see e.g., Harzhauser and Piller, 2007; de Leeuw et al., 2010; Kováč et al., 2017a, b; Báldi et al.,

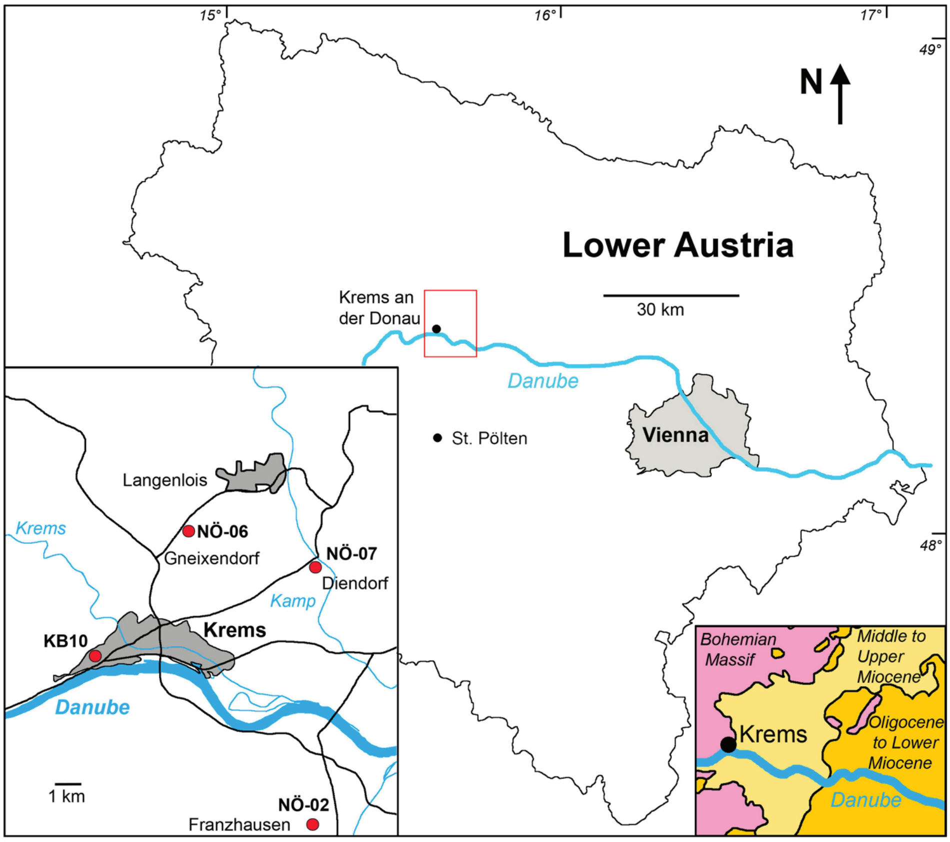

Figure 1: Position of the working area around Krems within Lower Austria. Lower left insert: exact position of the investigated drill cores KB10 (Landesgalerie Krems), NÖ-02 (Franzhausen), NÖ-06 (Gneixendorf), and NÖ-07 (Diendorf am Kamp). Lower right insert: simplified geology around the Krems Embayment.

2017). The stratigraphic ranges of the species often differ from those in the open ocean at least to some extent. Frequent changes of the tectono-sedimentary settings led to incomplete occurrences of index species or even lineages, e.g., by narrow corridors as connection to major seas or oceans (e.g., from Central Paratethys to Mediterranean, Ivančič et al., 2018). Furthermore, endemic species may occupy the ecologic niches of those from the open ocean. We therefore test in this contribution the validity of regional stratigraphic ranges (e.g., Cicha et al., 1998) and the applicability of regional index species.

We investigated four core sections that contain sediments from various formations. The 23 m long core KB10 contains sands or sandstones, siltstones and marls of Karpatian to Badenian age (Laa Formation, Gaindorf Formation) and is covered by Pleistocene gravel. The 316.4 m long core NÖ-02 yielded clayey, silty and sandy marls and sandlayers of Karpatian and possibly late Ottnangian age (Laa Formation and likely Traisen Formation) below Pleistocene gravels. We focussed on the interval between 15 am 93.3 m. Below this level, clayey silt of Egerian age (Linz-Melk Formation) and clayey, silty sand, marls as well as fine and coarse grained sand layers of middle Oligocene age (Pielach formation) were recorded in an unpublished report by Rögl, Roetzel and Rupp. The 163.55 m long core NÖ-06 consists of, from top to bottom, Pleistocene gravel and marls, Sarmatian silty marls, sand and gravel layers with plant debris and mollusks (Ziersdorf Formation), Badenian marls with sand and gravel layers (Gaindorf Formation) and possible late Ottnangian Traisen Formation above the crystalline basement (gneiss). In the 343 m long core NÖ-07, Badenian clayey marls with sand layers (Gaindorf Formation occur below Pleistocene sand and gravel. Badenian conglomerates (Hollenburg-Karlstetten Formation) and fossil-free silts and sands with coal seams (?Traisen Formation, Linz-Melk formation) follow until the end of the core. A further publication on a drill core from the area of investigation had its focus on Ottnangian strata (NÖ-03 Schaubing, Palzer-Khomenko, 2018). The investigated area is cross-cut by major and minor normal faults and strike-slip faults, in particular related to the Diendorf-Boskovice Fault System.

The increased knowledge on paleoenvironmental changes of paleosalinity or water depths, even to the scale of obliquity cycles, has been shown in recent times for the adjacent Korneuburg and Vienna Basins (e.g., Schenk et al., 2018; Kranner et al., 2021). This contribution shall provide the stratigraphic base for such investigations in the Alpine-Carpathian Foredeep.

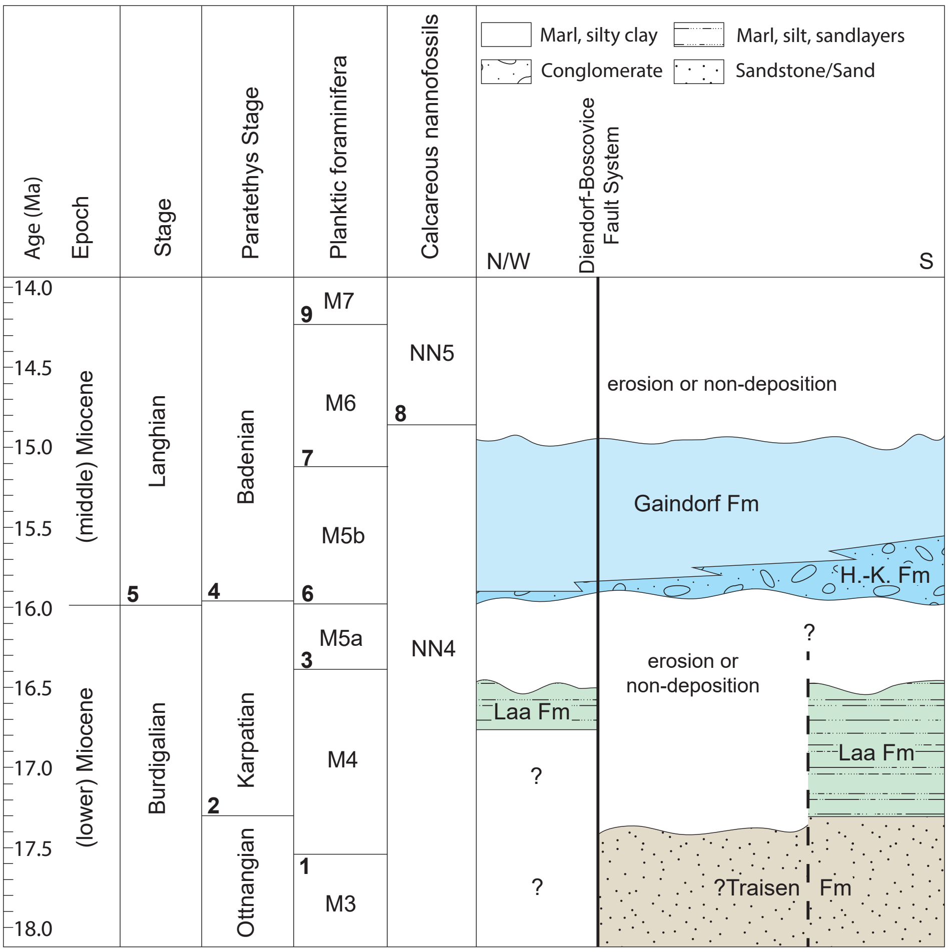

Figure 2: Biostratigraphic and chronostratigraphic events across the lower – middle Miocene boundary according to Wade et al. (2011), Hohenegger et al. (2014), Raffi et al. (2020) and simplified lithostratigraphic chart. 1: LAD (last appearance datum) *Catapsydrax dissimilis* 17.54 Ma (top of planktic foraminiferal zone M3), 2: Base of Karpatian Stage 17.30 Ma, 3: FAD (first appearance datum) *Praeorbulina sicana* 16.39 Ma, (base M5a), 4: Base of Badenian Stage 15.97 Ma (Raffi et al., 2020), 5: Base of Langhian Stage 15.99 Ma, 6: FAD *Praeorbulina glomerosa circularis* 15.98 Ma (base M5b), 7: FAD Orbulina suturalis 15.12 Ma (base M6), 8: LAD *Helicosphaera ampliaperta* 14.86 Ma (top of calcareous nannofossil zone NN4), 9: FAD *Fohsella peripheroacuta* 14.23 Ma (base M7). H.-K. Fm = Hollenburg-Karlstetten Formation.

2. Material and Methods

The four drill cores KB10 (Landesgalerie Krems), NÖ-02 (Franzhausen), NÖ-06 (Gneixendorf), and NÖ-07 (Diendorf am Kamp) were sampled to investigate their microfossil content (Fig. 1). KB10 reached 23 m core depth and was drilled by 3P Geotechnik in 2016 at the construction site for the new State Art Gallery in Krems (Posch-Trözmüller et al., 2018). This core was sampled completely except for the Holocene and Pleistocene cover (39 samples, 4 to 23 m core depth). Cores NÖ-02, NÖ-06, and NÖ-07 were drilled by Graz-Köflacher Eisenbahn und Bergbaugesellschaft for lignite prospection in 1985 and 1987 and were sampled only for their Karpatian (late Early Miocene) to Badenian (early Middle Miocene) intervals. This is 15 to 95 m for NÖ-02 (39 samples), 73 to 125 m for NÖ-06 (47 samples), and 33 to 260 m for NÖ-07 (47 samples) respectively. All investigated core sections are covered by Pleistocene and Holocene clays, sands, and gravels. In NÖ-06, about 40 m of lower Sarmatian sediments (pers. comm. Fred Rögl) were cored between the Badenian and Pleistocene strata. Marly samples were selected in equal intervals wherever possible, pure sands and sandstones were avoided. Sample intervals were ca. 0.5 m in KB10, ca. 2 m in NÖ-02, ca. 1.3 m in NÖ-06, and ca.4.8 m in NÖ-07. All drill cores are stored at the core repository of GeoSphere Austria.

Core	Longitude	Latitude
KB10	15°35’16.3’’	48°24’16.2’’
NÖ-02	15°42’43.1’’	48°20’37.3’’
NÖ-06	15°38’23.5’’	48°27’01.6’’
NÖ-07	15°43’10.5’’	48°26’34.9’’

Table 1: Co-ordinates of the drill cores investigated.

From the KB10 samples, 200 g of sediment were disintegrated completely with hydrogen peroxide and washed over a 0.063 mm sieve. The residues were dried and sieved into 0.125 and 0.063 mm-fractions to access species distribution in individual size fractions. These fractions were split into manageable subsamples (aliquots) and completely picked for foraminifera. From the NÖ-02, -06, and -07 samples, about 150 g were soaked with pure water for several days and afterwards washed over a 0.063 mm mesh sieve. The residue of each sample was weighted again to gain the amount of lost silt and clay for sedimentological interpretation. Each sample was split into manageable aliquots and foraminifera were picked completely. All picked foraminifera were mounted on microslides and classified to species level wherever possible. In order to identify the rare but age-indicative *Praeorbulina* and *Orbulina* specimens, we scanned the complete >0.250 mm fractions of all samples for these taxa.

Smear slides for investigations on calcareous nannoplankton were prepared from all samples according to the standard procedure explained in Perch-Nielsen (1985). All samples were examined under light microscope with 1000x magnification. Quantitative data were obtained by counting about 300 specimens wherever possible.

Microslides for foraminifera and calcareous nannoplankton are stored in the micropaleontology collection of the GeoSphere Austria (collection numbers GSA2022/001/0001 ff.). All micropaleontological and sedimentological data including detailed descriptions of the investigated cores can be found in the Tethys Research Data Repository of the GeoSphere Austria (https://www.tethys.at/) under https://doi.org/10.24341/tethys.194 to https://doi.org/10.24341/tethys.209.

3. Results, concepts for biostratigraphy and lithostratigraphy

The problem of incomplete records of species or lineages in the Central Paratethys is particularly evident for the *Trilobatus* - *Orbulina* lineage (e.g., Rögl et al., 2002) and thus also at the western end of that sea (this contribution). Figure 2 shows the stratigraphic sub-division with zonations for planktic foraminifera and calcareous nannofossils for the time interval investigated in this contribution. However, only the first appearance datum (FAD) of *Praeorbulina glomerosa circularis* and *Orbulina suturalis* and the last appearance datum (LAD) or abundance peaks of *Helicosphaera ampliaperta* delivered useful results due to the absence of other index species. We therefore apply a combination of all available index species from various taxonomic groups and include additional sedimentological information in order to obtain the most reliable stratigraphic dataset in this problematic setting.

3.1 Planktic foraminifera

Planktic foraminifera, together with calcareous nannofossils, form the base for the biostratigraphic subdivision in most marine basins. The zonations published in e.g., Kennett and Srinivasan (1983), Bolli and Saunders (1985), Wade et al. (2011) or Raffi et al. (2020) are widely accepted for Neogene open marine (paleo-) environments. But also for marginal seas, such zonations or range charts are available for e.g., the Paratethys Sea (Rögl, 1985 or Cicha et al., 1998). Based on the occurring species and their frequencies, the first and last occurrences (FOD, First Occurrence Datum; LOD Last Occurrence Datum) of *Praeorbulina glomerosa glomerosa* (Fig. 3.5), *Praeorbulina glomerosa circularis* (Fig. 3.6), *Orbulina suturalis* (Fig.3.7), *Globigerina falconensis* (Figs. 3.1, 2), *Globorotalia bykovae* (Figs. 3.3, 4), and *Cassigerinella* spp. (particularly *C. spinata*, Figs. 3.10, 11) are suitable to detect the Karpatian - Badenian stage boundary or even planktic foraminiferal zones. Occurrences of *Globigerinita uvula* (Figs. 3.8, 9) indicate Karpatian or younger sediments (Cicha et al., 1998). Figure 4 shows the stratigraphic ranges in the Central Paratethys

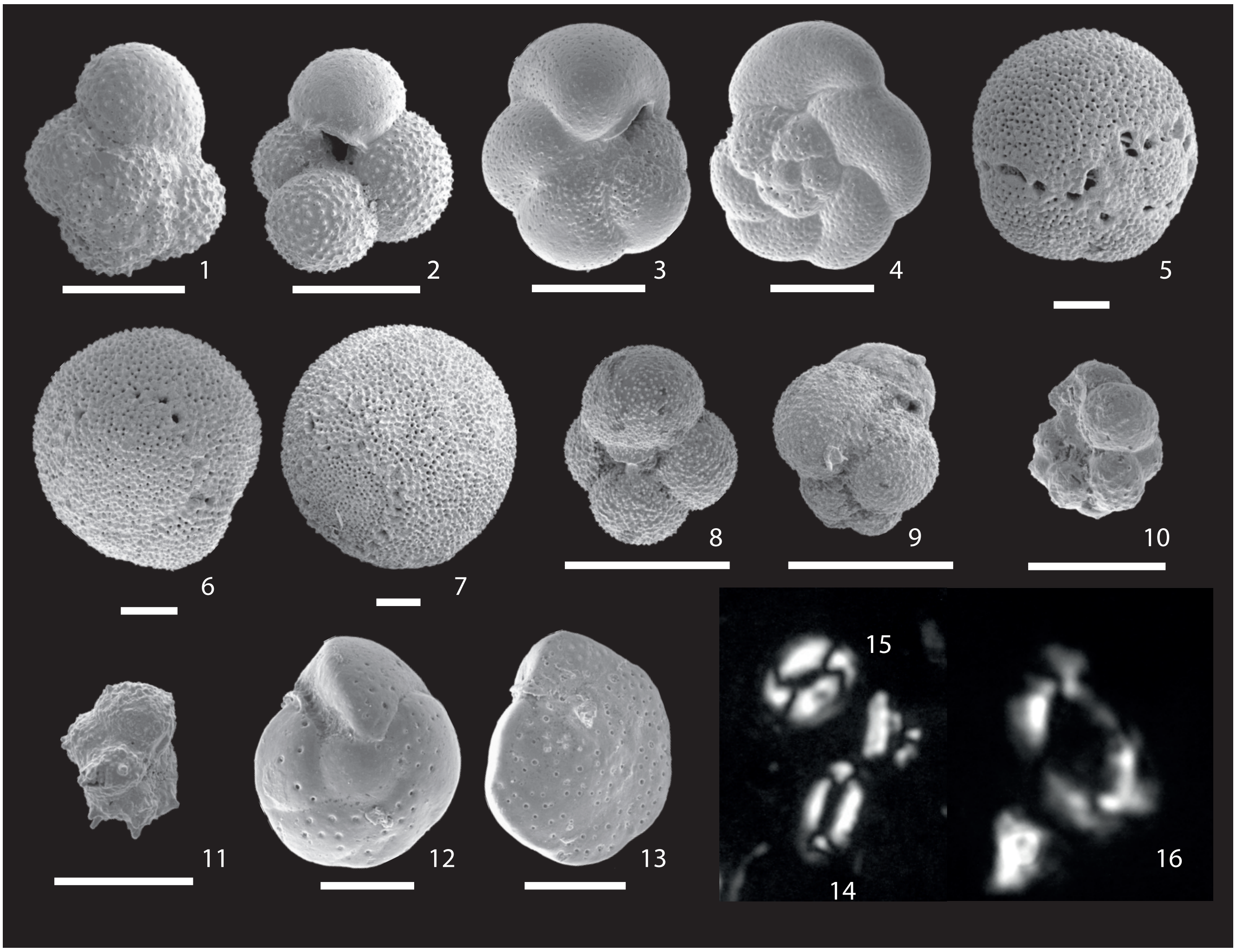

Figure 3: SEM-Micrographs and smear slide photographs of planktic and benthic foraminifera and calcareous nannofossil index species applied in this contribution. Length of scale bars of foraminifera 0.1 mm. Calcareous nannofossils with crossed nicols. 1: *Globigerina falconensis*, spiral view, sample KB10 7.0 m. 2: *Globigerina falconensis*, umbilical view, sample KB10 4.5 m. 3: *Globorotalia bykovae*, umbilical view, sample KB10 6.0 m. 4: *Globorotalia bykovae*, spiral view, sample KB10 6.0 m. 5: *Praeorbulina glomerosa glomerosa*, sample KB10 18.7 m. 6: *Praeorbulina glomerosa circularis*, sample KB10 19.0 m. 7: *Orbulina suturalis,* sample KB10 7.5 m. 8: *Globigerinita uvula,* umbilical view, sample NÖ-06-09. 9: *Globigerinita uvula*, lateral view, sample NÖ-06-09. 10: *Cassigerinella globulosa*, sample NÖ-06-09, 11: *Cassigerinella spinata*, sample NÖ-07-17. 12: *Cibicidoides lopjanicus*, umbilical view, sample NÖ-06-26. 13: *Cibicidoides lopjanicus*, spiral view, sample NÖ-06-11. 14, 16: *Helicosphaera ampliaperta*, sample KB10 20.0 m. 15*: Coccolithus pelagicus*, sample KB10 20.0 m.

according to Cicha et al. (1998), Rögl et al. (2002) and Raffi et al. (2020).

The *Trilobatus* - *Orbulina* lineage is, although neither frequent nor present in many samples, still the most important source of information for the correlation of the sections. Particular in the KB10 Borehole (Fig. 5,. S5), were the *Praeorbulina* and *Orbulina* species show the highest amounts of individuals, we were able to identify three planktic foraminifera zones. The complete absence of the genera *Praeorbulina* and *Orbulina* indicates a Karpatian age (planktic foraminiferal zone M4, Berggren et al., 1995). Presence of *Praeorbulina glomerosa glomerosa* and/or *Praeorbulina glomerosa circularis* (Figs. 3.5, 6) but absence of *Orbulina* indicates lower Badenian (M5b) ages. Presence of *Orbulina suturalis* (Fig. 3.7) and co-occurrence of *Praeorbulina* indicates a middle Badenian (M6) age. These results show that planktic foraminiferal zone M5a (only presence of *Praeorbulina sicana* and *P. glomerosa curva*) is missing and a distinct sedimentation gap of at least 0.41 Ma exists (with end of M4 at 16.39 Ma and beginning of M5b at 15.98 Ma, Wade et al., 2011; Raffi et al., 2020). This gap might cover a much wider interval since the exact amount of missing M4- and M5b-sediments is not known. In drill core NÖ-06, *Praeorbulina glomerosa glomerosa* and *Praeorbulina glomerosa circularis* were found in 11 samples at the middle and upper parts of the investigated section (Rögl and Spezzaferri, 2003 and this contribution, Fig. 6). *Orbulina suturalis* was found in two samples above 98 m core depth. In core NÖ-07, *Praeorbulina* spp. were found right above the conglomeratic layer at 237.5 m and up-section, *Orbulina suturalis* at 228.5 m and above (Fig. 7). This confirms earlier remarks on this

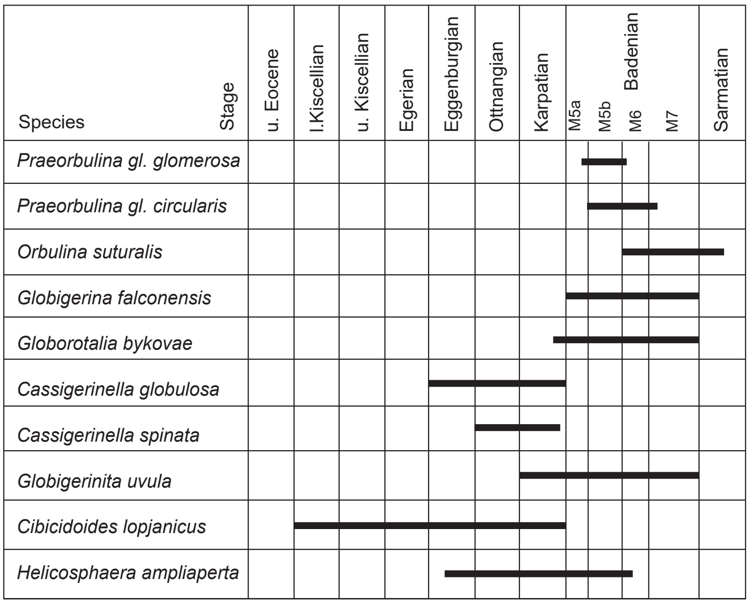

Figure 4: Chronostratigraphic ranges of foraminiferal and calcareous nannofossil index species in the Central Paratethys applied in this contribution (based on Cicha et al., 1998; Rögl et al., 2002; Raffi et al., 2020). Subdivision of the Badenian Stage according to Berggren et al. (1995, M-Zones).

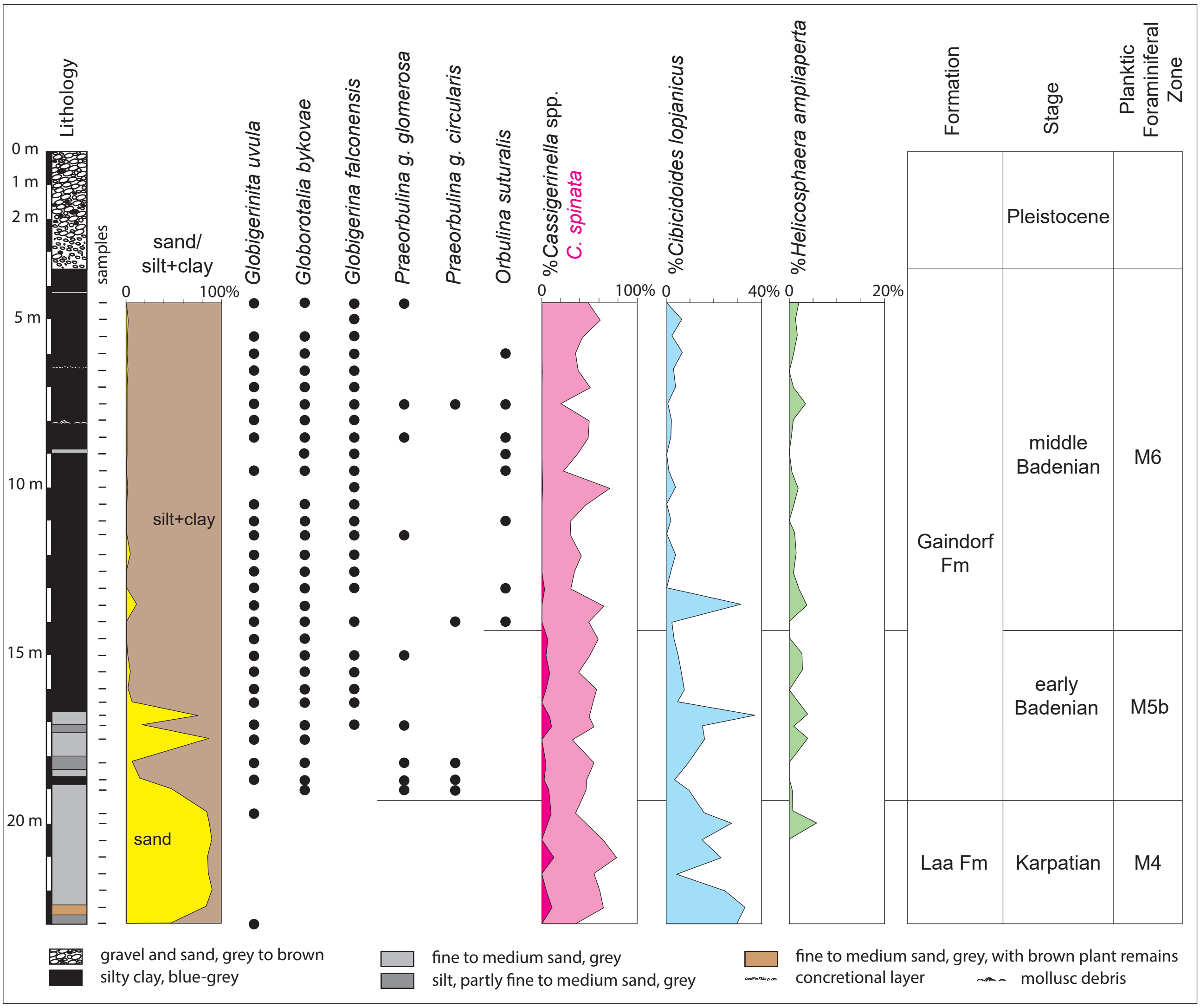

Figure 5: Core KB10: Lithology, presence or frequency of foraminiferal and calcareous nannofossil index species, and allocated formations and stages. Sand/silt and clay-ratio from washed samples only. Percentages of *Cassigerinella spp.* and *Cibicidoides lopjanicus* is among planktic foraminifera or benthic foraminifera only. Percentage of *Helicosphaera ampliaperta* without reworked Cretaceous or Paleogene nannofossils. In addition to the specimen analysed from the residue splits, *Praeorbulina glomerosa glomerosa* was found in samples 7.5 m, 17.1 m, and 18.2 to 19.0 m, as well as *Praeorbulina glomerosa* circularis in samples 18.2 and 19.0 m. Planktic foraminiferal zones according to Berggren et al. (1995)

core (Spiegler and Rögl, 1992; Spezzaferri and Rögl, 2004) and indicates a Badenian (early but not basal Badenian or younger) age for these parts of the sections. No *Praeorbulina* or *Orbulina* species were found in drill core NÖ-02 (Fig. 8).

Like several other species, *Globigerina falconensis* has its FAD before the base of the Badenian Stage or Middle Miocene (Kennett and Srinivasan, 1983). In the Central Paratethys however, it starts at the base of the Badenian (Cicha et al., 1998). In the KB10 core, its first record is in sample 17.1 m (Fig. 5). This species is rare in the KB10 drill core and we did not find specimens in the NÖ-core samples (Figs. 7, 8).

Globorotalia bykovae is an endemic species in the Paratethys and has its FAD in the upper part of the Karpatian, but remains rare until the Badenian (Cicha et al., 1998). This species occurs nearly continuously in the samples with *Praeorbulina* spp. or *Orbulina suturalis* of the KB10 core (Fig. 5) and is rather frequent in most samples of NÖ-06 (Fig. 6). In NÖ-07, it does not occur in many samples but with much higher numbers in the upper part (Fig. 7; max. 68 specimens at 35.5 m) compared to the lower part (max. 12 specimens at 237.5 m). It occurs only sporadically with one or two specimens per sample in the upper part of NÖ-02 (Fig. 8).

The percentages of the rather frequent *Cassigerinella* spp. (*C. globulosa*, Fig. 3.10) and unidentified *C. boudecensis*) in KB10 is shown in Figure 5. *Cassigerinella spinata* (red curve within *Cassigerinella* spp. in Fig 5.) occurs with much higher percentages in samples from below the FOD of *Praeorbulina* spp. (average 10%) than in samples with *Praeorbulina* spp. (av. 6%), and only sporadically with very low percentages (av. 1%) in samples with *Orbulina suturalis*. *Cassigerinella* spp. occur throughout the KB10 core with high percentages (around 50%). In the NÖ-cores, *C. spinata* has been found only in a few samples with very low numbers. However, the related *C. globulosa* occurs in almost all samples of the three investigated NÖ-cores, partly with very high numbers and dominating the assemblages (max. 90.7%, Figs. 6–8). The absolute stratigraphic ranges of all *Cassigerinella* species in the investigated cores are apparently longer than indicated in Cicha et al. (1998, see Fig. 4). The genus is distinctly less frequent in samples from the upper parts of the cores KB10, NÖ-06 and NÖ-07 (Figs. 5–7). It is the most frequent species in the entire core NÖ-02 (Fig. 8).

Globigerinita uvula has its general FAD in the Late Oligocene (Kennett and Srinivasan, 1983) but appears not before the Karpatian in the Central Paratethys (Cicha et al., 1998, Fig. 4). This species may therefore indicate a Karpatian or younger age if other index species do not occur (particularly Figs. 6–8). *Globigerinita uvula* occurs with relatively low to moderate numbers (max. 89 specimens per sample) in nearly all Badenian samples of KB10 and NÖ-06, about 3/5 of the Badenian samples of NÖ-07, but is less frequent in NÖ-02 (about 1/4 of the samples).

3.2 Benthic foraminifera

Among benthic foraminifera, only *Cibicidoides lopjanicus* (Figs. 3.12, 13) is of biostratigraphic relevance (Fig. 4). Other frequently used index species, such as from the genera *Uvigerina* or *Pappina* (e.g., Grill, 1941; Cicha et al., 1998) occur only sporadically or are even absent in long intervals of the investigated cores. In the Krems Embayment, the range of *C. lopjanicus* is wider than indicated in Cicha et al. (1998, Fig. 4) and the species occurs also in samples that contain *Praeorbulina* spp. and *Orbulina suturalis*. Its frequencies in those samples are, however, very reduced (see Figs. 5–8). For example, in KB10 its average content is 21.5% in samples from 19.7 to 23.0 m core depth (Karpatian, M4), 10.5% in 14.5 to 19.0 m core depth (lower Badenian, M5b), and 3.6% in 4.5 to 14.0 m core depth (middle Badenian, M6). In the more distal NÖ-cores, its average content corresponding to the intervals with *Praeorbulina* or *Orbulina* is 1.4% in NÖ-06 or 2.4% in NÖ-07. The average proportion is 6.2% in NÖ-02 (with 42.9% max.).

3.3 Calcareous nannoplankton

The found calcareous nannoplankton assemblages are dominated by *Coccolithus pelagicus* (Fig. 3.15, around 50%) in all cores investigated. The assemblages did not contain index species that would allow a distinction of Karpatian and Badenian strata. All investigated samples belong to the long NN4 Zone (Martini, 1971; Raffi et al., 2020) and yielded *Helicosphaera ampliaperta* (Fig. 3.14). However, Fornaciari and Rio (1996), Fornaciari et al. (1996) or Ćorić and Rögl (2004) reported a characteristic peak in relative abundance of *H. ampliaperta* in the Mediterranean and the Central Paratethys at the end of the Karpatian Stage (calcareous nannofossil Zones NN4a) or shortly before the Early/Middle Miocene boundary. We found such a peak in the core sections at 20,0 m in KB10 and at 23–28 m in NÖ-02 (see Figs. 5, 8). In NÖ-06, a first relative peak near 100 m core depth is already within the interval with *Praeorbulina* and therefore too young for correlation with the other specific peaks.

3.4 Sand layers and *Cibicidoides lopjanicus*

Due to the relatively short distances between the drill cores (several km), the stratigraphic sections may be correlated by sand-rich sedimentation events within the predominantly marly and clayey-silty successions (see Figs. 5–8). Because we sampled preferably fine-grained sediments, quantitative data are not continuously available. Here, high sand contents in the samples and additional unsampled sand layers were correlated (Fig. 9). Primary source of information for the age of the strata are the index fossils mentioned above (particularly the M5b/M6-boundary) but also quantitative data of *Cibicidoides lopjanicus* (%-peaks) were used to ensure correlation with the highest probability. In and below the intervals with *Praeorbulina* spp. and *Orbulina suturalis*, we found

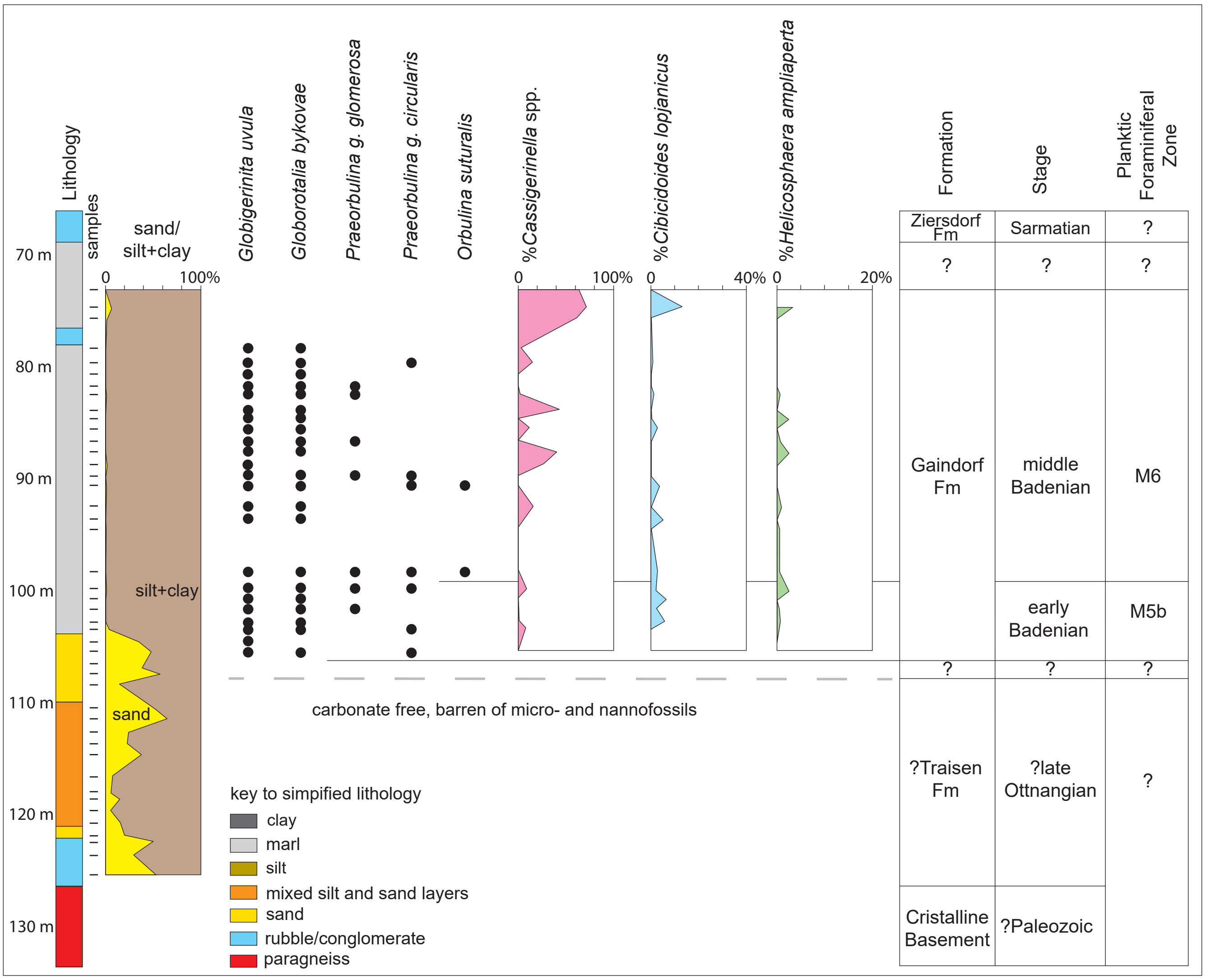

Figure 6: Core NÖ-06: Simplified lithology, presence or frequency of foraminiferal and calcareous nannofossil index species, and allocated formations and stages. Sand/silt and clay-ratio from washed samples only. *Praeorbulina g. circularis* and *Globorotalia bykovae* at 104.8 m from Rögl and Spezzaferri (2003). Percentages of *Cassigerinella* spp. and *Cibicidoides lopjanicus* is among planktic foraminifera or benthic foraminifera only. Percentage *of Helicosphaera ampliaperta* without reworked Cretaceous or Paleogene nannofossils. Above 69 m core depth, coarse sands with rubble and minor fine sand, silt and marl layers are not shown and are interpreted as lower Sarmatian sediments and Pleistocene river terraces.

a thick stack of sandy layers at the base of the KB10 core and a thin but distinct not-sampled layer at 9.9 m (Fig. 5). Also in NÖ-06, two sand or rubble layers were found in this interval, a thin one around 75 m core depth and a thick one below 105 m. In NÖ-07 with its much greater thickness, additional sand layers occur above the planktic foraminifera based M5b/M6-boundary in the otherwise marl dominated succession (Fig. 9). The correlation of the coarse grained layers of cores KB10, NÖ-06 und NÖ-07 is strongly supported in each case by four (I to IV in Fig. 9) peaks or small groups of peaks of *C. lopjanicus* percentage (paleoecologic signals) between and above the sand layers or stacks. One may even correlate two additional peak levels (IIa, IIIa) between cores NÖ-06 and NÖ-07. NÖ-02 differs from these three cores completely and shows constantly high sand contents down to 75 m core depth.

3.5 Drill core KB10

This core (total core length 23 m) has the highest number of investigated samples per meter core depth and therefore the potentially highest stratigraphic resolution (Fig. 5). It also covers a wide age range. Presence of *Globigerinita uvula* indicates a Karpatian or younger age for the lowermost sample. The first occurrence of *Praeorbulina g. circularis* shows a minimum age of 15.98 Ma for sample 19.0 m (FO of *Praeorbulina g. glomerosa* is before *P. g. circularis* (e.g., Wade et al., 2011; Fig. 4)) and indicates the base of Zone M5b in the section. The second zonal boundary is directly below sample 14.0 m. In this sample, the first occurrence of *Orbulina suturalis* indicates the base of Zone M6 (15.12 Ma; Raffi et al., 2020). *Praeorbulina* and *Orbulina* continue irregularly until the top of the section. We did not find a part of the section with *Praeorbulina g. glomerosa* only (*P. sicana* was not found in any of the four investigated sections), which would indicate the Zone M5a. Therefore, the resulting depositional gap covers a minimum of 0.41 My. The gap might cover a much longer period since there is only little information on its Karpatian parts. *Cassigerinella* spp. does not show any decrease in percentage of planktic foraminifera throughout the section, but *C. spinata* declines significantly in M6. *Cassigerinella* is assumed to become extinct within the Central Paratethys sea already at the end of the Karpatian Stage (Fig. 4, Cicha et al., 1998), but apparently not along its western shoreline. This is similar to the occurrence of the benthic foraminiferal species *Cibicidoides lopjanicus,* which is supposed to become extinct at the Karpatian-Badenian boundary, too (Fig. 4). However, this species continues in the Badenian samples but with significantly reduced percentages (Fig. 5). A small but distinct *Helicosphaera ampliaperta* peak at sample 20.0 m confirms the Karpatian age of this part of the section and points to a more or less complete end-Karpatian sedimentary succession. Thus, core KB10 constitutes of a Karpatian lower part (Laa Formation, planktic foraminiferal zone M4), an early Badenian middle portion (Gaindorf Formation, M5b), and a middle Badenian upper portion (Gaindorf Formation, M6; see Fig. 5).

3.6 Drill core NÖ-06

The 134 m long core penetrates the crystalline basement at a depth of 126.8 (Fig. 6). Below ca. 30 m Pleistocene gravel, sands and marls, about 40 m of lower Sarmatian sediments (Ziersdorf Formation; gravel, sands, marls, thin coal seams; pers. comm. Fred Rögl) were recorded. The first 17 m of sediments above the crystalline basement are carbonate free and barren of micro- and nannofossils and belong most likely to the Traisen Formation (conglomerates, sand, and mixed silt and sand layers; compare Gebhardt et al., 2013). However, due to the scarcity of information, older formations cannot be ruled out completely.

Some data on foraminifera were already published in Spiegler and Rögl (1992) and Spezzaferri and Rögl, (2004). Furthermore, at 104.8 m core depth, Rögl and Spezzaferri (2003) report the occurrence of *Praeorbulina g. circularis* (and of *Globorotalia bykovae*), indicating an early Badenian age (planktic foraminifera Zone M5b). The Badenian part (marls and sands) of the core contains *Globorotalia bykovae* regularly with relatively high numbers (up to 30 specimens per sample), except for the topmost three samples. We found further *Praeorbulina* specimens at several levels of the NÖ-06 core and *Orbulina suturalis* at 98.1 m (base M6) and 90.5 m core depth. *Cassigerinella* occurs with low percentages or is absent in samples from the lower and middle part but reaches high percentages above 70% in the topmost samples. We attribute this to an ecologic crisis since other planktic foraminiferal species became very rare or are absent (see below). *Cibicidoides lopjanicus* occurs with relatively low percentages but shows clear peaks. Core NÖ-06 constitutes of likely late Ottnangian Traisen Formation, a few meters thick calcareous interval without micro- and nannofossils and early to middle Badenian Gaindorf Formation (Fig. 6).

3.7 Drill core NÖ-07

The total length of the core is 347 m. We investigated samples from 33.5 to 259.5 m depth. Holocene and Pleistocene Sediments (clay, sand, gravel) were reported down to 32 m depths. Badenian gravel, sands and marls occur from 32 to 276 m. Below this depth, carbonate-free sands and clays occur (possibly Traisen Formation) and below 300 m well sorted medium sands (possibly Linz-Melk Formation) and sands, silts, clays and coal seams (possibly Pielach Formation) were reported. Some data on foraminifera were already published in Spezzaferri and Rögl (2004).

At 261 m core depth, the about 15 m thick conglomerates of the Hollenburg-Karlstetten Formation are overlain by *Globigerinita uvula*-bearing sediments (Fig. 7). A little up-section, at 237.5 m, the first occurrences of *Praeorbulina glomerosa glomerosa* and *Globorotalia bykovae* were recorded, indicating the M5b planktic foraminifera zone. The first *Orbulina suturalis* appear at 228.5 m and indicate the base of Zone M6. *Praeorbulina* and *Orbulina* occurs with very low numbers at several levels in the core. The amount of *Cassigerinella* spp. in the samples is variable and relatively high, but rarely above 50%. *Cibicidoides lopjanicus* occurs in most samples with low percentages but shows distinct peaks with up to 20%. *Helicosphaera ampliaperta* occurs only with low individual numbers and no relevant peaks. The Badenian Gaindorf Formation is characterized by higher peak numbers per sample of *G. bykovae* (max. 68). NÖ-07 shows late Ottnangian Traisen Formation at the base (below 276 m core depth) and 245 m of lower to middle Badenian Gaindorf and Hollenburg-Karlstetten Formations (Fig. 7). This core shows the thickest successions of Badenian deposits of all investigated cores.

3.8 Drill core NÖ-02

NÖ-02 has a total length of 316.4 m. We investigated the upper 93.5 m of this core only. Below this depth, partly microfossil bearing clayey silts, sands and marls of lower Miocene to middle Oligocene age (Egerian; Linz-Melk Formation, Pielach Formation) were reported. The investigated part of the core shows constantly high sand contents down to 76 m core depth (Fig. 8). The section from 93.5 to 76.0 m is carbonate-free and barren of micro- and nannofossils. This suggests, as for NÖ-07, late Ottnangian Traisen Formation. From 89 m up-section, rare micro- and nannofossils were found. Higher up, foraminifera are more frequent but are still much less abundant if compared with the other investigated drill cores. The samples contain *Globigerinita uvula*, pointing to an at least Karpatian age. Occasionally occurring *Globorotalia bykovae* are very rare. *Praeorbulina* or *Orbulina* were not found. *Cassigerinella* spp. occurs with high percentages (up to more than 90%) in almost all samples. The content of *Cibicidoides lopjanicus* among benthic foraminifera is highly variable but generally below 20%. It can increase to 40% in some samples from the upper part of the core. A significant increase in *Helicosphaera ampliaperta* at 32 m core depth is interpreted as the typical end-Karpatian peak occurrence of this species. We therefore assign all sediments between the Traisen Formation at the base and the Pleistocene gravel at the top to the Karpatian Laa Formation (Fig. 8).

4. Discussion

4.1 Correlation of cores

The chronostratigraphic subdivision of the investigated core sections is mainly based on the occurrence of index fossils (Fig. 10). These are *Praeorbulina glomerosa circularis, P. glomerosa glomerosa*, and *Orbulina suturalis* among planktic foraminifera, all of them indicative for the Badenian Stage. However, their presence is restricted to three of the four cores (KB10, NÖ-06, NÖ-07) and other concepts have to be applied. According to Cicha et al. (1998), *Cassigerinella* spp. and *Cibicidoides lopjanicus* do not occur in Badenian samples (Fig. 4). This is obviously not the case in the samples investigated here. These species occur with high abundances in many Badenian samples (Figs. 5–8). There is a general trend of lower numbers and percentages of *Cassigerinella* spp. (including and *C. spinata* if present, Fig. 5) as well as *C. lopjanicus* during the Badenian. However, our findings clearly disprove these species as indicators for the upper boundary of the Karpatian, at least in the Krems Embayment of Lower Austria.

On the other hand, the foraminiferal faunal composition of the Karpatian Laa Formation is distinctly different from the Badenian Gaindorf Formation. Higher contents of *Cassigerinella* spp., particularly in NÖ-02, indicate the Karpatian core sections. In addition to this, generally higher numbers and uninterrupted presence of *Globorotalia bykovae* points to the Badenian Stage. This distribution pattern is obviously of ecological origin, but can be used for the distinction of Laa and Gaindorf Formations. Similar to the prolonged occurrence of *Cassigerinella*, the range of *C. lopjanicus* extends long into the Badenian Stage, however with strongly decreased numbers and less continuous occurrences (e.g., Fig. 5). The last occurrences of both taxa in the western Central Paratethys are within the middle Badenian (this contribution). We did not find any reason to assume reworking such as extremely worn out or differently colored surfaces of the specimens found in clearly Badenian samples (presence of *Praeorbulina, Orbulina*).

The presence of *Globigerinita uvula* indicates an, at least, Karpatian age of the samples containing this species (Cicha et al. 1998). Thus, the lower boundary of the Laa Formation can be traced. The late Ottnangian Traisen Formation is generally barren of micro- and nannofossils. Its sediments are free of carbonate (Gebhardt et al., 2013) and are therefore easy to detect if compared with the calcareous marls or sands of the subsequent Laa and Gaindorf Formations.

Helicosphaera ampliaperta abundance peaks at the end of the Karpatian Stage (Figs. 5, 8) were used to identify this period and to confirm the age assignment achieved by other indicators. The characteristic peaks were found in cores KB10 and NÖ-02. In NÖ-06, sediments of this interval were not deposited, most likely due to tectonic reasons (see subchapter below). At the NÖ-07 drill site, the early Badenian Hollenburg-Karlstetten Conglomerate lies directly on late Ottnangian Traisen Formation.

Distinct sand layers (Fig. 9) can be correlated in the Badenian sections in cores KB10, NÖ-06, and NÖ-07. This correlation is supported by peaks of *C. lopjanicus* content and underlines the synchrony of sedimentation as well as paleoecological events in this relatively small basin. We assume that the debrites of the Hollenburg-Karlstetten Conglomerate may have passed by south of NÖ-07 during the Badenian and only the distal, sandy sediments were deposited in the area of KB10. Figure 10 summarises the bio- and lithostratigraphic results of the investigated cores and shows the correlation of the drilled sedimentary rocks.

4.2 Ecologic explanations for some exceptional distributions of foraminifera

Planktic, as well as benthic foraminifera are very rare at the top of drill core NÖ-06. Despite a minor increased sand content which may point to slightly increased sedimentation rates, there are no signs for reworking from older sediments. Although not frequent, small sized *Cassigerinella* dominated the planktic foraminiferal assemblages here. According to Spezzaferri et al. (2002), a strong decrease in salinity produces low diversity and dwarfed planktic assemblages. Based on stable isotope depth rankings, *Cassigerinella* is assumed to be an upper mixed layer dweller (Boersma and Shackleton, 1978) and therefore likely to be found in shallow water paleoenvironments. We therefore speculate that the strongly increased percentages of *Cassigerinella* spp. point to more stressful paleo-environments than before at this location, likely caused by decreased salinities or reduced paleo-water depth. *Cassigerinella* may play the role of a "disaster"-species in the planktic foraminiferal record of the Central Paratethys, similar to *Guembelitria* in the Cretaceous (e.g., Keller and Pardo, 2004).

Another interesting phenomenon is the trend of decreasing numbers of *Praeorbulina* spp. or *Orbulina suturalis* in the Badenian of the NÖ-06 and NÖ-07 cores. We can only speculate on paleoecological causes for this distribution. The most reasonable assumption appears to be the higher turbidity at the eastern locations due to the incoming feeder channel that carries erosional gravel, sand, mud and large amounts of freshwater from the rising Alps in the south. No *Praeorbulina* and *Orbulina*

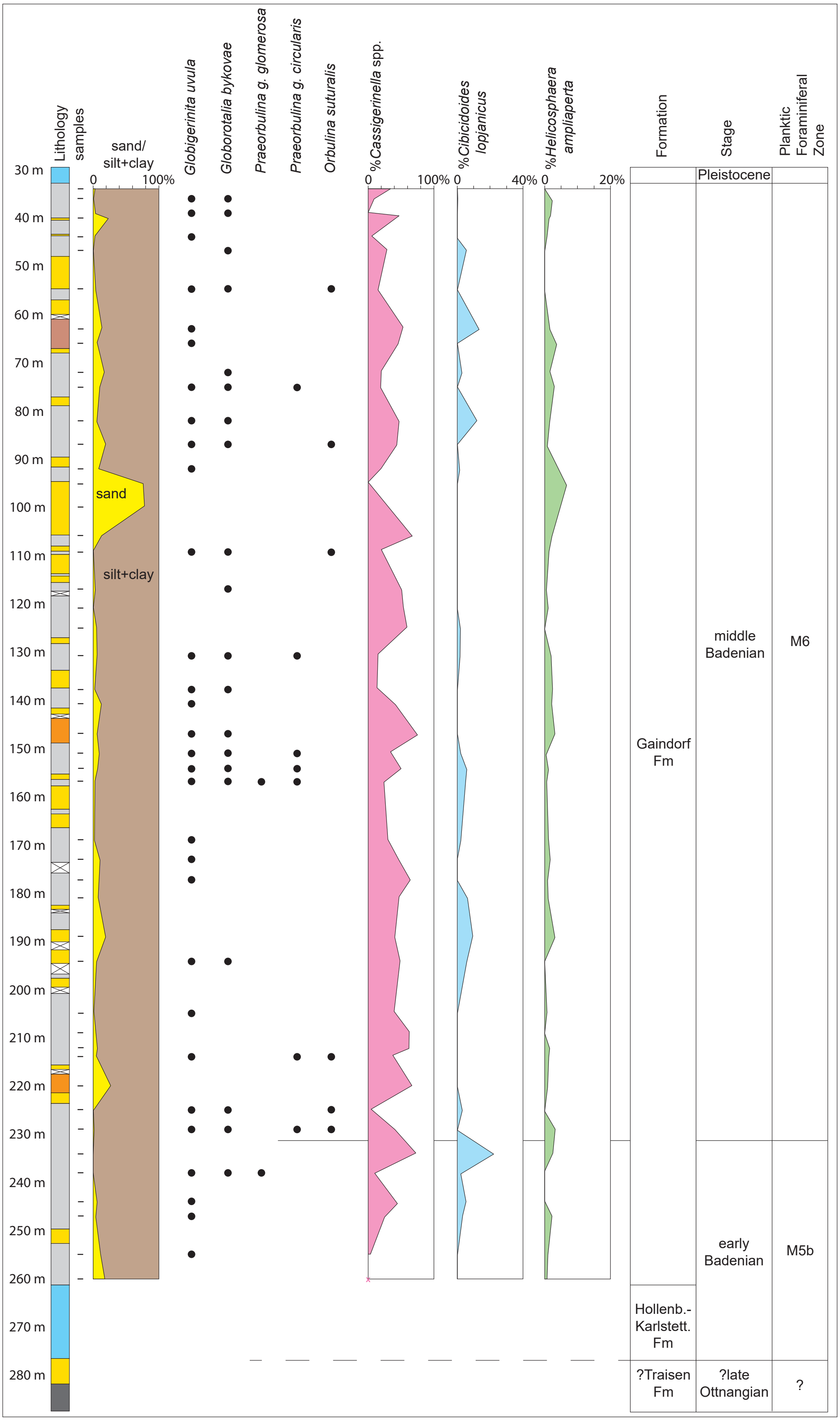

Figure 7: Core NÖ-07: Simplified lithology, presence or frequency of foraminiferal and calcareous nannofossil index species, and allocated formations and stages. Sand/silt and clay-ratio from washed samples only. Percentages of *Cassigerinella* spp. and *Cibicidoides lopjanicus* is among planktic foraminifera or benthic foraminifera only. Pink cross at base of *Cassigerinella* spp. indicates occurrence of two single specimens only. Percentage of *Helicosphaera ampliaperta* without reworked Cretaceous or Paleogene nannofossils. See Fig. 6 for key to simplified lithology. Hollenb.-Karlstett. FM = Hollenburg-Karlstetten Formation.

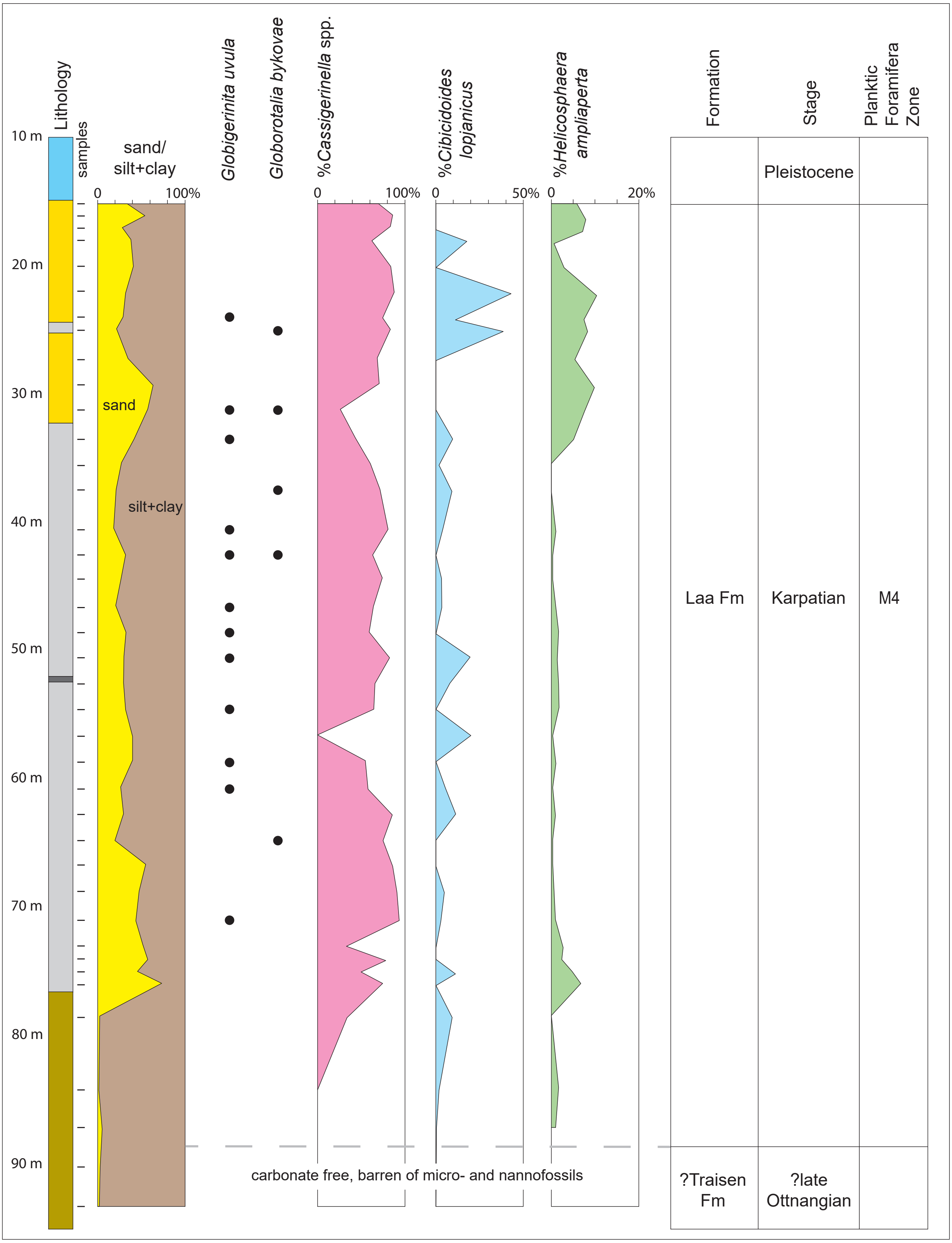

Figure 8: Core NÖ-02: Simplified lithology, presence or frequency of foraminiferal and calcareous nannofossil index species, and allocated formations and stages. Sand/silt and clay-ratio from washed samples only. Percentages of *Cassigerinella* spp. and *Cibicidoides lopjanicus* is among planktic foraminifera or benthic foraminifera only. Percentage of *Helicosphaera ampliaperta* without reworked Cretaceous or Paleogene nannofossils. See Figure 6 for key to simplified lithology.

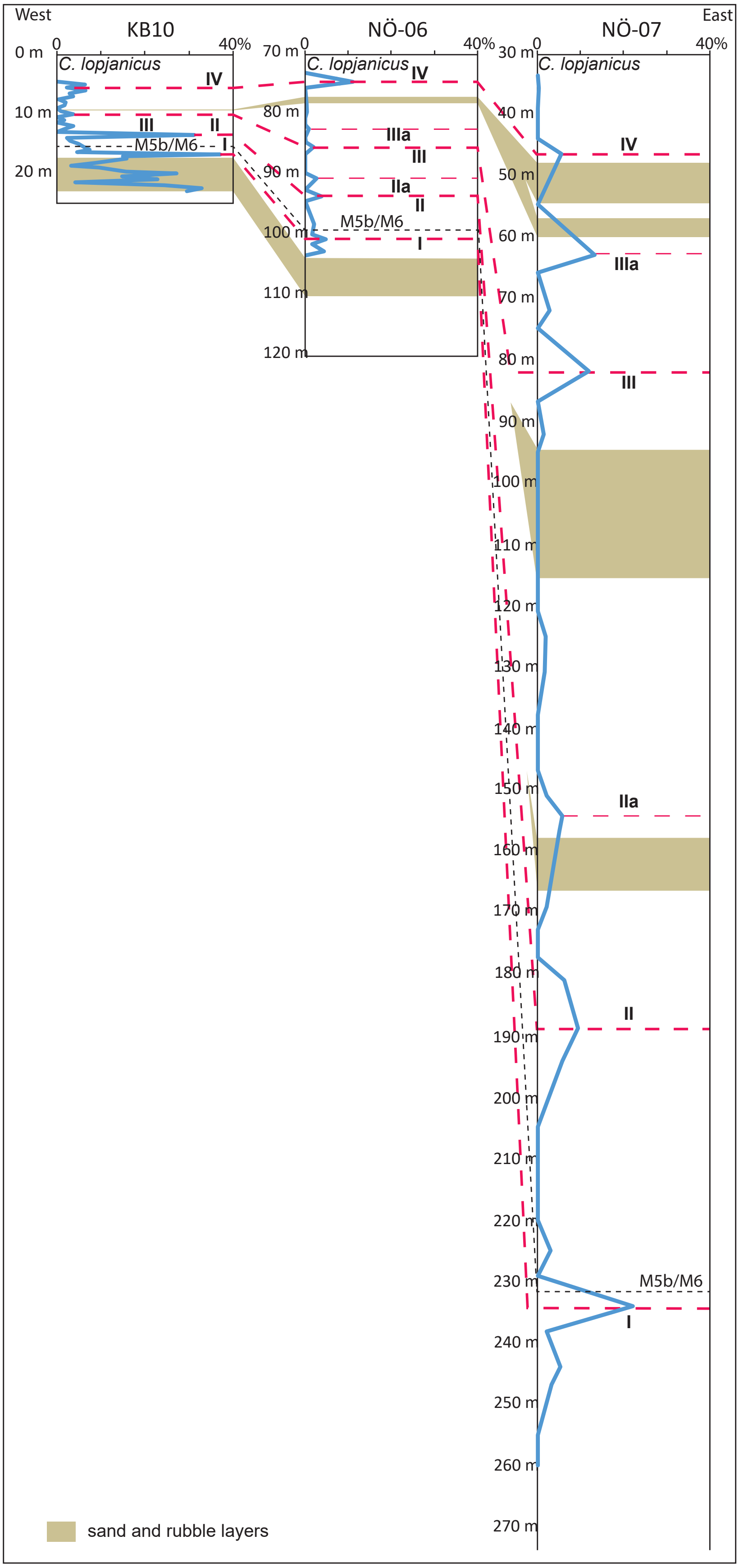

Figure 9: Correlation of drill cores KB10, NÖ-06, and NÖ-07 by coarse grained layers (sand or rubble) and percentage of *Cibicidoides lopjanicus* (blue lines) in the benthic foraminiferal assemblages. Note four (I-V; stippled lines) or two additional intervals (IIa, IIIa) of increased content of *C. lopjanicus*. M5b/M6-boundary for orientation.

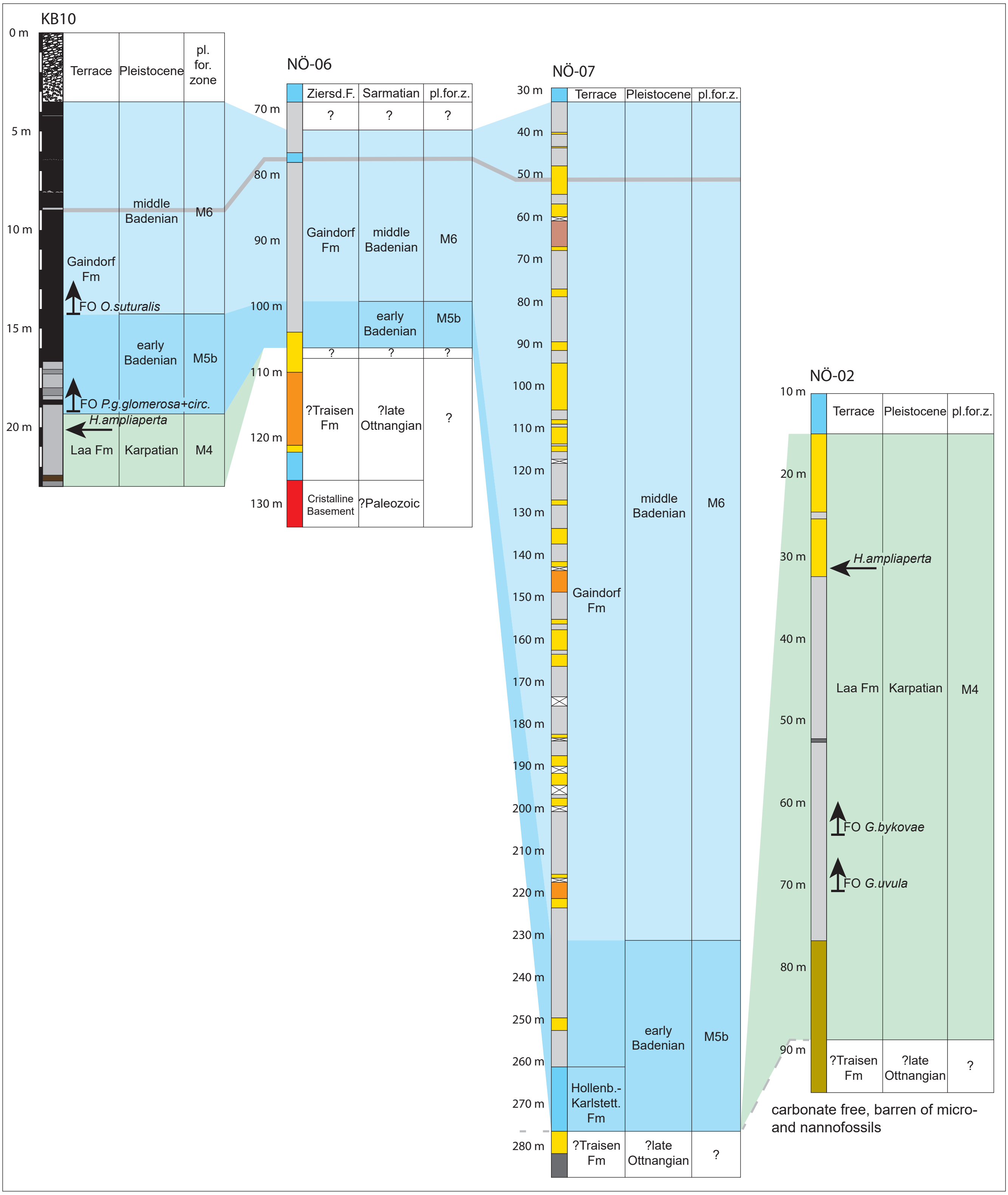

Figure 10: Correlation of all core sections investigated in this contribution. Thicknesses of drill cores not the same scale. Grey lines indicate correlated sand layers. See Figures 5 or 6 for key to lithology. Hollenb.-Karlstett. Fm = Hollenburg-Karlstetten Formation, Ziersd.F. = Ziersdorf Formation, pl. for. zone = planktic foraminiferal zone, FO = first occurrence. Horizontal arrows indicate peak occurrences.

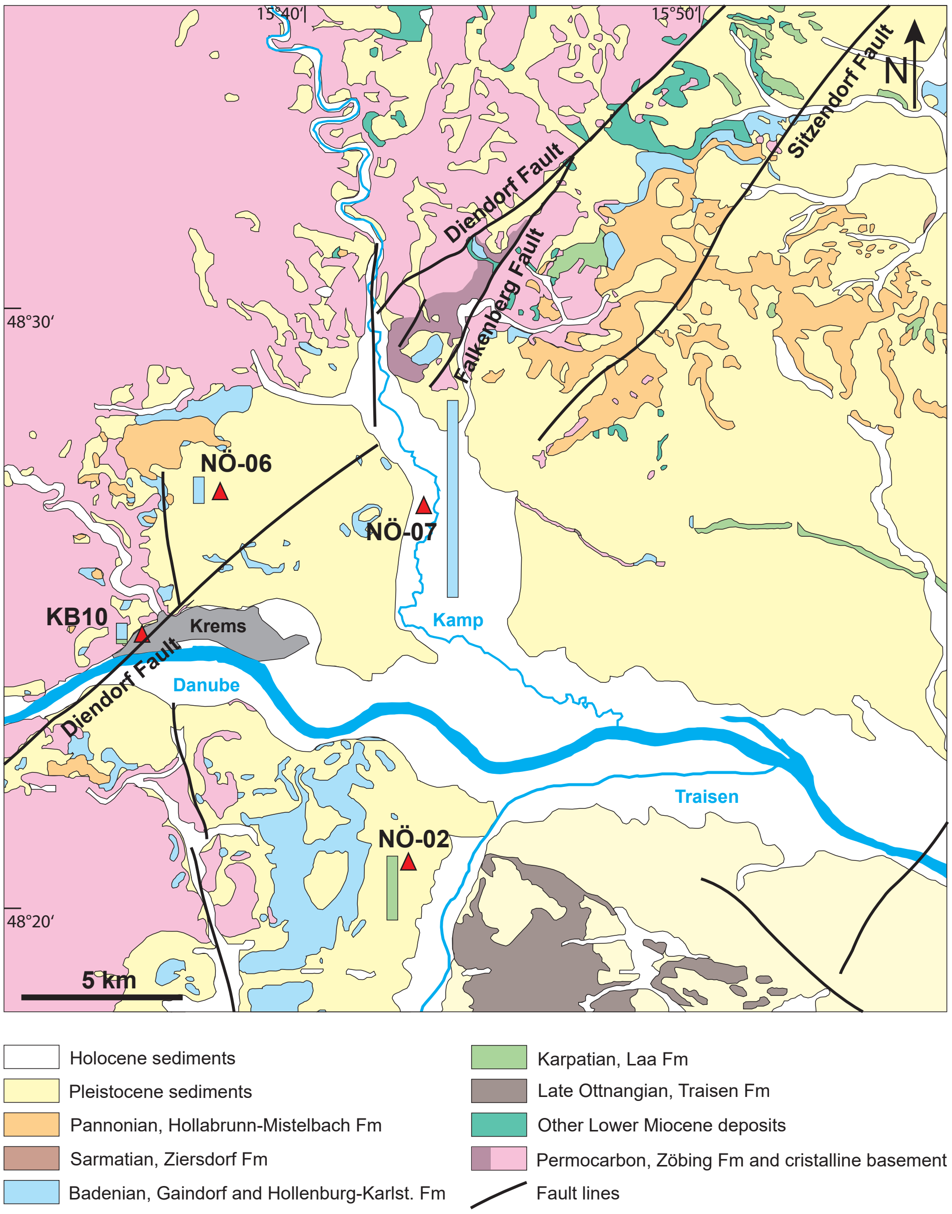

Figure 11: Geological map and major fault lines, particularly of the Diendorf-Boskovice Fault System, in the Krems Embayment, and location of investigated drill cores with thicknesses of Badenian and Karpatian sediments. Local geology and faults based on the geological map of Lower Austria (Schnabel et al., 2002), names of faults from Roetzel (1996), Lenhardt et al. (2007) and Nehyba et al. (2012).

specimens were reported from the marl intercalations of the Hollenburg-Karlstetten Formation (Grill, 1957). Sedimentation rates and sediment supply are much lower in the west, particularly at the KB10 site, and may support the thriving and reproduction of these symbiont bearing planktic foraminifera (e.g., Schiebel and Hemleben, 2017).

4.3 Thicknesses, tectonic development and the role of the Diendorf-Boskovice Fault System

The drill core KB10 is located closely to but clearly northwest of the Diendorf Fault (Fig. 11). It shows a relatively thin Badenian succession (Gaindorf Formation, Figs. 5, 11) deposited after Karpatian sediment layers (Laa Formation) with even less thickness exposed. However, the complete Karpatian succession was not accessible by the core. Northeast of this site and east of an adjoined secondary fault (Fig. 11), a crystalline block is covered with probable late Ottnangian Traisen Formation and the Badenian Gaindorf Formation (core NÖ-06, Figs. 6, 11). The Badenian sedimentation rate is assumed to be twice as high as at the KB10 site, as shown by the double thickness for this interval. Reckoning the thicknesses of the planktic foraminiferal zones, there is nearly no difference between both cores for M5b but a 2.5 times increase for NÖ-06 during M6. The tectonic block carrying NÖ-06 is surrounded by three faults and represents the most landward part of the Krems Embayment (Fig. 11). Southeast of the Diendorf Fault, the core NÖ-07 indicates a 16 times higher sedimentation rate for the Badenian interval if compared with KB 10 (Figs. 7, 11), pointing to much higher sedimentation rates southeast of the Diendorf Fault. For the M5b interval, the factor is 8-fold, and for M6 it is even 20-fold. South of the Danube River, 74 m

Karpatian Laa Formation lies above Lower Miocene to middle Oligocene sediments. No Badenian rocks were found in core NÖ-02 (Fig. 8).

Consequently, we interpret the different sediment thicknesses of specific periods in the cores as results of displacement along the faults of the Diendorf-Boskovice Fault System and its adjoined secondary faults. The data imply normal faulting with eastward subsidence at the N-S trending secondary fault between NÖ-06 and KB10 during the middle Badenian (M6). Less accommodation space was available on landward blocks (i.e., closer to the crystalline Moldanubian basement in the northwest) than in the basinal area southeast of the Diendorf Fault (Alpine Carpathian Foredeep or Molasse Basin). Given the far greater thicknesses of the drilled Badenian sediments southeast of the Diendorf Fault, particularly of NÖ-07 compared to KB10 and NÖ-06, a main phase of tectonic activity during the Badenian is suggested at the Diendorf Fault and probably at a N-S trending fault. The deepening of the basin even accelerated from early to middle Badenian times as the increase in sediment thickness in NÖ-07 is higher for M6 than for M5b (Fig.10).

The well NÖ-02 is located in the Traisen Valley and yielded about 74 m of Laa Formation, overlying Lower Miocene to middle Oligocene sediments. A little higher in altitude and west of the drill location of NÖ-02, lower Badenian conglomerates and marls with a thickness of up to 185 m are cropping out (Grill, 1957; Hollenburg-Karlstetten Formation, Fig. 11). This shows the thickness relation of Badenian sediments if compared with the basin center (e.g., 245 m at NÖ-07). It further shows that the depositional center apparently shifted northward during the transition from the Karpatian to the Badenian Stage, i.e., during the Styrian Tectonic Phase. Also before the Badenian and Karpatian, vertical movements play an important role in basin formation. Pre-Karpatian sediments of great thickness were deposited and recorded in drill cores (NÖ-03 Schaubing ca. 100 m, Palzer-Khomenko et al, 2018; NÖ-05 Theiss >128 m and NÖ-02 >220 m, unpublished reports) as well as in open pit mines (e.g., Fuchs et al, 1984). Thus, additional west-east striking normal faults can be assumed in the area of investigation.

Thrusting in the Subalpine Molasse in Lower Austria lasted until the Karpatian (Decker and Peresson, 1996; Beidinger and Decker, 2014; Ortner et al., 2021 in press). In Upper Austria (i.e., west of the investigated area), tilting and uplift of the area occurred during this time (Gusterhuber et al., 2012). However, in the Krems Embayment at the southeastern margin of the Bohemian Massif, subsidence of small tectonic blocks has taken place, with no Karpatian sediments deposited (or at least not preserved) at the NÖ-06 and NÖ-07 sites. A slow and smooth shift of the basin center in this very short time interval appears to be unlikely. We suggest, that a reactivation of the left-lateral Diendorf-Boskovice Fault System contributed to these processes. Especially vertical movements along both, the subparallel faults of the system (e.g., Diendorf Fault, Sitzendorf Fault; Fig. 11) and the N-S trending secondary faults lead to formation of accommodation space for sediments during several periods of the Oligocene and Early Miocene and particularly during the Badenian time, as reported in this contribution. The vertical tectonic movements are assumed to be the result of an interplay of differential exhumation of the Bohemian Spur (Gusterhuber et al., 2012) and tectonic microbasin formation in the strike-slip regime of the Diendorf-Boskovice Fault System, causing normal faulting at the secondary faults.

South of the Danube River (NÖ-02 location), the supply of eroded sediments from the rising Alps (conglomerates, sands etc.) is much higher than from the Bohemian Massif into the northern locations. This shows the importance of the Alps as sediment source area during the Karpatian and Badenian Stages in this tectonically active area.

5. Conclusions

Four drill cores were investigated to analyse the bio- and lithostratigraphic relations within the Krems Embayment. The investigated core sections cover long parts of the late Ottnangian, the Karpatian and the Badenian Stages: KB10 - Karpatian (M4) to middle Badenian (M5b – M6, M5a is missing) or NN4; NÖ-02 – late Ottnangian to Karpatian (M4, NN4); NÖ-06 – late Ottnangian (M4) to middle Badenian (M6) with only a few meters of possible Karpatian sediments and M5a missing or NN4; NÖ-07 – late Ottnangian (M4) to middle Badenian (M6, Karpatian M4 and M5a are missing) or NN4.

Important biostratigraphic indicators for the Badenian Stage (Gaindorf Formation) are *Praeorbulina glomerosa glomerosa, P. glomerosa circularis*, and *Orbulina suturalis*. The Karpatian (Laa Formation) is indicated by the absence of *Praeorbulina*, *Orbulina, Globigerina falconensis*, low numbers of *Globorotalia bykovae*, presence of *Globigerinita uvula*, and a prominent peak in *Helicosphaera ampliaperta* abundance at the end of the Karpatian.

Cibicidoides lopjanicus and *Cassigerinella* spp. occur with rather high percentages also in Badenian samples. Therefore, they show much longer stratigraphic ranges than known from literature data on foraminifera from the Central Paratethys and cannot be used as indicators for Karpatian deposits.

The well-known depositional gap at the Karpatian-Badenian boundary has also been found in the Krems Embayment. Its minimum duration was 0.41 My (M5a) but may have lasted much longer. This supports the assumption of a combination of a global sea level drop and local regional tectonic movements.

The combination of bio- and lithostratigraphic data (here correlation of coarse grained (sand) layers) allows the correlation across major faults even if biostratigraphic indicators are missing due to paleoenvironmental or paleogeographical reasons. The Diendorf-Boskovice Fault System played an important role during basin formation. Tectonic activity during the early to middle

Badenian Stage produced most of the accommodation space during this period. The results of this study show the complex interaction of sedimentation, tectonic activity and paleobiological developments in this peripheral part of a marginal sea.

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