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An integrated stratigraphy of the Pannonian (Late Miocene) in the Vienna Basin

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Abstract

The Upper Miocene Pannonian stage is represented in the Vienna Basin by an up to 1200 m thick siliciclastic succession comprising lacustrine and terrestrial deposits. The Pannonian is a crucial time in the development of the Vienna Basin as it is characterised by the retreat of Lake Pannon from the Vienna Basin giving place to terrestrial-fluvial settings. Here, for the first time, we integrate the maze of Pannonian lithostratigraphic terms and zones used by palaeontologists, oil companies and field geologists into a rigid lithostratigraphic scheme. This concept allows a clear correlation of surface outcrops with the basin-fill. The letter-zones of Papp (1951) are refined and applied to representative well-logs. This and the integration of biostratigraphic and magnetostratigraphic data, allow a strongly improved estimation of the chronostratigraphic content of each zone.

In terms of sequence stratigraphy, the Lower to Middle Pannonian lake deposits are interpreted as a single 3rd order cycle which starts at the Middle Miocene/Upper Miocene boundary due to the influence of the glacio-eustatic sea-level lowstand TB3.1. Comparisons with geophysical logs from the Styrian Basin document that lake level oscillations during the TST of this 3rd order cycle are well reflected in both basins. Correspondingly, the maximum extension of Lake Pannon in the Middle Pannonian is documented in all Pannonian basins. Hence, the sedimentary record of the Vienna Basin reflects the “history” of Lake Pannon during the early Late Miocene rather than being exclusively an expression of local tectonics.

Furthermore, the cyclicity in the sedimentary successions most obvious in geophysical logs suggests a trigger, such as astronomical forcing, which is independent of geodynamics and pure autocyclic processes. According to this preliminary approach, the 2.35-myr eccentricity cycle might have influenced the development of Lake Pannon. For example, the Sarmatian/Pannonian boundary and the major reduction of Lake Pannon in the Late Pannonian correlate well with two minima of that cycle, whereas the maximum extension took place during a 2.35-myr maximum. The dramatic shift in the composition of fossil mammal assemblages from the Early/Middle Pannonian to the Late Pannonian, which reflects an increase in seasonality and in aridity, supports this interpretation.

1. Introduction

The internal structure and facies architecture of the Pannonian (Upper Miocene) of the Vienna Basin is accurately documented by well-log data and by a “hermetic” mollusc-based biostratigraphy, which is poorly calibrated in terms of absolute time. Starting with Fuchs (1875), the biostratigraphic value of the Pannonian mollusc fauna for a zonation of the deposits was recognized. The pioneer phase of hydrocarbon exploration during the early 20th century fundamentally increased our knowledge of Pannonian deposits (e.g. Friedl, 1936; Janoschek, 1942, 1943). Finally, these results were summarized by Papp (1951), who applied a letter-zonation to the poorly defined eco-biozones used by geologists. By doing this, he tried to sidestep the confusion that arose by the quite different use of already proposed zones, named after various index fossils (e.g. *Congeria subglobosa* Zone sensu Friedl, 1936 versus *Congeria subglobosa* Zone sensu Janoschek, 1943). Note that Papp (1951) based his zones on surface outcrops at Leobersdorf in Lower Austria, which offer insight only into nearshore settings. Each zone is represented by several meters of sediment, separated by considerable gaps. Consequently, as already realized by Papp (1951), it was difficult to define the boundaries of his zones in more basinal successions. He therefore stated that the proposed boundaries in the various wells crossing the Pannonian are rather vague and may be erroneous by up to 30 m. Following the state-of-the-art-concepts of stratigraphic nomenclature of Salvador (1994) and Steininger and Piller (1999), however, these letter-(bio)zones have to be “re-named” after characteristic taxa as suggested by various authors such as Rögl and Daxner-Höck (1996) and Magyar et al. (1999a). In fact, the use of the various zonations in the Vienna Basin resulted in an arbitrary mixture of lithostratigraphy and ecostratigraphy. In this paper, we follow a slightly modified biostratigraphic scheme which is based on the biozones defined by Magyar et al. (1999a) (Fig. 1). The attempts of Rögl and Daxner-Höck (1996) and Daxner-Höck (1993, 1996, 2001) to evaluate the scattered mammal faunas found in Pannonian deposits of the Vienna Basin yielded first reliable calibrations with the European mammal-zones. These zones have been accurately dated during the last years by Krijgsman et al. (1996) in Spain. Based on these “pinpoints” and cornerstones, we summarize the biostratigraphy and sequence stratigraphy of the Pannonian.

2. Outline of Pannonian lithostratigraphy in the Vienna Basin

The Vienna Basin is a rhombohedral SSW-NNE oriented Neogene pull-apart basin of about 200 km length and 55 km width (Royden, 1985; Wessely, 1988). It extends from Gloggnitz in Austria in the south up to Napajedl in the Czech Republic in the north. This classic pull-apart basin formed in the Miocene between the Alps and the Carpathians along sinistral fault systems, enabling extrusion of crustal blocks from the Eastern Alps (e.g. Linzer et al., 2002; Ratschbacher et al., 1991). A detailed overview of the evolution of the

Vienna Basin and its depositional environments, including an extensive list of references, is presented in Royden (1985), Wessely (1988) and Kováč et al. (2004). In this paper, however, we only address the Pannonian (Late Miocene) basin-fill.

Due to the strongly structured and complex basin geometry, the thickness of Pannonian deposits varies considerably within different tectonic parts of the Vienna Basin. A huge amount of surface and well-log data, however, allows a quite accurate reconstruction of the distribution and the relationship of the various Pannonian strata throughout the basin. Most of the important sections and wells on which the following considerations are based on are presented in Fig. 2.

The maximum thickness of the Pannonian, about 1270 m, is recorded near Niedersulz in the northern Vienna Basin (Janoschek, 1951). A mainly lithology-based concept was developed in the early 20th century by the Austrian oil companies (OMV, RAG), which divided the Pannonian strata into the Lower, Middle and Upper Pannonian (e.g. Kreutzer, 1971). These entities were further subdivided on the basis of alternating pelitic and coarser siliciclastic layers. Consequently, the Lower Pannonian was defined by 5 coarse horizons termed LP 1 to 5 (Kreutzer, 1990); the Middle Pannonian was defined by 2 horizons (MP, MP2), and a series of sand/gravel horizons was mapped within the Upper Pannonian strata. The latter have been described as horizons OP 1-35 by Bernhard (1993), who also included parts of the Middle Pannonian as discussed below.

Traditionally, the Lower Pannonian was correlated with the zones A-C, the Middle Pannonian with D-E and the Upper Pannonian with the zones F-H of Papp (1951). During the last decades, the latter 3 zones have been correlated with the Pontian stage by many authors (e.g. Brix, 1988; Rögl and Steininger, 1990). However, as emphasized by Rögl et al. (1993), Magyar (1995) and Magyar et al. (1999a), the use of the term Pontian within Lake Pannon deposits is problematic. The base of the Pontian stage is dated by Magyar et al. (1999a) at either 7 or 8 Ma. Hence, the deposits of the Vienna Basin "labelled" as zones F, G and H cannot be considered as Pontian because the mammal faunas of zone F are about 1-2 Ma older. Consequently, in this paper we treat these deposits as Upper Pannonian. In the following, a short summary of Pannonian strata and depositional systems of the Vienna Basin is given. A more detailed overview of the Pannonian surface geology of the Vienna Basin is given by Janoschek (1942, 1943, 1951), Grill (1968) and Brix (1988).

For an easier reading of the proposed sedimentary units, the zones of Papp (1951) have been applied to the litho- and geophysical-logs of the Vienna Basin. An internal subdivision as indicated in Fig. 3 is proposed to label either distinct lithological units or to highlight internal high-frequency cycles.

2.1. Lower Pannonian

The lowermost Pannonian sediments in the Vienna Basin are only known from basinal settings. In the northern part of the basin they comprise a 12-20 m thick unit of sand and gravel which was termed "Übergangsschichten" or "Zwischensand" (= "transitional beds") in the older literature (e.g. Janoschek, 1942; Papp, 1951). These terms erroneously suggest a transitional position between the Sarmatian and the Pannonian, based on the co-occurrence of marine Sarmatian molluscs within mass-occurrences of fluvial-deltaic *Melanopsis impressa*. In fact, these beds document a phase during which fluvial facies penetrated far into the basin, synchronously reworking older Sarmatian strata (A in Fig. 3). One of these rivers entering the Vienna Basin in the north is predicted by Jiřiček (1985) based on freshwater marls in the Hradište Graben (Moravia). This phase correlates with zone A of Papp (1951). In the northern Vienna Basin, these deposits

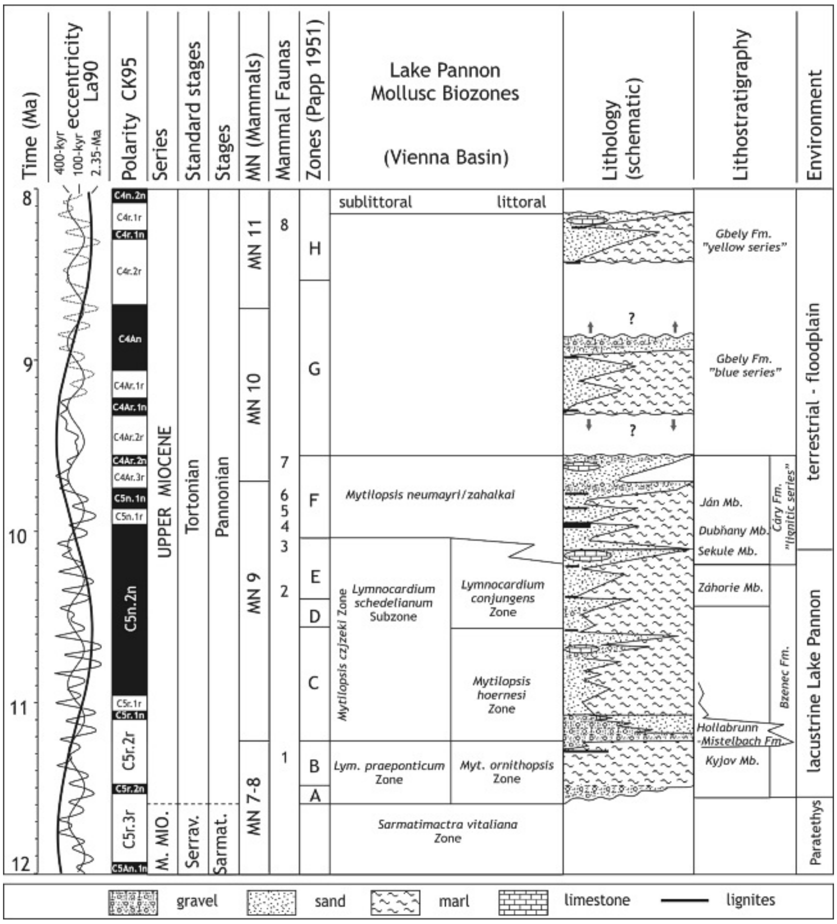

Figure 1: Chronstratigraphy, biostratigraphy and lithostratigraphy of the Pannonian in the Vienna Basin. Biostratigraphy modified from Magyar et al. (1999a); the use of *Mytilopsis* in the names of the mollusc biozones instead of Congeria follows the revision of Nuttall (1990). The Serravallian/Tortonian boundary is drawn according to the suggestions of Lirer et al. (2002) and Hilgen et al. (2000, 2003b). Astronomical cycles after Laskar (1990), geomagnetic polarity time scale after Cande and Kent (1995).
Note that the position of the lower part of the Gbely Formation is only tentative. The biostratigraphically indicative mammal sites are: 1. Kyjov, 2. Vösendorf, Hennersdorf, Inzersdorf, 3. Richardhof/Golfplatz, 4. Zillingdorf, 5. Götzendorf/Sandberg, 6. Stixneusiedl, 7. Neusiedl/See, Richardhof/Wald, 8. Eichkogel

represent the basal part of the *Bzenec Formation*, which was defined by Čtyroký (2000) based on the drillings at Kyjov in the Czech Republic.

A rather uniform, 50-100 m thick, monotonous unit of marl and sand follows with a 20-50 m thick marker unit of ostracod-bearing, green-gray marly clay in the top (so-called "schiefrige Tonmergel", Papp, 1985a). These units span the *Mytilopsis ornithopsis* Zone and correspond to zone B of Papp (1951). This prodelta- and basinal facies can be easily recognized in geophysical logs due to its "shale-line-appearance". The corresponding marginal facies is rarely preserved. Lower parts of the fluvial gravel of the *Hollabrunn-Mistelbach Formation* (Roetzel et al., 1999) correspond to that phase in the Mistelbach subbasin. In the northern tip of the Vienna Basin, a small lagoon formed in the Hradište Graben, that was cut off from the main basin by about 30-50 m of fluvial sand and gravel, which are also part of the *Bzenec Formation*. Within that depression, a succession of lignites and clays formed (Petrascheck, 1922/24; Jiříček, 1985), which is termed the *Kyjov Member* by Čtyroký (2000) (Fig. 1). In the southern Vienna Basin, marginal deposits, consisting of several meters of sand, marly sand and scattered gravel have been designated as "Beds of Leobersdorf" by Brix (1988). Despite the considerable time-gaps in that condensed section, the molluscs of the nearshore deposits of Leobersdorf formed the basis for the definition of zones B, C and D of Papp (1951).

The marly prodelta facies of the "schiefrige Tonmergel" is followed by the deltaic facies of the "großen unterpannonen Sand" [=big Lower Pannonian sand] (Janoschek, 1951). This unit (C_1-C_2 in Fig. 3) is mainly a sandy succession with scattered gravels up to 200 m thick with a typical, moderately serrated, cylinder-shaped curve in geophysical logs (cf. Fig. 3 and Janoschek, 1943). It is correlated with parts of the *Mytilopsis hoernesi* Zone and with zone C, respectively.

The "große unterpannone Sand" is linked with the prograding delta of the "Palaeo-Danube" in the northwestern part of the Vienna Basin. The corresponding gravel of the *Hollabrunn-Mistelbach Formation* (Roetzel et al., 1999) is the most characteristic Lower Pannonian sediment in surface outcrops. This formation can be traced via a WSW-ENE trending line in the Molasse Basin from Krems in Lower Austria towards Mistelbach in the northern Vienna Basin (Fig. 2). In surface outcrops, the formation extends for about 80 km in length and up to 15 km in width. The deposits give evidence of a fluvial system that entered the Vienna Basin near Mistelbach and shed its delta into the northern part of the Vienna Basin. The gravel, sand and pelites crop out in several pits and reach a thickness of up to 40 m. These outcrops reflect a delta plain, which was structured by several distributary channels of a braided river covering large parts of the Mistelbach subbasin (Harzhauser et al., 2003). Drillings document that the delta and its lobes reached far into the basin. The branches reach via the Matzen area down to Aderklaa (Kreutzer, 1990) in the south and into the Slovakian Suchohrad depression in the east (Kováč et al., 1998). In terms of letter zonation, the deposition of the Hollabrunn-Mistelbach Formation starts in zone B, indicated by mass-occurrences of the gastropod *Melanopsis impressa* co-occurring with the index fossil *Mytilopsis ornithopsis*. Such occurrences have been listed in detail by Grill (1968) from several localities in the Mistelbach Basin. However, the larger part of the formation,

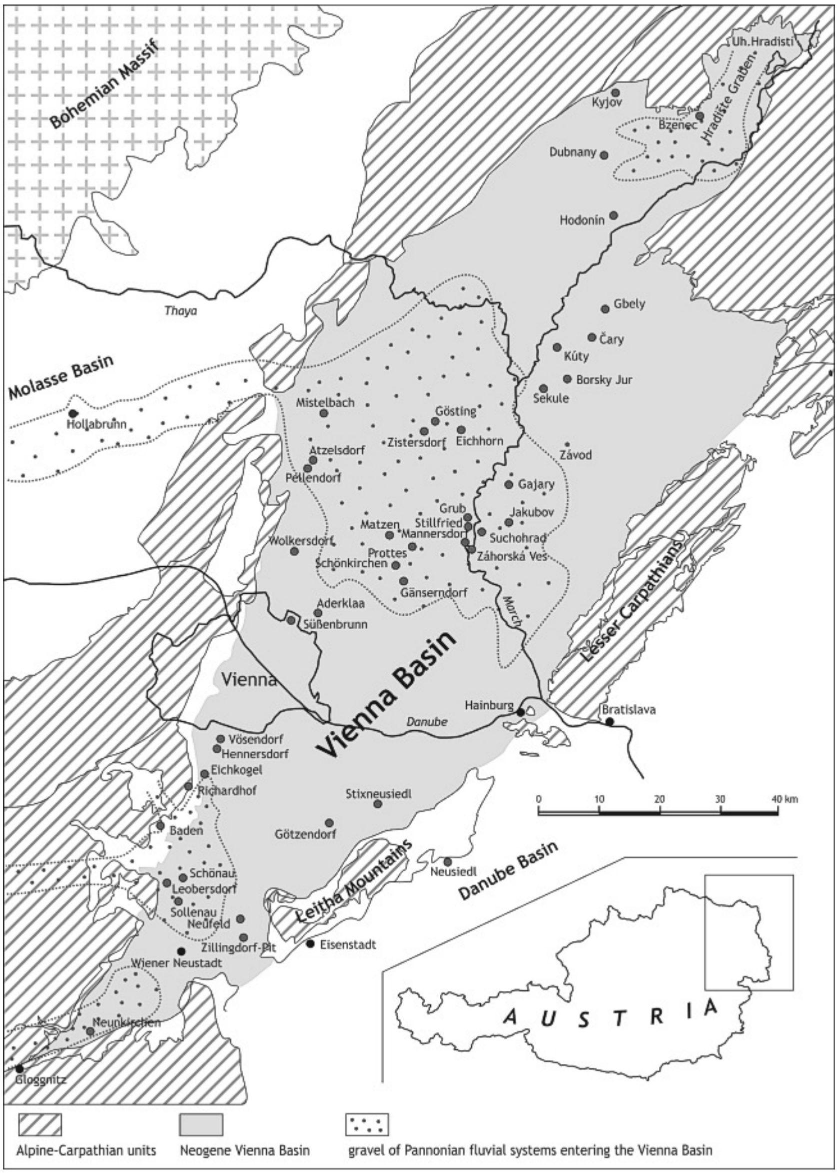

Figure 2: The Vienna Basin within Alpine-Carpathian units. Important localities mentioned in the text are indicated. Dotted lines and small dots show the distribution of Pannonian delta lobes, modified from Wessely (1988), Jiříček and Seifert (1990), Seifert in Sauer et al. (1992).

including most of mammal- and/or plant-bearing localities such as Atzelsdorf and Pellendorf, belong to zone C, and is based on the occurrence of *Hippotherium primigenium* (Daxner-Höck, 1996) or on the mollusc fauna (*Mytilopsis hoernesi* Zone). In the Vienna Basin the Hollabrunn-Mistelbach Formation and the related clastics of the “großen unterpannonen Sand” are restricted to the Lower Pannonian. In contrast, the surface occurrences of this formation in the Molasse Basin document a range up to the Upper Pannonian (e.g. Hohenwarth, Zapfe, 1957).

Deltaic systems are also recorded from the southern Vienna Basin, such as the *Triesting Schotter* and *Piesting Schotter* and the *Lindenberg Konglomerat* (Brix, 1988). Superimposed deposits of Middle Pannonian age suggest an Early Pannonian age. According to Brix (1988), these gravels and boulders were transported from the northwest, whereas the Piesting Schotter was derived from the southwest. Both deltas amalgamate near Berndorf, where the gravels attain a thickness of 127 m (Brix, 1980, 1988). In Baden, a similar development is represented by the up to 40 m thick *Hartberg Konglomerat*.

Above the “großen unterpannonen Sand” which should be treated as a subsurface extension of the Hollabrunn-Mistelbach Formation another 250 m thick succession of Lower Pannonian deposits follows. Most logs of the central Vienna Basin, such as Gösting, Aderklaa, Zistersdorf, Gajary and Schönkirchen, display a short but characteristic shale-line pattern above the “big Lower Pannonian sand” (within C_3 in Fig. 3). This line reflects a strong transgressional phase within the *Mytilopsis hoernesi* Zone. As a consequence, the delta plain on the Mistelbach subbasin was flooded and the riverine system was pushed back. At the Atzelsdorf section, fluvial gravel (with *Hippotherium*) is overlain by yellow marls, and at Pellendorf dark clay with sublittoral lymnocardiids replaces the floodplain facies (Harzhauser et al., 2003).

In basinal settings, a thick unit of interbedded marl, silt, sand and gravel follows, which are characterized in geophysical logs by a quick succession of broad, funnel-shaped curves passing upwards into serrated, sharply cut, funnel-shaped curves. Hence, the total Lower Pannonian encompassing zones A, B and C is represented by a ~500 m thick basin-fill in the northern Vienna Basin, whereas a thickness of only 140 m is reported by Janoschek (1942) for the southern part of the basin.

Following Čtyroký (2000), all the above-mentioned Lower Pannonian deposits represent the lower and middle part of the *Bzenec Formation*.

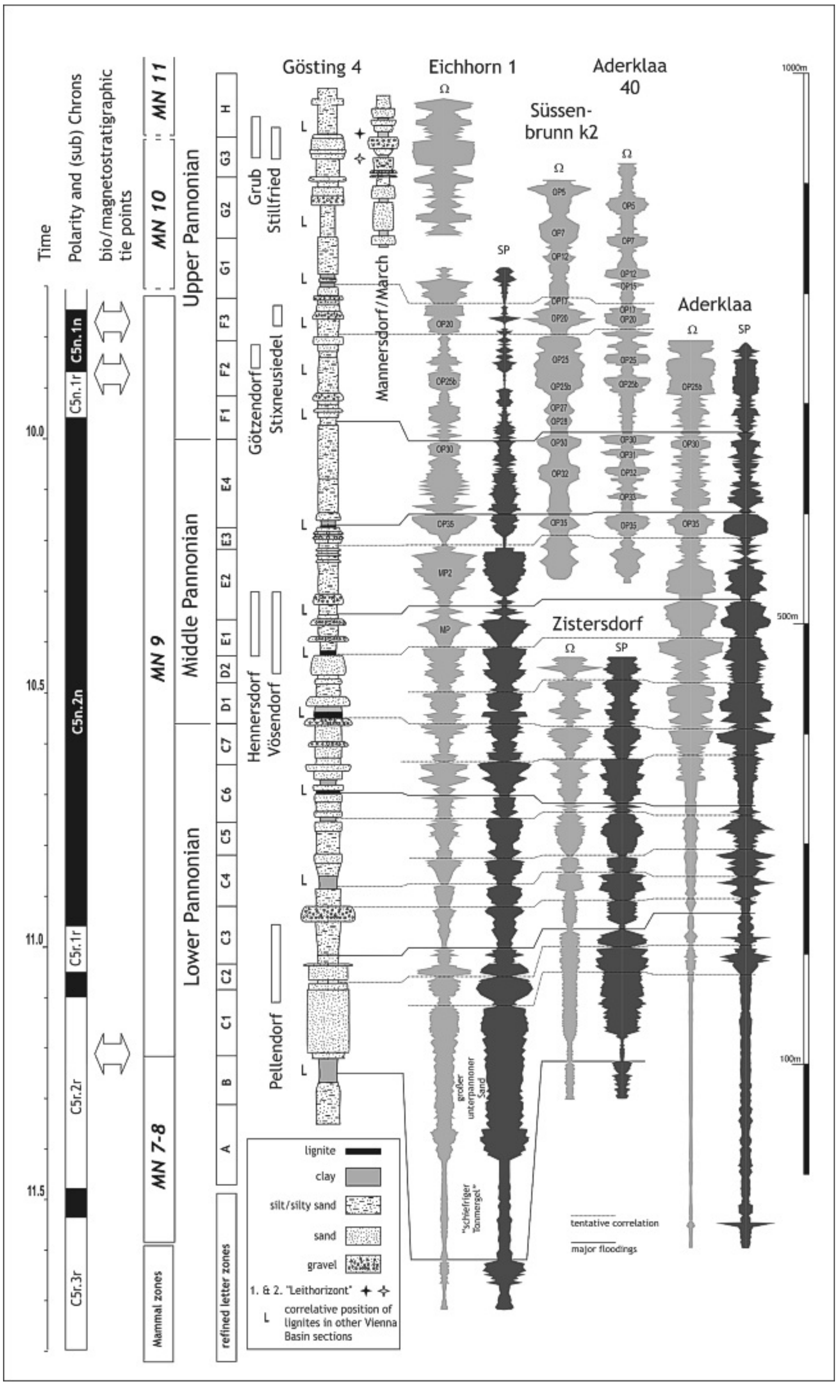

Figure 3: Tentative correlation of Pannonian deposits within the Vienna Basin. The lithological succession of the Gösting 4 well is correlated with geophysical logs from various parts of the central Vienna Basin (data from Friedl, 1936; Janoschek, 1942, 1943; Rögl and Summesberger, 1978; Bernhard, 1993). A biostratigraphic correlation of the Gösting 4 log was performed earlier by Papp (1951). Consequently, the zone concept of Papp (1951) was applied in a lithostratigraphic manner and a further subdivision was performed. The spontaneous potential logs (SP), and the restivity logs (Ω) are separated and mirrored to allow an easier recognition of correlative log patterns. Important surface outcrops are indicated left to the Gösting 4 log.
A dating is only possible at the boundary of zone B/C based on the first occurrence of *Hippotherium* and in Zone F based on the mammal faunas from Götzendorf and Stixneusiedl (see text for details).

2.2. Middle Pannonian

The term Middle Pannonian includes all deposits that have been assigned to zones D and E by Papp (1951). Zone D (basal *Lymnocardium schedelianum* Subzone) represents a rather thin unit of interbedded sand and marl, which is reminiscent of the upper parts of the Lower Pannonian (serrated, funnel-shaped curves) (Fig. 3). A lignitic layer in the basal part (base D_1 in Fig. 3) was used as a marker bed for well-log correlation (Janoschek, 1951). The total thickness in the Aderklaa and Eichhorn wells is about 100 m. It must be noted that the corresponding zone D was based on an only 2 m thick section at Leobersdorf in the southern part of the Vienna Basin by Papp (1951). Sediments of the lower Middle Pannonian include marginal freshwater limestones and multilayered onkoids at the base of the *Lymnocardium schedelianum* Subzone at Leobersdorf (Papp, 1951). The more prominent part of the Middle Pannonian is composed of clay and sand and belongs to zone E, which corresponds to the middle and upper *Lymnocardium schedelianum* Subzone within the *Mytilopsis czjzeki* Zone (= *Congeria subglobosa* Zone of Rögl and Daxner-Höck, 1996) (Fig. 1). The blue-green marls and clays of this zone informally termed Inzersdorf Tegel (Brix, 1989) are widespread throughout the Vienna Basin. In the Slovakian part of the basin, Vass (2002) separates this part of the Bzenec Formation as *Záhorie Member*, which was originally defined as a formation by Bartek (1989). This lithostratigraphic unit comprises deposits that were described earlier by Jiřiček (1985) as cyclothemes E_1, E_2 and E_3 and does not cover the entire Lower and Middle Pannonian, as indicated by Kováč et al. (1998). The holostratotype of the Pannonian stage was defined within that unit by Papp (1985b) at Vösendorf in the southern Vienna Basin. The thickness of the Záhorie Member is about 100 m with a maximum thickness of 200 m in the area of the Steinberg fault (e.g. Gösting) and even 340 m in the Götzendorf 1 well in the southern Vienna Basin (Brix, 1989). In geophysical logs, this unit splits into two coarsening upward cycles, differing clearly from the underlying strata by thicker single cycles (Bernhard, 1993) (Fig. 3). At the Gösting 4 well, both cycles start with a thin layer of lignite (E_1, E_2). The geophysical logs are very characteristic, reflecting the coarsening upward trends in 2 funnel-shaped curves of approximately equal thickness. The upper sequence differs in the cylinder-shaped top part. Both cycles seem to be composed of two smaller cycles, which obscure the pattern in some wells in the central Vienna Basin, such as in the Aderklaa area. The overlying ~100 m thick unit of sand with intercalations of gravel start with a layer of clay with lignites (E_3-E_4 in Fig. 3) and are still of Middle Pannonian age based on the occurrence of *Congeria subglobosa.*

In contrast, Bernhard (1993) treated these units already as Upper Pannonian including his horizons OP35-30. This misfit might result from the quick change of patterns in the geophysical logs, which indicate the development of fluvial channels in the former Lake Pannon area.

2.3. Upper Pannonian

The Upper Pannonian is represented by a rather uniform facies in the entire Vienna Basin. According to Papp (1951), it comprises the zones F, G and H, and is characterized by the ubiquitous occurrence of thin lignite seams in its basal parts and by a sandy-marly upper part. During the Late Pannonian, the margin of Lake Pannon had retreated from the Vienna Basin. Floodplain deposits and freshwater lakes developed which were not connected to Lake Pannon. Therefore, a direct correlation of Upper Pannonian deposits with the mollusc zones of Magyar et al. (1999a) is impossible within the Vienna Basin. A local mollusc zone termed *Mytilopsis neumayri/Mytilopsis zahalkai* Zone is frequently used in the literature for the zone F (Rögl and Daxner-Höck, 1996; Daxner-Höck, 1996).

The lignite-bearing part of the Upper Pannonian has been termed as the lignitic series (Friedl, 1936; Janoschek, 1943; Pokorný, 1945) and zone F was assigned to these sediments by Papp (1951). In the northern Vienna Basin, a lithostratigraphic frame was presented by Bartek (1989) who introduced the *Čáry Formation* based on numerous wells in the Slovakian part of the basin (Kúty, Gbely, Čáry, Sekule). This 200 m thick formation consists of lignites, lignitic clay, silt and sand. Bartek (1989) proposed a threefold subdivision into the *Sekule Member* (top of zone E), the *Dubňany Member* (representing the main lignite seam) and the uppermost *Ján Member* (Dubňany Member and Ján Member cover the zone F). In the southern Vienna Basin, a similar build up is documented from two abandoned mining areas and the term Lower Neufeld beds was proposed by Brix (1988; 1989) for these deposits. This informal term, however, seems to be synonymous with the correctly defined Čáry Formation. Similarly, the Dubňany Formation introduced by Čtyroký (2000) should be abandoned because of the homonymy with the Dubňany Member (Vass, 2002).

Along the western margin of the southern Vienna Basin the lignite seams crop out in the area of Sollenau, Dornau, Schönau and south of Leobersdorf (Brix, 1988). Their counterparts along the eastern margin were exploited in Zillingdorf, Neudörfl, Neufeld/Leitha and Pöttsching. The main lignite seams attain a thickness of 1.5 m and 6.1 m in the Sollenau pits (Weber and Weiss, 1983) and increase in thickness up to 6 m and 10 m at Zillingdorf, where even in situ trunks and large mammals have been recorded (Petrascheck, 1922/24). The underlying base of the lignite is very uniform in the southern Vienna Basin, and consists of a 6-28 m thick layer of marl with an underlying 20-30 m thick unit of sand. According to Ruttner (1952), the marls bear *Congeria subglobosa* along with lymnocardiids and, hence, are correlated with the upper *Lymnocardium schedelianum* Subzone of Magyar et al. (1999a) and with the lower part of the local *Mytilopsis neumayri/Mytilopsis zahalkai* Zone. This unit corresponds to the Sekule Member of the Čáry Formation as defined by Bartek (1989) and represents the topmost part of the Middle Pannonian zone E. Within that level, first occurrences of pure freshwater molluscs, such as *Emmericia canaliculata* were recorded at well Schönau/Triesting (Wilser, 1923). This indicates that the margin of Lake Pannon started to prograde basinwards already in the upper *Lymnocardium schedelianum* Subzone. At that time, the characteristic freshwater fauna of the diachronous *Mytilopsis neumayri/Mytilopsis zahalkai* Zone started to thrive in littoral settings. The marly freshwater limestones of Richardhof-Golfplatz in the southern Vienna Basin represent a special development within the lower Upper Pannonian and are probably age-equivalents of the Sekule member. Along the palaeocoast, these marls and limestones are replaced by an iterative succession of limestone beds of 0.5-1 m thickness with intercalations of 1-2 m thick breccias consisting of

Triassic limestone (Küpper and Bobies, 1927). This points to an oscillating lake-level and to repeated progradation of talus fans.

The lignite-bearing Čáry Formation is overlain by a 450 m thick succession of marl, clay and silt with intercalations of sand, gravel, rare lignites and sporadic freshwater limestones in the top. These deposits referred to as zone G by Papp (1951) were combined as the *Gbely Formation* by Bartek (1989) and Čtyroký (2000), which was based on a type-section in the Kúty 100 well. In the southern Vienna Basin, Brix (1988) introduced the informal term Upper Neufeld beds for correlative deposits. Both terms unite two lithostratigraphic entities which have been frequently used in the older literature. The first is the "Blaue Serie" (=blue series) consisting of up to 350 m of blue-green clays, with layers of yellowish sand and very rare lignitic clay. The top of the lower part of the Gbely Formation consists, in some parts of the central and northern basin, of an up to 40 m thick layer of sand (so-called "Zwischensand"), which is underlain and overlain by two characteristic, nearly black layers of clay (called first and second "Leithorizont" by the oil companies; see also Fig. 4). The latter is characterized by strong bioturbation (e.g. Stillfried section), a rarely observed feature in Pannonian deposits in the Vienna Basin. The bioturbation might point to a relatively long time of low sedimentation.

This upper clay defines the base of the overlying part of the Gbely Formation, which was called the "Bunte Serie" (= variegated series) by Janoschek (1942, 1943, 1951) and the "Gelbe Serie" (= yellow series) or zone H by Papp (1951) (Fig. 4). This up to 100 m thick unit differs from the "Blaue Serie" mainly in colour, in the increasing silt/sand content, and in the occurrence of marl-concretions and scattered limestone successions. These limestones are represented by rather isolated occurrences, such as at Moosbrunn and at the famous Eichkogel section. Despite the proximity to the marly limestones of the Richardhof section, the limestones of the Eichkogel are distinctly younger (see biostratigraphy below). The succession, already described by Richarz (1921) and Küpper and Bobies (1927), is formed by 10-12 m thick limestones underlain by few meters of marly silt. Thermal springs have been postulated as the trigger for the formation of these freshwater limestones (Küpper and Bobies, 1927). The underlying unit (of about 30 m of sand, marl and silt, along with an up to 10 m thick limestone bed and a lowermost silty sand) is usually termed "Eichkogel" in the literature; it bears specimens of *Congeria subglobosa* and is therefore distinctly older than the limestone (zone E). Consequently, as already discussed by Küpper et al. (1951), zones F and G (Čáry Formation and lower parts of the Gbely Formation) are missing in the Eichkogel section. This section, unfortunately, does not outcrop anymore and is now part of a nature reserve. Thus, the literature-based log remains problematic.

Apart from scattered mammal faunas from fluvial gravel, described for example from Wolkersdorf and Prottes (Bachmayer et al., 1961; Bachmayer and Młynarski, 1985) the upper part of the Gbely Formation (Gelbe Serie) is usually barren of fossils.

In the southern Vienna Basin, the Pannonian sedimentation terminates with the fluvial *Rohrbach Conglomerate*. This huge alluvial fan enters the basin from the southwest in the area of Gloggnitz and extends in northeastern direction up to Wiener Neustadt. Due to the Alpine source-area, it is composed of limestone and dolostone gravel intercalated with sand and silt. Based on palynological evidence, large parts of the unit have been vaguely dated as Dacian (Küpper et al., 1952; Küpper, 1962). Its deposition, however, started during the latest Pannonian as proven by Brix (1988). The gravel interfingers with the Upper Neufeld beds and attains a maximum thickness of 280 m (well Diepolz, Petrascheck, 1922/24).

3. Biostratigraphic and magnetostratigraphic tie-points

Because of the intensively studied evolutionary lineages of the

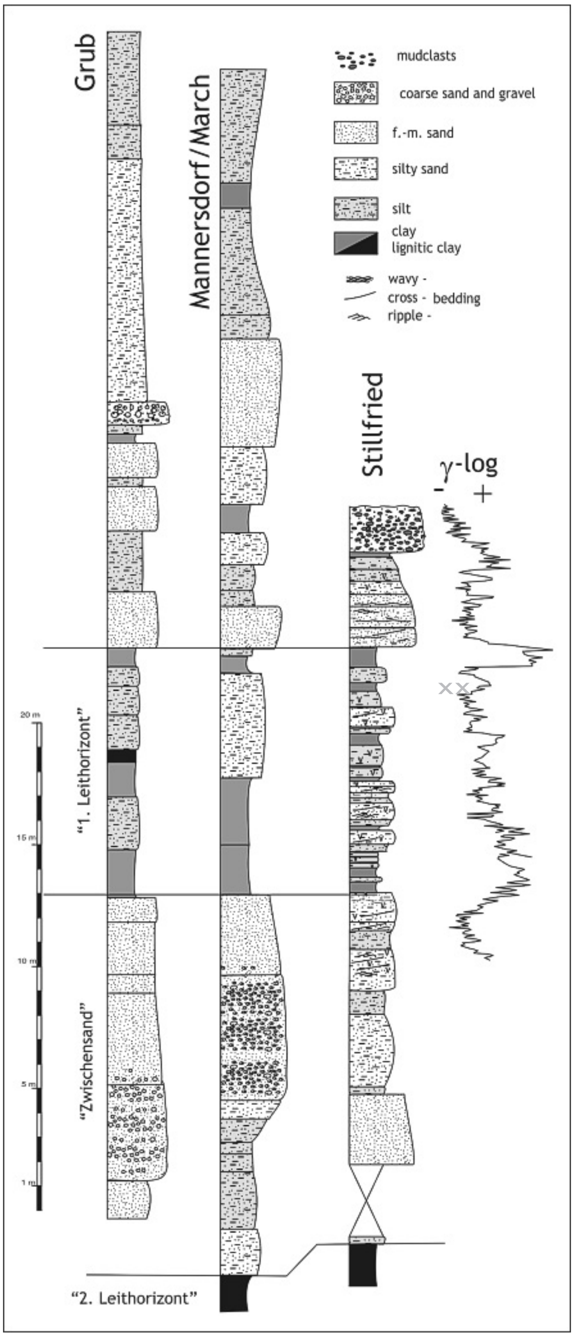

Figure 4: Three sections of the central Vienna Basin, yielding deposits of the Upper Pannonian zones G_3 and H (compare Fig. 3). The marker horizon "1. Leithorizont" indicates the onset of zone H. Strong bioturbation, which is unique in Pannonian deposits of the Vienna Basin and high amplitudes of the γ-log characterize this unit. This unit and the underlying coarse "Zwischensand" are thus proper candidates to trace the hiatus between the zones G and H as suspected in Fig. 2.

endemic mollusc fauna, the biostratigraphic resolution of the Pannonian deposits in the Vienna Basin is quite good (see Magyar et al., 1999a for details). In addition, rich vertebrate assemblages are known from the Pannonian of the Vienna Basin. These represent a chronological sequence from MN9 to MN11 (Fig. 1) and give insight into different environments and climatic conditions throughout the Vallesian and the Early Turolian.

This rigid framework, however, has only few absolute dated tie-points. Hence, no compelling absolute dating exists for the lowermost Pannonian strata, which have been assigned to the zone A. The first occurrence of the three-toed horse *Hippotherium* defines the base of MN9 and marks the onset of the lower Vallesian (Crusafont-Pairo, 1950). This event was estimated after 11.5 Ma and before 11.1 Ma, when the horses already arrived in western Europe (Garcés et al., 1997). Generally, the first occurrence of *Hippotherium* in Central Europe, has so far been placed at 11.1-11.2 Ma based on findings in gravel of zone C (*Mytilopsis hoernesi* Zone) at the Gaiselberg section in the northern Vienna Basin (Bernor et al., 1988). The stratigraphically oldest record of *Hippotherium primigenium* is recorded by Jiřiček (1985) and Čtyroký (1987, 2000) from the top of the lignites in the Hovorany mine in the Czech Republic. These lignites belong to the Kyjov Member and are dated as late *Mytilopsis ornithopsis* Zone (= upper part of zone B).

The entire overlying part of the Bzenec Formation corresponds to the sublittoral *Mytilopsis czjzeki* Zone of Magyar et al. (1999a) and spans the littoral *Mytilopsis hoernesi* Zone. No absolute dating of this zone is available from the Vienna Basin. The following Záhorie Member includes the sublittoral *Lymnocardium schedelianum* Subzone within the *Mytilopsis czjzeki* Zone and the *Lymnocardium conjungens* Zone in littoral settings. A magnetostratigraphic dating of the upper *Lymnocardium schedelianum* Subzone points to a position within the late subchron C5n.2n (Magyar et al., 1999a).

No direct correlation with Lake Pannon mollusc zones of Magyar et al. (1999a) is possible in the overlying Čáry Formation due to the retreat of the lake from the Vienna Basin. The *Mytilopsis neumayri/Mytilopsis zahalkai* Zone, as proposed by Rögl and Daxner-Höck (1996) is thus only of local value within the Vienna Basin. This zone spans the entire Čáry Formation (including the Sekule Member). This is an important re-definition of that local mollusc zone, as it was formerly only correlated with deposits of zone F, whereas the Sekule Member represents the uppermost part of the zone E. Consequently, in littoral settings, the *Mytilopsis neumayri/Mytilopsis zahalkai* Zone is a local equivalent of the uppermost *Lymnocardium schedelianum* Subzone of Magyar et al. (1999a) (e.g. Richardhof-Golfplatz). However, the larger part of the *Mytilopsis neumayri/Mytilopsis zahalkai* Zone is equivalent to the *Lymnocardium soproniense* Subzone of Lake Pannon settings.

The correlative mammal faunas from Richardhof-Golfplatz and Götzendorf are dated to the upper part of mammal zone MN9 (Daxner-Höck, 1993, 1996). Within that zone, the evolutionary level of the faunas suggests a position of Richardhof-Golfplatz below Götzendorf (Čáry Formation) and above Vösendorf and Hennersdorf (Záhorie Member). Additionally, magnetostratigraphic data (Daxner-Höck, 2001) allow a dating of the fossiliferous sand of Götzendorf with subchron C5n.1n and a correlation to C5n.1r for the underlying clay, pointing to an age between 9.7 and 9.9 Ma (Fig. 3). These ages agree well with the proposed range of the synchronous *Lymnocardium soproniense* Subzone in Lake Pannon settings of Magyar et al. (1999a).

Finally, no dating of the Gbely Formation is available. Only few mammal faunas form the basis for correlation. The Neusiedl and Richardhof-Wald sections are thus dated as MN10 indicated by an important phase of immigration by murids (*Progonomys*) in Central Europe. The Eichkogel section in the southern Vienna Basin yields an assemblage typical for zone MN11. This indicates a late Vallesian age for the lower part of the Gbely Formation and a Turolian age for the upper part of the Gbely Formation. The frame of these mammal biozones is presented by Krijgsman et al. (1996) for Spain. According to these authors, the MN7-8/MN9 (Aragonian/Vallesian) boundary occurs in subchron C5r.1n at 11.1 Ma, the MN9/MN10 boundary in subchron C4Ar.3r at 9.7±0.1 Ma, and the MN10/MN11 (Vallesian/Turolian) boundary in chron C4An at 8.7±0.1 Ma. Faunas of MN12 age are missing in the Vienna Basin. The MN11/MN12 boundary, which is calibrated to C4n.1n, indicating an age of 7.5±0.1 Ma, may thus serve as the uppermost possible date for the basin-fill. Most of these boundaries are accepted in this paper because they are in good accordance with the Central European record.

4. Sequence stratigraphy

In the last decades sequence stratigraphy has been frequently applied to the Pannonian strata, starting with Pogácsás and Seifert (1991). Besides the initial study in the Vienna Basin, the main target area was the Pannonian Basin, which was the focus of investigations by Vakarcs et al. (1998), Sacchi et al. (1998) and others. The most recent study by Kosi et al. (2003) discussed the sequence stratigraphy of the Lower Pannonian of the Styrian Basin.

Except for the key studies of Kováč et al. (1998, 2004 in press) on the northern part of the basin and a few other studies (e.g. Hudáckova et al., 2000; Harzhauser et al., 2003) the Vienna Basin is distinctly less well-investigated. New lithostratigraphic and sequence stratigraphic results from the Styrian Basin (Gross, 2003; Kosi et al., 2003) reflect some striking similarities with the lithostratigraphic development in the Vienna Basin (see also Fig. 5).

The Sarmatian/Pannonian boundary coincides with a type 1 sequence boundary which is related to a relative sea level fall in the latest Sarmatian (Kosi et al., 2003; Kováč et al., 2004 in press). This event seems to be linked with the glacio-eustatic sea-level lowstand of the TB3.1. cycle of Haq et al. (1988), which has been dated at around 11.5-11.6 Ma. (Hilgen et al., 2000, 2003a, 2003b). Due to this lowstand, emersion of most Sarmatian nearshore deposits along the margins of the Vienna Basin took place (Jekelius, 1943). At the same time, Middle Miocene marine corallinacean limestones of the already vanished Paratethys Sea became exposed in many areas (Steinberg, Leitha Mountains, Lesser Carpathians). This phase was a prerequisite for extensive erosion during the Early Pannonian. A strong discordance between the deposits of the Sarmatian stage (Middle Miocene) and the Pannonian is present in surface outcrops but is also evident in many core drillings (e.g. Suchohrad-Gajary area in Slovakia: Jiřiček, 1985).

The Lower Pannonian strata correspond to a 3rd order lowstand systems tract (LST) (A-C_2 in Fig. 3). The sand and gravel of the basal Bzenec Formation, formerly assigned to zone A, represent lowstand wedge deposits. Fluvial facies penetrated far into the basin, synchronously reworking older Sarmatian strata. Within that LST, a sequence of at least one higher-order can be detected. First transgressive pulses of a high-order sequence are documented by the overlying clay and marl of the so-called "schiefrige Tonmergel" in basinal settings (B in Fig. 3). The lignitic Kyjov Member, according to Kováč et al. (1998) linked with an initial transgressive phase, represents such a phase in marginal settings. These deposits correspond to the Eisengraben Member of the Styrian Basin, which is interpreted by Kosi et al. (2003) as a transgressive systems tract (TST). The overlying prograding delta front of the Hollabrunn-Mistelbach Formation and of the "großen unterpannonen Sand" (C_{1-2} in Fig. 3) has a Styrian counterpart in the highstand systems tract (HST) of the Sieglegg Member. Thus, the lower part of the Bzenec Formation, including the Hollabrunn-Mistelbach Formation, the Kyjov Member and the "großen unterpannonen Sand" are equivalents of the LPa-1 sequence defined by Kosi et al. (2003) in the Styrian Basin (Fig. 5).

As indicated by the geophysical logs of the Vienna Basin and by the Pellendorf and Atzelsdorf sections on the Mistelbach block, the deltaic facies are transgressed by Lake Pannon during the *Mytilopsis hoernesi* Zone (Harzhauser et al., 2003; C_3 in Fig. 3). This event marks the beginning of the 3^{rd} order TST (C_3-E_1 in Fig. 3). About 4 higher-order sequences modulate this TST. The basal one was defined in the Styrian Basin as LPa-2 by Kosi et al. (2003) (Fig. 5). The formation displays a very characteristic succession of "depressed", funnel-shaped cycles which have a striking counterpart in the upper part of the Bzenec Formation in the Aderklaa, Zistersdorf and Eichhorn wells (Fig. 3). Consequently, the upper part of the Bzenec Formation is correlated with the LPa-2 sequence. Within the Middle Pannonian part of the 3^{rd} order TST (D_1-E_1 in Fig. 3), another high-order cycle is indicated by synsedimentary intraclasts or by gravel as represented in the Gösting 4 well. Finally, the TST culminates in the maximum flooding surface (mfs) in the Middle Pannonian (within zone E), coinciding with oxygen-depleted bottom conditions (Harzhauser and Mandic, 2004) and blooms of dinoflagellates (Kováč et al., 1998).

The upper Middle Pannonian is characterized by the progradation of sand and gravel into the basin (E_2-E_4 in Fig. 3), probably related to a 3^{rd} order HST. Floodplain conditions and isolated lakes developed at the Middle/Upper Pannonian boundary. Consequently, due to the retreat of Lake Pannon from the Vienna Basin, a sequence-stratigraphic approach for the Upper Pannonian deposits is problematic. Furthermore, considerable gaps seem to occur between the Čáry and the Gbely Formations and within the Gbely Formation, as indicated by the biostratigraphic dating of MN 11 for the upper Gbely Formation versus MN9 for the Čáry Formation.

5. Cyclic sedimentation in the Vienna Basin

The typical pattern of funnel-shaped curves in geophysical logs indicates that some sedimentary cyclicity of Pannonian deposits in the Vienna Basin is present during the Early and Middle Pannonian (Fig. 3). This pattern is also documented in Lower Pannonian of the Styrian Basin (Fig. 5), indicating that these cycles are not fully obscured by local tectonic movement but reflect oscillations in the relative lake level in both basins.

Moreover, the Vienna Basin experienced two major phases of lignite formation. The first appears in the Lower Pannonian, reflected by the

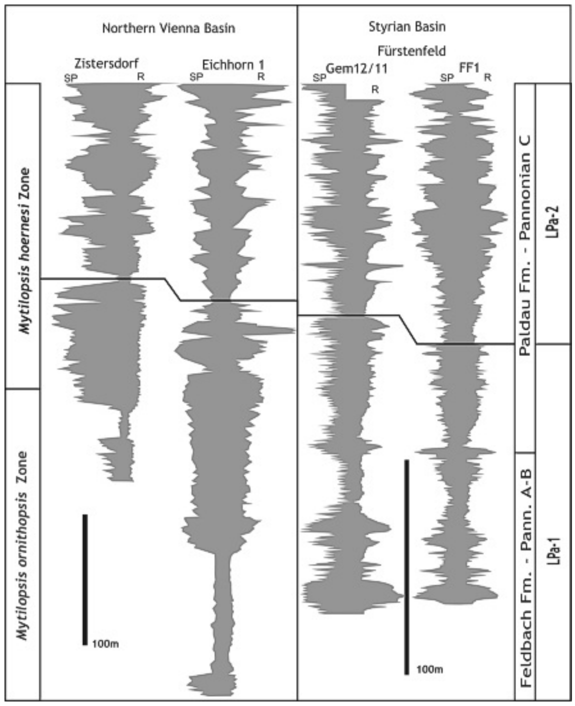

Figure 5: Geophysical logs (spontaneous potential SP, and restivity R/Ω) of Lower Pannonian deposits from the Vienna Basin (after Janoschek, 1942, 1943) and the Styrian Basin (after Kosi et al., 2003). Both basins mirror a very similar development which is most obvious in the upper part of the logs (short, funnel-shaped curves). Despite the different tectonic regimes in both basins, and the slight difference in thicknesses of the basin-fills, the overall signature is not fully obscured.

lignite seams of the Kyjov Member (top of B in Fig. 3) and the second in the basal Upper Pannonian, reflected by the Čáry Formation (top E_4 to F_3 in Fig. 3). In the intervening deposits, lignites occur frequently at the base of high-frequency sequences (e.g. at the boundaries of C_2/C_3, C_6, base D_1, D_2/E_1, base E_2, base E_4 in Fig. 3). Similarly, after the lignite-phase of the Čáry Formation, several intercalations of lignitic clays are recorded in the Gbely Formation which partly served as marker horizons for well-log correlation (base G_1, base G_2, G_3, base H). Some cyclicity is obvious in upper Middle Pannonian and Upper Pannonian strata based on well-logs in the central Vienna Basin (E_3-H). Bernhard (1993) deciphered a succession of pelitic-sandy units interbedded with coarse layers of sand and gravel. The latter horizons are labeled as Op1- OP35 by oil companies and were correlated throughout large parts of the central Vienna Basin. The succession was interpreted by Bernhard (1993) as an alternation of floodplain deposits interrupted by coarse deposits of braided river systems. Hence, they reflect a rather regular alternation of lacustrine environments with high water tables and phases of river progradation, coupled with the deposition of gravels and sand in channels and crevasse splays. The regular pattern is interrupted several times due to the amalgamation of channels (compound units sensu Bernhard, 1993). These channels are especially well developed within the horizons OP 25 and OP17/20 (Fig. 3) and hint at gaps in sedimentation, hence, indicating phases of erosion. These gaps are tentatively indicated in Fig. 1, and seem to occur at the base, in the middle and within the upper part of the Gbely Formation, resulting in three separated packages. Therefore, despite these opportunities to correlate sedimentary units measuring several meters to tens of meters thickness throughout the Vienna Basin, a bed-to-bed correlation is strongly hampered by syntectonic movements, by paleo-relief and by erosion.

6. Astronomical forcing in Lake Pannon deposits?

Only few attempts have been made to correlate sedimentary cycles and depositional environments of the Pannonian with the Milankovitch cyclicity band. Based on numerical cycle analysis and magnetostratigraphy of numerous boreholes of the Pannonian Basin in Hungary, Juhász et al. (1997) deduced 3 types of cycles in Pannonian sediments with periods of ~19 kyr, ~50 kyr and ~400 kyr. Later, Juhász et al. (1999) refined the data and predicted a periodicity of 19 kyr, 71 kyr and 370 kyr cycles, which they related to the 21-kyr precession, the 41-kyr obliquity, and the 400-kyr eccentricity cycle, respectively. Recently, a correlation of uppermost Pannonian deposits to the eccentricity cycle was presented by Sprovieri et al. (2003) in the Iharosberény-1 well in Hungary.

Even the entire Pannonian sequence might represent a large astronomical cycle. New astronomically based data indicate that the age of the Serravallian/Tortonian boundary is about 11.5-11.6 Ma (Hilgen et al., 2000, Lirer et al., 2002) corresponding to the glacio-eustatic sea-level lowstand of TB3.1. This sea-level lowstand at about 11.6 Ma coincides with a minimum of the 2.35-myr cycle of the eccentricity band according to the Laskar (1990) solution. This dating agrees with published radiometric data concerning the Sarmatian/ Pannonian boundary (Vass et al., 1987). Hence, the Sarmatian/ Pannonian boundary is thought to correspond to the Serravallian/ Tortonian boundary, which in turn is related to the global galcio-eustatic event. Based on this correlation, some influence of the 2.35-myr eccentricity cycle on Lake Pannon's history can be deduced: The transgressive systems tract and the maximum flooding may correspond to the maximum of that component. Geophysical logs clearly document a well-developed periodicity of funnel-shaped curves from the Lower to the Middle Pannonian (Fig. 3). These curves are most regular in the upper Lower and the Middle Pannonian, and seem to coincide with the maximum of the 2.35-myr component. Hence, the transgression and maximum extension during the maximum of the 2.35-myr cycle applies for the entire Lake Pannon and is not restricted to the Vienna Basin (cf. Magyar et al., 1999b). Finally, the desiccation of the Vienna Basin resulted in a considerable gap in sedimentation which could be related to the following 2.35-myr eccentricity minimum. Outside the Vienna Basin, this phase corresponds to a general shrinkage of the lake (Magyar et al., 1999b).

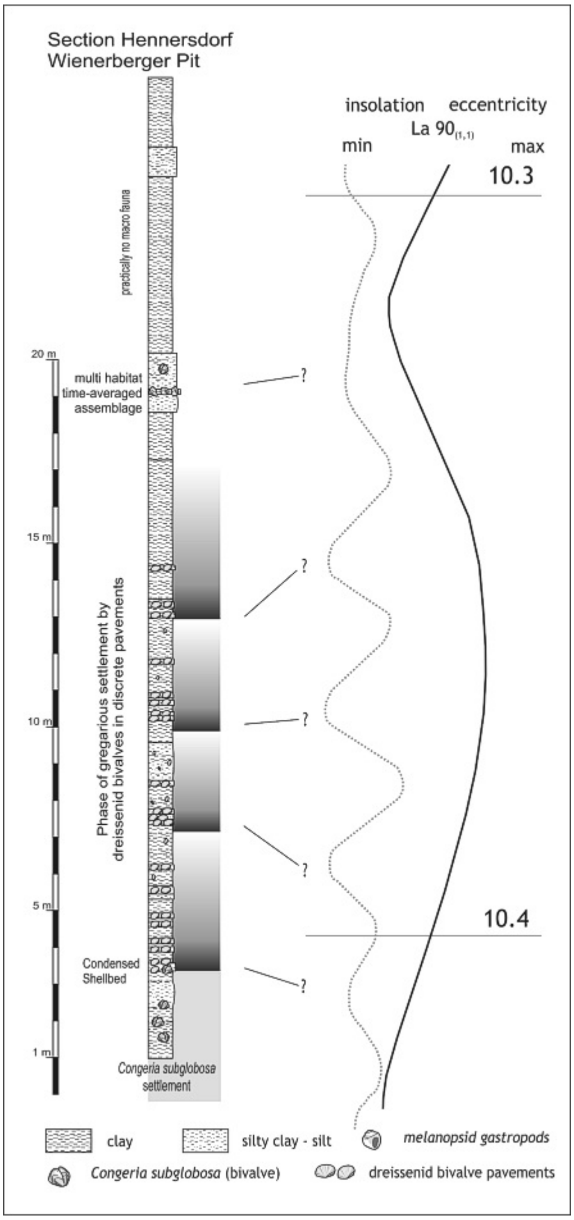

Figure 6: Comparison of cycles in Middle Pannonian deposits at the Hennersdorf section (after Harzhauser and Mandic, 2004) with the astronomical target curves of Laskar (1990). The stratigraphic position is an approximate estimation based on the lithological correlation as proposed in Fig. 3. The lack of absolute datings prohibits any straightforward correlation. However, the cyclicity observed in settlement patterns of dreissenid bivalves might be influenced by insolation. Hence, four smaller cycles are indicated by the succession of pavements of dreissenid bivalves within an oxygen-depleted lake bottom environment. These interruptions point to periodically improved bottom conditions, probably linked to insolation minima.

6.1. Phase relations between sedimentary cycles and orbital parameters

The regular coarsening upward pattern observed in geophysical logs in Lower and Middle Pannonian strata in the Vienna Basin and in the Styrian Basin roughly reflect periodic oscillations of the lake level which might be the result of astronomical forcing by eccentricity and/or by obliquity cycles. During the last years, the impact of astronomical forcing in cyclic sedimentation in late Neogene lacustrine basins has been excellently depicted. The key areas are the Calatayud and Teruel Basins in Spain (Abdul Aziz, 2001; Abdul Aziz et al., 2003), the Ptolemais and Megalopolis Basins in Greece (van Vugt et al., 1998; van Vugt, 2000) and the Oltenia Basin in Romania (van Vugt et al., 2001). Generally, two types of lithological cycles predominated in these basins. The first type represents siliciclastic depositional systems with a lignite-siliciclastics cyclicity, whereas the second one is predominated by carbonate-lignite or carbonate-clay cycles. Due to the different sedimentary regimes, however, strong differences in the expression of precession and eccentricity are mirrored in the lithological cycles. Hence, van Vugt et al. (2001) concluded that carbonate dominated basins are susceptible to precession whereas siliciclastic basins are more sensitive to eccentricity. As the Pannonian basin-fill of the Vienna Basin lacks relevant carbonate cycles but offers more than 1000 m of siliciclastics with intercalated lignites, the Megalopolis and Oltenia Basins might serve as references. In the Pleistocene Megalopolis Basin, detrital material (clay, silt, sand) alternates with lignite seams. Palynological evidence (Oltenia) indicates that the lithological cycles reflect orbitally controlled glacial/interglacial cycles, driven by the 100-kyr eccentricity cycle. The phase relation is such that lignites correspond to 100-kyr eccentricity maxima (van Vugt, 2000; Okuda et al., 2002). The intervening smaller-scale cycles which divide the main lignite seams correspond with the 21 kyr insolation maxima. The same interrelation was documented by van Vugt et al. (2001) for the Lupoia section in the Oltenia Basin. The formation of lignites in the Vienna Basin is clearly less important and less regular than in the Greek and Romanian basins, and could be partly explained by the deep sublittoral settings for Lake Pannon during the late Early and Middle Pannonian. However, based on the documented relation from other siliciclastic/lignitic basins in Greece and Romania, the iterative lignite formation throughout the Pannonian could be coupled to 100-kyr eccentricity maxima. Such an impact of the 100-kyr periodicity on continental climate and lake ecology has also be noted by Colman et al. (1995) in Lake Baikal. Also the 400-kyr eccentricity cycle might be expressed in the sedimentary record of the Vienna Basin. Juhász et al. (1999) already predicted that the 400-kyr eccentricity cycles could be responsible for the major floodings indicated in C_3, D_1, and E_2 (Fig. 3). Clearly, any considerations on the astronomical origin of the Pannonian deposits remains speculative due to the poor biostratigraphic and magnetostratigraphic backbone. However, the authors present these ideas as a first attempt to discuss the Vienna Basin's sedimentary fill in the light of orbital forcing:

In the Vienna Basin, the settlement of dreissenid bivalves in otherwise oxygen-depleted areas of Lake Pannon in the *Lymnocardium schedelianum* Subzone at the Hennersdorf section was discussed by Harzhauser and Mandic (2004) to reflect high-frequency orbital forcing of the climate. Based on the position of the correlative section Vösendorf, which is the holostratotype of the Pannonian stage (see Papp, 1985b, for details), this Middle Pannonian section is correlated with cycle E_1-E_2 of Fig. 3. A magnetostratigraphic dating of the Hennersdorf section to subchron C5n.2n was proposed by Magyar et al. (1999a). Recently, Harzhauser and Mandic (2004) described the section in detail and concluded that it represents a deep bottom lake setting. The alternating bivalve fauna indicates a repeated change in the oxygenation of the hypolimnion, allowing opportunistic dreissenid bivalves to settle at the lake bottom during short-termed "ecological windows". Four of such cycles have been recognized. Each cycle starts with a phase of repeated settlement, expressed by 2-4 layers of "boom-and-burst" populations of dreissenid bivalves. These layers rapidly fade out during each cycle, giving place to monotonous clay lacking any fauna. The intervening phases between the settlement episodes are predominated by oxygen-depleted bottom conditions and might also be linked to minor floodings. Based on the suggested correlation of the unit E_1 in Fig. 3, the cycles at the Hennersdorf section may be explained as an expression of insolation within a 100-kyr eccentricity maximum (Fig. 6). Whatever mechanism might have triggered the development, it is likely that during individual insolation minima periodical mixing of the epilimnion with the oxygen-depleted hypolimnion occurred, which allowed bivalves to settle at the lake bottom. Similarly, obliquity or precession cycles have been hypothesised by Pipík (1998) to have caused shifts in ostracod assemblages in synchronous deposits of the adjacent western Danube Basin.

Another surface outcrop which allows a more detailed logging is Stixneusiedl in the southern Vienna Basin (Fig. 7). The section consists of 20 m of clay, silt sand and rare gravel within the top part of the Čáry Formation. Based on the mammal fauna it was estimated to be slightly younger than the calibrated Götzendorf/Sandberg fauna, and consequently the section is correlated with cycle F_3 of Fig. 3. Based on the bio- and magnetostratigraphic dating of Götzendorf, it can be correlated with the astronomical target curves. The sedimentary succession points to repeated shifts from fluvial settings to lake environments. The resulting γ-log of Stixneusiedl displays highest values in pelites and silt layers corresponding to high water tables. This γ-log reveals a striking parallel to the insolation curve (Fig. 7). In this case, high γ-log values would indicate insolation maxima with high water tables. In contrast, the weaker middle maximum in the γ-log would correspond to a single flooding within a predominance of fluvial settings. However, the scenario might also be simply a result of autocyclic or tectonic processes. Any correlation of these Upper Pannonian strata to higher astronomical cycles (e.g. 100-kyr, 400-kyr), however, is obscured by the drastic change in the geodynamic system of the Vienna Basin during the Late Pannonian. Decker and Peresson (1996) and Cloetingh and Lankreijer (2001) discuss a strong change in the large-scale stress field within the Vienna Basin starting already in the Middle Pannonian. Instead of N-S compression and E-W extension, an E-W compressive stress field evolved, resulting in basin inversion and ceasing the pull-apart kinematics. A continuous deposition is thus extremely unlikely. Sedimentation of lacustrine facies of the Gbely Formation might therefore reflect very discrete, hydrologically "opportune" phases.

7. Conclusions

The Sarmatian/Pannonian boundary is still not defined by a stratotype. A radiometric determined age of approximately 11.5 Ma was proposed by many authors such as Vass et al. (1987), Rögl and Daxner-Höck (1996) and Kováč et al. (1998). This age does not correspond to the former Serravallian/Tortonian boundary that was placed at 11.20 Ma by Berggren et al. (1995). New astronomically based data on the age of the Serravallian/Tortonian boundary, however, point to an absolute age of either 11.539 Ma (Lirer et al., 2002) or 11.608 Ma (Hilgen et al., 2000), and even suggest that it corresponds to the glacio-eustatic sea-level lowstand of TB3.1 [a GSSP, however, is still under debate (Hilgen et al., 2003b)]. Hence, we suggest that this major and global sea-level fluctuation is also reflected in the Pannonian basins area, which ultimately resulted in the withdrawal of the Paratethys at the end of the Sarmatian. A 3rd order cycle, which marks the Tortonian transgression in the Mediterranean area, coincides with a rise in water table of Lake Pannon. This development may be linked to the 2.35-myr component of the eccentricity cycle, culminating in the maximum flooding of Lake Pannon during the maximum of that eccentricity cycle. This is in strong contrast to the alleged asynchronous rhythm of water table changes discussed by Juhász et al. (1997), resulting from poor correlations. However, our interpretation is supported by the data of Sprovieri et al. (2003), who documented a synchronous isotopic and sedimentary record in Lake Pannon and the Mediterranean Sea as a result of climatic teleconnection.

The successive predominance of dry conditions in the Vienna Basin from the Early to the Late Pannonian, is strongly supported by the overall trend in mammal faunas. The small mammal faunas of the Early Vallesian (MN9) indicate extended wetlands with rather humid, forested environments accompanied by dense vegetation during the heyday of Lake Pannon. The mammal fauna of the late Vallesian (MN10) comprises a high diversity of semi-aquatic, arboreal and gliding rodents. Nevertheless, the number of ground dwellers increases which might point to the successive spreading of open woodlands and to a trend towards advanced seasonality. The subsequent sedimentary gap between the Čáry Formation and the Gbely Formation seems to coincide with the 2.35-myr eccentricity cycle minimum, which occurs roughly between 9.3 and 9.6 Ma. This hiatus also coincides with a major faunal turn-over within the mammal assemblages of the Vienna Basin.

The Lower Turolian (MN11) mammal fauna, represented by the large mammals from the Mannersdorf, Wolkersdorf and Prottes sections and by the small mammals from the Eichkogel section, are characterized by murid-cricetid-dominated associations and by a dramatic increase of carnivores (Hyaenidae) and ruminants (Bovidae and Giraffidae). The dominance of ground-dwelling rodents, the diversity of ruminants and the occurrence of the porcupine *Hystrix* hint at more dry conditions, a seasonal climate and relatively open woodland-environments. Similarly, as summarized by van Dam (1997), various climate-related records of the NE Atlantic-Mediterranean region document strong shifts within that interval. In the Vienna Basin, this phase, which is also characterised by repeated interruptions in Upper Pannonian sedimentation, might best be interpreted as a period of dry climate conditions which was strongly accentuated by a change of the geodynamic system from pull-apart kinematics towards basin inversion (Decker and Peresson, 1996).

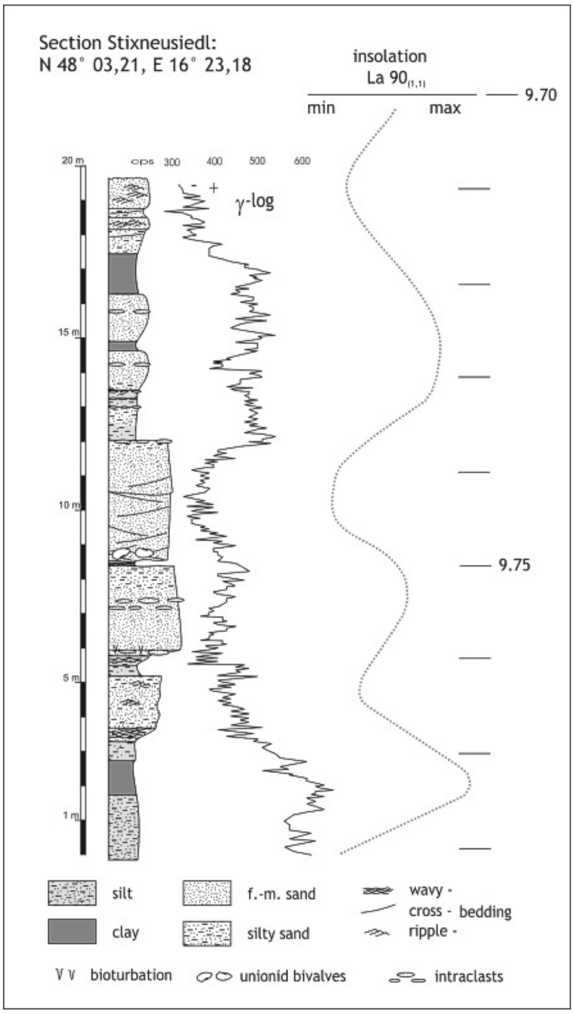

Figure 7: Based on the datings of the mammal faunas from Götzendorf and Stixneusiedl, the age of the Stixneusiedl section can roughly be estimated to range between 9.7 and 9.8 Ma. Although a straightforward correlation is impossible at present, a parallel trend of the γ-log pattern and the insolation curve could be alleged. The lower and upper maxima are well reflected by floodings and the deposition of clay, whilst the low-amplitude insolation maximum in the middle might relate to a weak flooding within a generally fluvial-influenced unit. However, autocyclic and/or tectonic overprint cannot be excluded.

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