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Sequence stratigraphy in a classic pull-apart basin (Neogene, Vienna Basin). A 3D seismic based integrated approach

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Abstract: This paper presents an improved sequence stratigraphic framework for the southern and central Vienna Basin (Austria) based on the integration of 3D seismic reflection data, well data, surface outcrops and refined biostratigraphy. The 3D survey used for this study is positioned close to the margin of the Vienna Basin, which increases the stratigraphic importance of this analysis. Distal basin facies, so far only known from seismic and well data, are compared and correlated to their proximal equivalents in surface outcrops. The investigated part of the basin is characterized by a syn-sedimentary horst and graben structure, with Badenian (Langhian and Lower Serravallian) platform carbonates on the elevated areas and fine-grained marine clastic sediments in adjacent subbasins. This integrated approach allows the separation of the Neogene sediments in the southern Vienna Basin into five Middle and Upper Miocene 3rd order depositional cycles: the Badenian is separated into three depositional cycles and the Sarmatian (Middle and Upper Serravallian) and the Pannonian (Tortonian) represent one depositional cycle each. The three Badenian cycles are correlated with the TB 2.3., TB 2.4. and TB 2.5. cycles from global sea-level charts. A major sea-level drop of 90–120 m can be calculated for the boundary between TB 2.3. and TB 2.4. at roughly 14.2 Ma. The Sarmatian cycle corresponds to the TB 2.6. cycle and the Pannonian to the TB 3.1. cycle. Since these sequence boundaries are dated in other European basins, their correlation to the Vienna Basin provides improved time constraints for the stratigraphic evolution of the Vienna Basin. The results from this study in the southern Vienna Basin can be extrapolated to the central and probably also to the northern parts of the basin.

Key words: Miocene, Austria, Vienna Basin, sequence stratigraphy, global sea level, 3D seismic.

Introduction

The Central European Vienna Basin is one of the most studied, classic pull-apart basins (e.g. Royden 1985). It formed along sinistral fault systems during Miocene lateral extrusion of the Eastern Alps (e.g. Royden 1985; Ratschbacher et al. 1991; Linzer et al. 2002) (see Fig. 1a). The basin fill consists of shallow marine and terrestial sediments of Early to Middle Miocene age (e.g. Seifert 1996) up to 5500 m thick in the central parts of the basin. A detailed stratigraphy based on the correlation of well logs has been established for the southern and central Vienna Basin (e.g. Kreutzer 1978; Wessely 1988; Weissenbäck 1996). In these areas 2D seismic sections resolved the complex depositional and structural history of the basin, which resulted in a local sequence stratigraphic framework for Miocene sediments (e.g. Matzen area, Kreutzer 1986 and Weissenbäck 1996) (Fig. 1a).

At present, the mapped sequences and stratigraphic concepts are restricted to the depositional environment of the central Vienna Basin (e.g. Matzen area). A well-constrained correlation to other parts of the Vienna Basin, the southern Vienna Basin in particular, and to regional or global sequences is still missing. Lack of radiometric age dates hampers exact timing of sequence boundaries which are so far mainly based on local bio(eco)-stratigraphic correlations.

In this study we present a new 3D seismic-based sequence stratigraphic interpretation for the southern Vienna Basin, based on sedimentological evidence and new biostratigraphic data from nearby outcrops and well data. A detailed facies reconstruction of one of the major fault blocks located at the eastern border of this pull-apart basin documents its sedimentary evolution.

For this sequence stratigraphic interpretation we combine locally established stratigraphic concepts (Kreutzer 1986; Weissenbäck 1996) with a 3D seismic survey from OMV (3D seismic block Moosbrunn, see Fig. 1b for position) and biostratigraphic data. The 3D seismic dataset allows the analysis of sedimentary sequences deposited in distal environments. The lithological and biostratigraphic interpretation of major sequences is based on well data and surface outcrops in the Leitha Mountains (Fig. 1b) linked to the distal environment covered by the 3D seismic.

The objective of this study is to incorporate stratigraphic data from the central Vienna Basin into a sequence stratigraphic framework for the Austrian part of the Vienna Basin, which is in agreement with the global sea level chart of Hardenbol et al. (1998). This sequence stratigraphic framework is also likely to be applicable for the entire Vienna Basin.

For the first time an age control of the general tectono-stratigraphic evolution of the southern Vienna Basin is es-

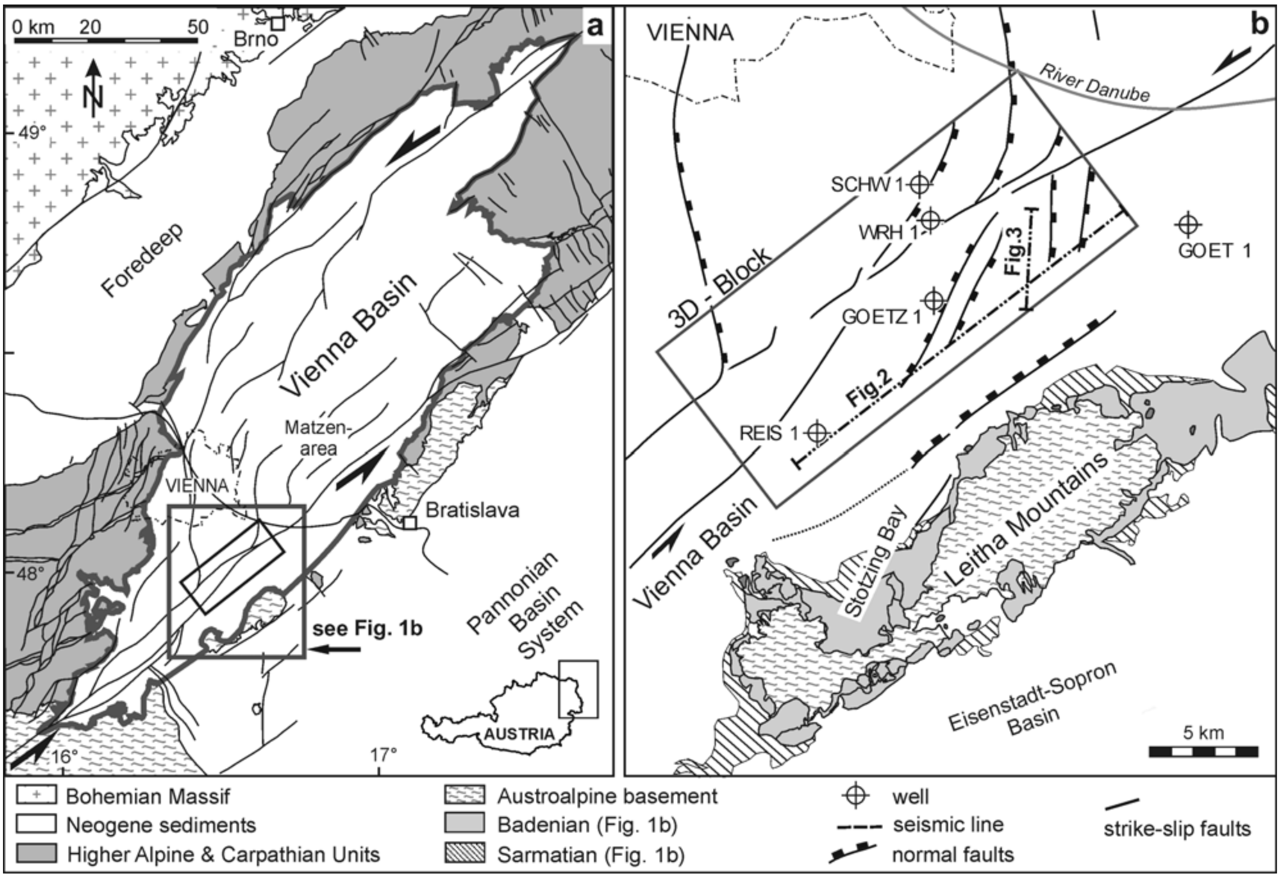

Fig. 1. a — Position of the Vienna Basin between the Eastern Alps and the Western Carpathians (modified after Decker et al. 2003). **b** — Close up of the Leitha Mountains and the position of the 3D seismic block Moosbrunn (OMV).

tablished based on the correlation to 3rd order sea-level changes. Our interdisciplinary approach allows a finer resolution of the time-dependent structural and sedimentary evolution of the Vienna Basin.

Tectonic and lithostratigraphic evolution of the Vienna Basin

The formation and geological history of the Vienna Basin is divided into four major stages (see also Royden 1985, 1988; Jiříček & Seifert 1990; Ratschbacher et al. 1991; Decker 1996; Decker et al. 2004; Kováč et al. 2004):

1 — Formation of a piggyback basin (Lower Miocene)
2 — pull-apart basin (Middle to Upper Miocene)
3 — E-W compression and basin inversion (Upper Miocene)
4 — E-W extension (Pleistocene–Recent)

The sequence stratigraphic framework presented in this paper concentrates on Lower to Middle Miocene strata, that is only on the piggyback and pull-apart stages of the Vienna Basin. During the pull-apart phase the Vienna Basin is separated into several fault blocks, where local variations in sedimentary evolution may exist. The following section gives an overview on the overall tectonic and sedimentary evolution of the Vienna Basin, focusing on the southern Vienna Basin and the Leitha Mountains. To complete the picture, the Upper Miocene and younger basin history is briefly summarized.

Piggyback basin (Lower Miocene)

The formation of the Vienna Basin started in the Early Miocene as an E-W trending piggyback basin on top of the Alpine thrust belt (e.g. Decker 1996). This basin was active from the Eggenburgian (Table 1) to the Early Karpatian (Seifert 1996). According to Kováč et al. (1993a; 2004) and Lankreijer et al. (1995) the Eggenburgian and Ottnangian lateral stress fields indicate NW-SE compression. Eggenburgian sediments are not known from the southern Vienna Basin. Sedimentation of lacustrine to brackish-littoral deposits in the central Vienna Basin started during the Ottnangian and Early Karpatian with the deposition of the Bockfliess Formation (Table 1) (Rögl et al. 2002), which is covered discordantly by the lacustrine–terrestrial deposits of the Gänserndorf Formation (Kreutzer 1992b). The top of the Gänserndorf Formation grades into the overlying Aderklaa Formation without a major unconformity. Sandstones, interbedded pelites and occasional fine conglomerates characterize the deposits of the limnic-fluvial Aderklaa Formation, which was also deposited in the southern part of the basin (Weissenbäck 1996; see also Fig. 2a).

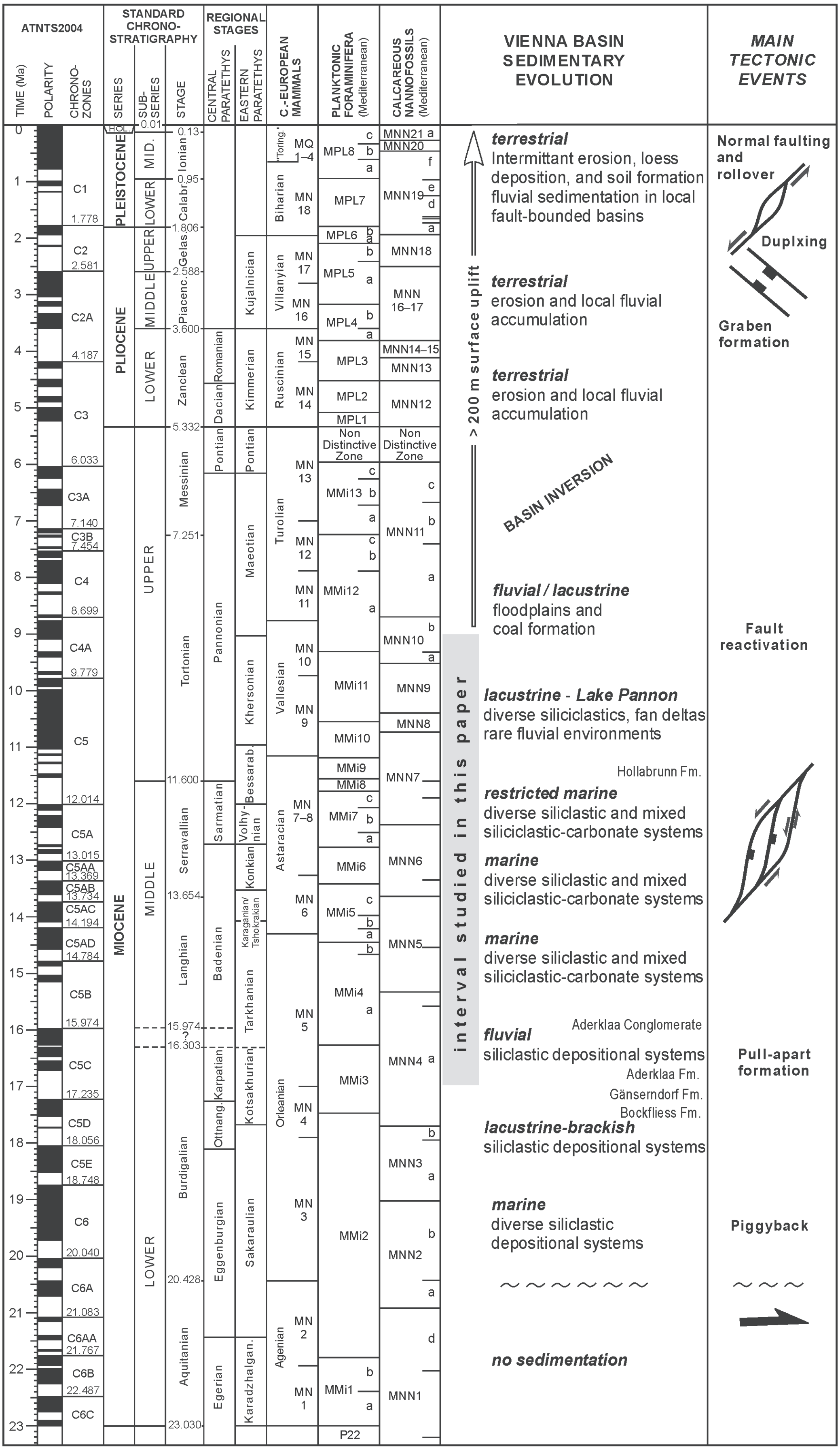

Table 1: Stratigraphy and evolution of the Vienna Basin from the Miocene to the present correlated with the main tectonic events (after Decker 1996; Decker et al. 2003). Biozones according to Sprovieri (1992), Steininger (1999), Fornaciari & Rio (1996), Sprovieri et al. (2002) all zones recalibrated according to Gradstein & Ogg (2004).

Pull-apart basin (Middle to Upper Miocene)

In the Late Karpatian, thrusting developed into lateral extrusion (Table 1), and causing a geometric change from a piggyback basin into a rhombic pull-apart basin (Royden 1985, 1988; Wessely 1988; Tomek & Thon 1988; Kováč et al. 1993a,b, 1997; Fodor 1995; Lankreijer et al. 1995; Decker 1996; Seifert 1996). One of the major basin bounding faults developed close to the Leitha Mountains (Fig. 1) and follows the major presently active area in the Vienna Basin (Hinsch & Decker 2003; Decker et al. 2004).

This change in tectonic regime (Wagreich & Schmid 2002) is locally documented as a major regressive event at the Karpatian/Badenian boundary, which can be found in many Paratethyan nearshore settings (Rögl et al. 2002). In the southern Vienna Basin, sedimentation started discordantly during the Early Badenian with the deposition of the Aderklaa Conglomerate (Table 1) in a braided river system during the Early Badenian sea-level lowstand (Weissenbäck 1996).

During these times, sediments were generally transported northwards, with some sedimentation originating from the SSE across the future Leitha Mountains and Eisenstadt-Sopron Basin (Fig. 1b). This drainage system became obsolete with the onset of subsidence in the Eisenstadt-Sopron Basin. Consequently, the first marine incursion approximately 14.5 Ma ago reached as far as the Eisenstadt-Sopron Basin and made the Leitha Mountains a peninsula, with connection to the mainland in the east (Fuchs 1965). Corallinacean limestone developed during this first transgressive event along the flanks of the Leitha Mountains.

In the central Vienna Basin the Badenian sediments are divided into proximal deltaic clastics and a distal basinal facies, which is characterized by sandy marls and clay ("Baden Tegel" Papp & Steininger 1978). An estimated water depth for this period ranges between 100 m and 150 m (e.g. Kreutzer 1986), carbonates formed in areas with little input of clastic material.

On the eastern border of the Vienna Basin the Leitha Mountains were completely covered by water during periods of sea-level highstand in the Badenian, which resulted in the growth of thick corallinacean limestone beds (Leitha Platform and marine shoal stage, Schmid et al. 2001). Detailed sedimentological and paleoecological studies of these limestones (e.g. Fuchs 1965; Dullo 1983; Riegl & Piller 2000; Schmid et al. 2001) revealed three major episodes of carbonate production in a time interval of about 2 Myr, which are separated by distinct layers of marl. Breccias, vadose silt, vadose leaching and caliche formation indicate considerable sea-level fluctuations and phases of emersion of the carbonate platform (Dullo 1983; Schmid et al. 2001; see also Fig. 2b).

A sea-level drop at the Badenian/Sarmatian boundary exposed the Leitha Mountains and their Badenian sedimentary cover. Again, the mountain ridge formed an island (see Fig. 2c) until the Pannonian Lake was filled during the Late Pannonian (Harzhauser & Tempfer 2004; Harzhauser et al. 2004). Valleys formed and the Badenian platforms were intensely eroded (Kroh et al. 2002). A renewed transgression of the Sarmatian eroded the topographically lower parts of the Badenian limestone (Harzhauser & Piller 2004a). This resulted in the detrital Leitha limestone, channel deposits and rare au-

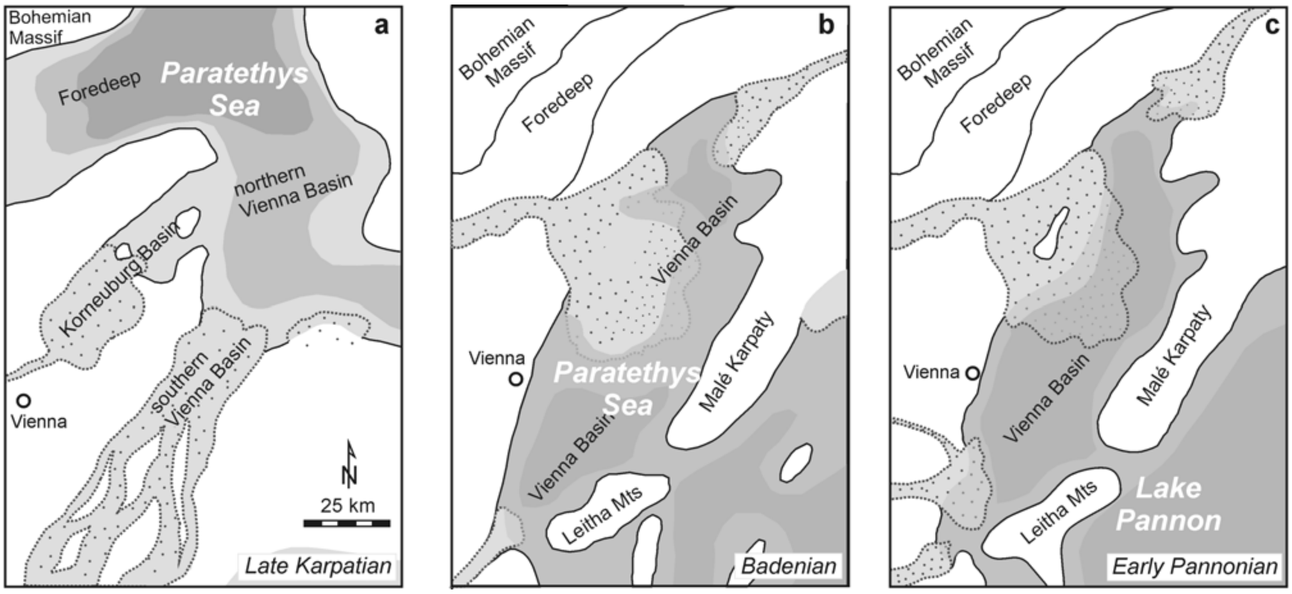

Fig. 2. Paleogeographical cartoon maps of the Vienna Basin (modified after Sauer et al. 1992 and Kováč et al. 2004) at three stages: **a** — The Vienna Basin at Late Karpatian age with major fluvial systems entering the basin from the south, depositing the Gänserndorf and Aderklaa Formation. **b** — Badenian age with deltaic systems entering the central and northern basin. During this interval (and the following Sarmatian) the Leitha Mountains are an island. **c** — the Vienna Basin during the Early Pannonian, large delta systems in the north and the Leitha Mountains an island until the Middle Pannonian.

tochthonous bryozoan/serpulid limestone, representing the uppermost Miocene sediments found in the Leitha Mountains. Sand and carbonate deposition continued throughout the Sarmatian in most parts of the Vienna Basin (Harzhauser & Piller 2004b). The general tectonic regime of SW–NE extension continued from the Badenian to the Sarmatian.

The Pannonian period began with a transgression (Harzhauser et al. 2003, 2004) covering most of the Sarmatian deposits. Primarily clay and sand was deposited in a lacustrine environment (Lake Pannon) during the Early and Middle Pannonian. During the Late Pannonian the Vienna Basin was filled mainly with alluvial sediments.

E-W compression and basin inversion (Upper Miocene–Pliocene)

In the latest Pannonian and Pliocene the large-scale stress field (Table 1) (Decker & Peresson 1996; Cloetingh & Lankreijer 2001) indicates low-strain N-S shortening for the central part of the Vienna Basin. Instead of N-S compression and E-W extension, an E-W compressive stress field evolved, resulting in basin inversion (see Table 1) and sediment deformation (Peresson & Decker 1997).

SW-NE extension (Pleistocene–Recent?)

Fault-controlled subsidence due to a sinistral trans-tensional regime accompanied by recent seismic activity was detected along the eastern limit of the basin (e.g. Mitterndorf Basin) (Gutdeutsch & Aric 1988; Decker et al. 2004; Hinsch & Decker 2004). Faults along the Leitha Mountains are still active today.

Seismic facies and seismic stratigraphy

Database and terminology

This study considers a 3D reflection seismic survey, well data, detailed lithological and stratigraphic information from surface outcrops and biostratigraphy. Seismic data were processed by OMV. The well data (OMV) include mainly geophysical data (gamma ray and EM logs), velocity data, and lithologs from cuttings. The wells are correlated to the seismic survey by velocity information from checkshot surveys and velocity functions (e.g. 1 s TWT (Two Way Time) corresponds to 1100 m depth, 2 s TWT to 2600 m and 2.2 s TWT to approx. 3000 m). Four wells within the area of the seismic survey and one well to the NE of the block in combination with several surface outcrops along the nearby Leitha Mountains provide stratigraphic control.

The sequence stratigraphic framework proposed in this paper follows the methodology and terminology of Hubbard et al. (1986), Sarg (1988), Posamentier & Vail (1988), Posamentier et al. (1988), Van Wagoner et al. (1988) and Miall (1997).

Setting of the 3D seismic block

The seismic facies and stratigraphy was interpreted on the 3D reflection seismic survey "Moosbrunn" (OMV, Austria, Fig. 1a,b indicate location). The seismic lines presented in this study are shown in Figs. 3, 4 (see Fig. 1b for location). Table 2 describes the geometry and reflection character of the seismic sequences. SB is used as an abbreviation for sequence boundary.

The SW-NE seismic section (Fig. 3) shows 3 paleogeographic areas with different facies (Fig. 3b). The southern

Table 2: Description of the main seismic features in the 3D seismic block Moosbrunn (OMV). The lithology is confirmed by well data and outcrop information.

Sequence	Sequence boundary	Thickness (ms TWT)	Character of seismic facies	Lithology
Pa 1	Type 1	400–1000	Medium strength continuous parallel reflectors. In certain areas incised valleys with onlaps on channel walls.	Sands and clays deposited in lacustrine/fluvial environment, lignite.
Sa 1	Type 1	200–450	Thick & chaotic high amplitude reflectors on the base, incised channels followed onlapping reflectors. Medium strength prograding reflectors in the upper part.	Coarse sand and carbonate debris filling incised channels. Sand and carbonate in higher stratigraphic position.
Ba 3	Type 2	250	High amplitudes at its base, progradation and downlapping, parallel and continuous further up and low amplitude and progradation on the top.	Sand, clay in the lower parts, carbonate on top.
Ba 2	Type 1	0–400	Base is irregular with high amplitudes truncating Ba 1, downlap on its base. Medium amplitude, parallel & highly continuous in the upper part, aggradational onlapping. Progradation and occasionally downlap on the top.	Coarse, eroded material (carbonate debris?) on the base followed by sand and silt. Carbonate and sand on top.
Ba 1	Type 1	20–450	Medium to high amplitude, sub-parallel & highly continuous, truncates Ka 1, onlap in the lower parts, progradation an downlap in the upper parts.	Fluvial gravel and coarse sand on the base, marine sand and carbonate in the upper parts.
Ka 1	Type 1	0–700	Medium to high amplitude, sub-parallel, partly with prograding structures and channels.	Sand and clay deposited in a lacustrine/fluvial environment.
Basement			Transparent to low amplitude, mostly chaotic.	Dolomite and quartzite.

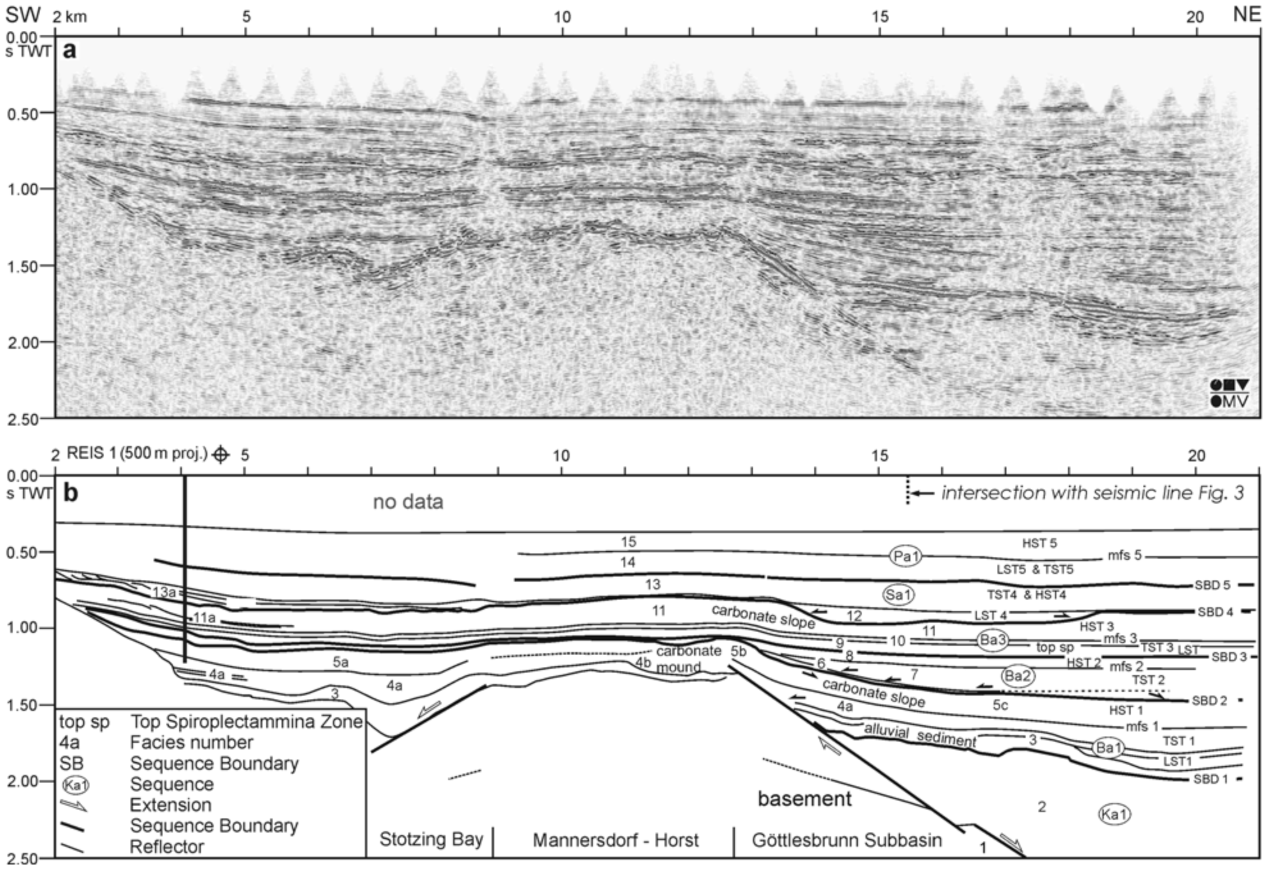

Fig. 3. a — SW-NE trending seismic section from the 3D seismic survey Moosbrunn (data with courtesy of OMV). **b** — its corresponding interpretation (see Fig. 1b for position). Vertical exaggeration is approximately 2.9 at 2 s TWT.

Stotzing Bay is dominated by clastic sedimentation, which can be directly compared and correlated with surface outcrops and wells. Normal faults separate the middle part of the section, which represented a topographic high (Mannersdorf Horst, Fig. 3) during the Badenian. This structure offered ideal conditions for the growth of a carbonate platform during the warm temperate to subtropical Badenian. Similar limestones (corallinacean limestone with rare and scattered patch reefs and coral carpets) are typical for both flanks of the Leitha Mountains.

The northern part of the seismic section covers the southern margin of the Göttlesbrunn Subbasin (Fig. 3), where the Neogene sediments reach a thickness of up to 3000 m (Kröll & Wessely 1993).

Seismic stratigraphy

Basement, Unit 1

The basement of the Miocene sediments in the Moosbrunn 3D seismic block is formed by pre-Cenozoic rocks, predominantly Central Alpine Crystalline units and to the SW of the 3D block Central Alpine Permian-Mesozoic units (Kröll & Wessely 1993), which also form most of the Leitha Mountains. The lithology is constrained by the wells Goetzendorf 1 (GOETZ 1) and Wienerherrberg 1 (WRH 1) as well as surface outcrops.

Karpatian Strata (Ka 1), Unit 2

Sediments of Unit 2 were deposited in en-echelon half-graben structures (Fig. 3; 14–20 km, Fig. 4, Ka 1). The deposits are interpreted as equivalents of Upper Karpatian fluvial/deltaic Aderklaa Formation (Table 1) (Weissenbäck 1996). The Aderklaa Formation lies directly on the basement, a thickness of about 200 m for the Aderklaa Formation (Table 2), is documented in the nearby well WRH 1.

Badenian Sequence 1 (Ba 1), Units 3, 4, 5

Unit 3 represents a group of strong and very distinct reflectors with a thickness of 15–25 ms TWT (20 to 30 m). It correlates with the Aderklaa Conglomerate in wells WRH 1 and Goetttlesbrunn 1 (GOET 1) (Table 1), which was deposited with an angular unconformity on the tilted (due to thrusting in the Late Karpatian) Karpatian strata. The top layer of Unit 3 has a thickness of 30 ms TWT (approx. 50 m), which is relatively constant throughout the 3D survey. The Aderklaa Conglomerate represents the lowstand system tract (LST) deposits of the Early Badenian (see also Weissenbäck 1996 and Kováč et al. 2004).

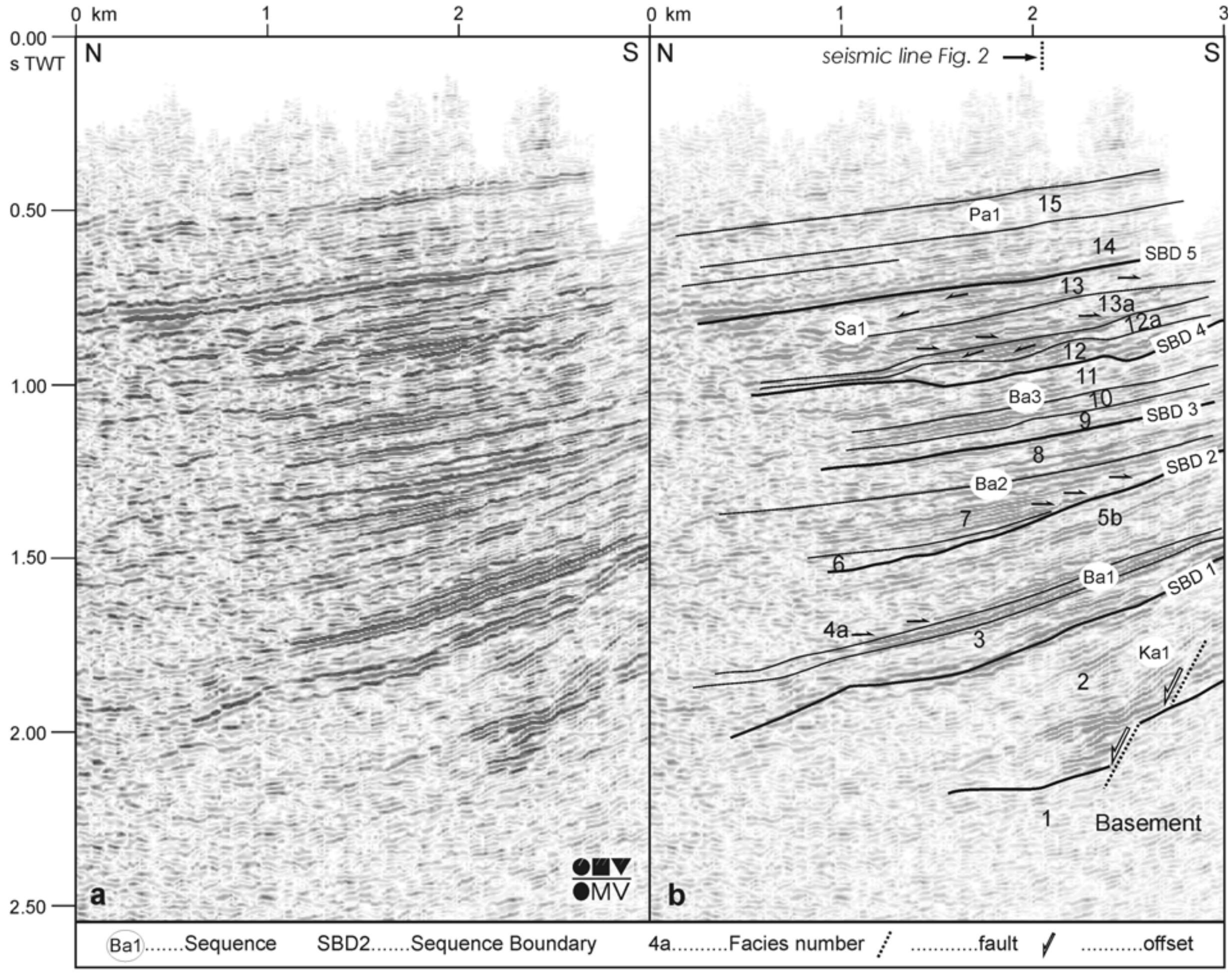

Fig. 4. a — N-S trending seismic section from the 3D seismic survey Moosbrunn (data with courtesy of OMV). **b** — its corresponding interpretation (see Fig. 1b for position). The Badenian-Sarmatian boundary (SB 4) is very well pronounced in this section. Vertical exaggeration is approximately 1.7 at 2 s TWT.

Unit 4 developed during the transgressive system tract (TST) of the Early Badenian (Unit 4a in Fig. 3, 4–5 km). Most of the deposits are interpreted as transgressive sands; the low amplitude reflectors of Unit 4b are interpreted as carbonates. Comparisons with unpublished well reports (OMV) allow the correlation of Unit 4 with the Lower Lagenidae Zone (Rögl et al. 2002). The maximum flooding surface 1 (mfs 1) (this study) separating Subunit 4a from Unit 5 is equivalent to the mfs 1 in Weissenbäck (1996).

Unit 5 represents the highstand system tract (HST) of Sequence Ba 1, mainly consisting of sand and carbonate (several carbonate layers each up to 30 m, Fig. 3 well Reisenberg 1 (REIS 1, TWT 1.1 s–1.2 s depth). Unit 5b represents a prograding carbonate mound and an adjacent slope of presumably carbonate debris. The co-occurrence of *Praeorbulina glomerosa circularis* and *Orbulina suturalis* (internal report of Geological Survey Vienna by Ch. Rupp) in sediments of a correlated outcrop identifies the deposits as uppermost Lower Lagenidae Zone or lower Upper Lagenidae Zone (sensu Rögl et al. 2002).

Badenian Sequence 2 (Ba 2), Units 6, 7, 8

The high amplitude reflectors of Unit 6 (Figs. 3, 4) with downlap on SB 2 are interpreted as a lowstand wedge, which forms the base of Sequence Ba 2. The lowstand system tract (LST) is thin in the investigated area, but massive sand and gravel layers are found in the central and northern Vienna Basin (Zwerndorf Member) in a comparable position. These LST sediments formed as a result of a major sea-level drop causing emersion and erosion of the carbonate body (Unit 5b) on the Mannersdorf Horst. Similarly, the Spannberg ridge in the Matzen area seems to get exposed simultaneously (cf. Fig. 3 in Kreutzer & Hlavatý 1990).

Unit 7 is a well-developed transgressive wedge attaining a thickness of up to 300 ms (approx. 350 m, Figs. 3, 4) with medium strength, parallel reflectors. A transgressive wedge in a stratigraphically equal position in the central Vienna Basin is described in detail by Kreutzer (1986, 1992b) and Kreutzer & Hlavatý (1990), where it covers parts of the Upper Lagenidae Zone and lower parts of the *Spiroplectammina* Zone (Fig. 5).

Unit 8, showing progradational features and discontinuous, partly parallel or wavy reflectors of low amplitude, interpreted as HST sediments. Units 7 and 8 are strongly condensed in the SW of the section.

Badenian Sequence 3 (Ba 3), Units 9, 10, 11

Unit 9 indicates the onset of a new cycle, separated from Sequence Ba 2 by the very strong reflector SB 3 (Fig. 3 and Fig. 4). It is interpreted as LST, composed of wavy and discontinuous reflectors with prograding geometries. However, there are few erosional features and no angular unconformity with Unit 8, hence SB 3 is interpreted as a type 2 sequence boundary.

During the following TST (Unit 10) the LST sediments are overlain by onlapping sets that terminate in a strong reflector, which is considered as mfs 3. Vass et al. (1988) documented a corresponding flooding surface in the adjacent Malé Karpaty Mountains. The first reflector of TST 3 can be correlated with the boundary between the *Spiroplectammina* and the *Bulimina/Bolivina* Zones in well Goetz 1.

The central part of the section shows mound-shaped features in Unit 11 similar to Subunit 5b. Sub-parallel and continuous reflectors with prograding geometries form the lower part of Unit 11. The upper reflectors have low amplitudes and are not continuous. This mound structure is connected to a prograding slope with downlaps equivalent to Subunit 5c. These highstand system tract sediments are interpreted as thick corallinacean limestones (Unit 11), which formed along the Leitha Mountains. Recently, Riegl & Piller (2000) described biostromal coral carpets from this area. The deposition of thin corallinacean limestones starts at the same time in the central Vienna Basin (Kreutzer 1978).

Sarmatian Sequence 1 (Sa 1), Units 12, 12a, 13 & 13a

The onset of sequence Sa 1 is marked by the erosive discordance SB 4. Strong, thick, and partly chaotic reflectors with downlaps on the channel floors and onlaps on the channel walls indicate coarse filling of deeply incised channels (Unit 12, Figs. 3, 4). Carbonate debris from the eroded platform fills these channels. Unit 12 is covered by high amplitude down-lapping sediments (Unit 12a) in certain areas of the 3D block (Fig. 3).

Sub-parallel reflectors of medium amplitude and onlaps represent the TST (Unit 13, Fig. 4). Unit 13a represents the HST, with low amplitude reflectors interpreted as fine sand and carbonate.

Pannonian Sequence 1 (Pa 1), Units 14, 15

In some areas of the 3D block the base of Unit 14 is erosive; channels cut in the top of sequence Sa 1. The reflectors are parallel, continuous and of medium amplitude. LST and TST are combined in this unit since no clear boundary could be mapped. Correlation with well REIS 1 identifies Unit 14 as Lower Pannonian.

Unit 15 represents the HST of this sequence. The reflectors are parallel, continuous and of low amplitude. Silt and clay dominate this section (single layers of sand and lignite). It was deposited during the Middle Pannonian (correlation with well REIS 1).

Discussion

In the following section, the Neogene evolution of the southern Vienna Basin will be discussed combining results from the previous section and biostratigraphic ages from drilling samples and surface outcrops, sequence stratigraphic interpretations and the regional tectonic setting. Additionally, sediments from the southern Vienna Basin will be compared with Neogene deposits in neighbouring basins.

A correlation of sequence boundaries in the Vienna Basin to global sea-level curves from Haq et al. (1988) and Hardenbol et al. (1998) is discussed (see also Fig. 5).

Karpatian

The basal Neogene (Lower Miocene) deposits are Upper Karpatian fluvial/deltaic sediments of sequence Ka 1. SB 1 is the Karpatian/Badenian boundary and corresponds to the Burdigalian/Langhian boundary, which is dated at either 16.4 Ma (Berggren et al. 1995; Hardenbol et al. 1998) based on the FAD of *Praeorbulina*, or at 15.97 Ma (Gradstein & Ogg 2004) referring to a paleomagnetic event. Typically, this sequence boundary appears as an angular unconformity in the Vienna Basin. Tilting of Karpatian deposits reflects the regional tectonic change from a piggyback to a pull-apart basin in the Upper Karpatian. However, the duration of the resulting hiatus, which coincides with erosion of up to 400 m of Karpatian sediments (Weissenbäck 1996), is not well documented in the Austrian part of the basin.

Badenian

The Middle Miocene starts with coarse clastics of the Aderklaa Conglomerate (Unit 3) representing the LST of the first Badenian cycle (Ba 1), including Unit 3 to Unit 5. During Sequence Ba 1 the first thick carbonate body developed on top of the Mannersdorf Horst. The unconformity SB 2 marks the top of cycle Ba 1. Due to the simultaneous occurrence of *Orbulina* and *Praeorbulina* in the underlying deposits of the Stotzing Bay (Rögl et al. 2002) this boundary can be correlated to the 14.2 Ma hiatus (cf. Shevenell et al. 2004). This sequence boundary SB 2 is associated with a major sea-level drop, which is well documented throughout the Vienna Basin, in particular in the Matzen oilfield (Kreutzer 1986; Weissenbäck 1996) and in many marginal settings such as the central Vienna Basin (Niederleis, Lower Austria) and the Eisenstadt-Sopron Basin (Fig. 1b). The top of the first Badenian sequence can be correlated with this regressive event (Mandic et al. 2002; Kroh et al. 2003).

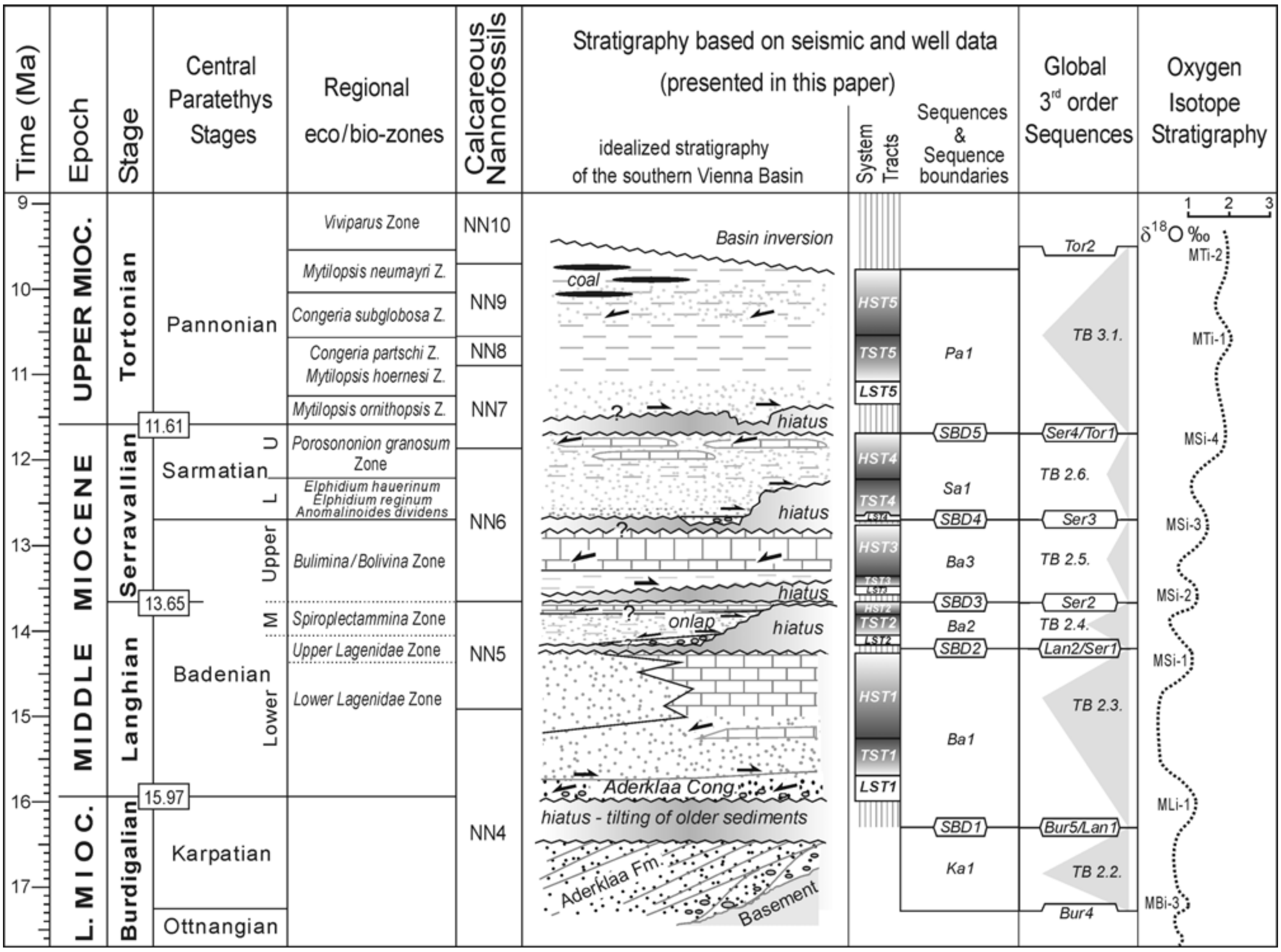

Fig. 5. Stratigraphy of the southern Vienna Basin based on 3D seismic data, well and outcrop information presented in this paper is compared to standard stratigraphy. Global cycles from Haq et al. (1988) and Hardenbol et al. (1998), oxygen isotope stratigraphy adapted after Abreu & Haddad (1998). Note that the Ser 4/Tor 1 and Ser 2 boundary are adjusted following Gradstein & Ogg (2004). Hence, the Ser 2 boundary corresponds to the Langhian/Serravallian boundary, whereas the Lan 2/Ser 1 boundary is positioned in the Langhian. The Ser 3 boundary at 12.7 Ma is adopted uncritically. Because of the frequent use of the Calcareous Nannoplankton Zones of Martini (1971) in the Paratethys literature they have been recalibrated here according to Gradstein & Ogg (2004).

The second cycle (Ba 2) represents a thin low stand wedge (Unit 6) and a well-developed transgressive wedge (Unit 7), which was also found in the central Vienna Basin (Kreutzer 1986). Deposits similar to Unit 6 and 7 are found in equivalent stratigraphic position throughout the Vienna Basin (e.g. Kapounek & Papp 1969; Kreutzer 1992b; Weissenbäck 1995), thus supporting the interpretation of Sequence Ba 2 as a type 1 Sequence.

The preceding regression is characterized by a pronounced shift of the onset of the transgressive wedge 3.5 km to the NE and 0.25 s TWT down (see Fig. 3, 13 km to 16.5 km). To estimate the difference in sea level between Unit 5b and the onset of Unit 7 the differential compaction of sediments on the Mannersdorf Horst and in the Goettlesbrunn Subbasin as well as local subsidence has to be taken into account. This approximation results in an overall sea-level change between 90 to 120 m. The transgressive sediments of sequence Ba 2 are followed by thin HST sediments (Unit 8).

Sequence Ba 2 ends with the boundary SB 3. The stratigraphic position of the associated sea-level drop suggests a correlation to the Wielician crises (Steininger et al. 1978), which was characterized by the deposition of evaporites in the Carpathian Foreland Basin. This sea-level change around the Serravallian boundary (e.g. Steininger et al. 1978; Kasprzyk 1999; Chira 2000; Hudáčková et al. 2000) affected wide areas of the Central Paratethys (Rögl 1998). It is possible this event correlates with the glacio-eustatic event at 14.2 Ma leading into the Mid-Miocene climate transition (Shevenell et al. 2004).

The renewed flooding of the third Badenian cycle (Ba 3) is biostratigraphically dated in the Slovak part of the Vienna Basin with the onset of the nannoplankton Zone NN6 (e.g. Hudáčková et al. 2000). The base of this biozone is defined by the last occurrence of *Sphenolithus heteromorphus* (Deflandre) and corresponds to the Langhian/Serravallian boundary (see also Fig. 5), which was recently calibrated by Foresi et al. (2002) at 13.59 Ma (see also Gradstein & Ogg 2004).

Sarmatian

The strong erosion at SB 4 indicates a considerable hiatus (incised valleys Figs. 3, 4); parts of the Upper Badenian and Lower Sarmatian were removed. It is interpreted as part of the LST 4 at the Badenian/Sarmatian boundary. Incised valleys (Fig. 3, Unit 12), developed along the margin of the Vienna Basin, and were later filled during the onset of an early TST 4 at roughly 12.7 Ma (Harzhauser & Piller 2004b).

At least 3 high-frequency sea-level drops have been observed in the Lower Sarmatian deposits of the Vienna Basin and the Eisenstadt-Sopron Basin by Harzhauser & Piller (2004a). The most intense regression caused the exposure of the Leitha Mountains during the entire *Elphidium hauerinum* Zone and the lowermost *Porosononion granosum* Zone (Fig. 5). This drop in relative sea level is most likely reflected as a basinward shift of coarse sediments and is also documented in the high amplitude reflectors of Unit 12a (Fig. 4) in the latest Early Sarmatian. Biostratigraphic data are missing for those beds and thus the exact stratigraphic position remains unclear in the discussed 3D block. The correlation between the Vienna Basin and the Styrian Basin, dates the regressive event to about 12.2 Ma (Harzhauser & Piller 2004b). In the Styrian Basin this event formed up to 100 m thick coarse clastics of Carinthian gravel (Harzhauser & Piller 2004b).

The Late Sarmatian starts with a strong transgression. Associated sediments are well developed along the margin of the southern Vienna Basin (Wessely 1961; Harzhauser & Piller 2004b). Deposits of the following HST 4 are known throughout the Vienna Basin and consist of mixed siliciclastic-oolitic sediments of the upper *Ervilia* Zone (approx. 12 Ma). This cycle is also well developed in the Styrian Basin (Southern Austria) as discussed in Kosi et al. (2003).

Pannonian

A significant relative sea-level drop occurred at the Sarmatian/Pannonian boundary at about 11.6 Ma (Harzhauser et al. 2004). Deep erosive channels were formed during the following sea level low stand, visible in seismic Unit 14. During the LST 5 of the Early Pannonian, fluvial gravel of the Hollabrunn Formation (Table 1) was deposited in the central Vienna Basin (Harzhauser et al. 2003, 2004). In the neighbouring Eisenstadt-Sopron Basin fluvial gravel with *Melanopsis impressa* was deposited above Sarmatian marine sediments at the same time (Harzhauser et al. 2002). The pelitic and sandy deposits of the TST 5 cover the *Mytilopsis hoernesi* Zone, the *Congeria partschi* Zone and parts of the *Congeria subglobosa* Zone (Fig. 5). Harzhauser et al. (2002, 2003, 2004) describe, facially and temporally equivalent sediments from the northern Vienna Basin and the Eisenstadt-Sopron Basin. The following mfs 5 was found in the northern and central Vienna Basin within the *Congeria subglobosa* Zone (Kováč et al. 1998; Harzhauser & Mandić 2004). Seismic Unit 15 represents the HST of the sequence Pa 1. Lignites, from the top of this unit (well REIS 1, depth 240–300 m TWT) allow a correlation with lignites of the nearby Neufeld Formation and other deposits in the northern Vienna Basin (Kováč et al. 1998). At that time, Lake Pannon retreated from the Vienna Basin and its NW coast shifted towards the Danube Basin (Magyar et al. 1999). Consequently, extended floodplains with local lacustrine systems developed in the Vienna Basin (Harzhauser & Tempfer 2004).

Correlations of sequence boundaries in the Vienna Basin to global sea-level changes

This work describes three sequences for the Badenian of the southern and central Vienna Basin. Our correlation separates the Badenian clearly into two sequences, which cover the Langhian Stage and a third one representing the lower Serravallian. We propose a correlation of those sequences with the TB 2.3., TB 2.4. and TB 2.5. global cycles of Haq et al. (1988) and the sequence boundaries Bur-5/Lan-1, Lan-2/Ser-1 and Ser-2 of Hardenbol et al. (1998). Vakarcs et al. (1998) describes these depositional sequences as 3rd order cycles (see Fig. 5). The most prominent Badenian sequence is Ba 2. Its stratigraphic position and the considerable magnitude in sea-level drop suggest a relation to the global sea-level drop at about 14.2 Ma, which is correlated to the expansion of the East Antarctic ice sheet (Flower & Kennett 1993; Shevenell et al. 2004).

Consequently, a correlation of the unconformities at the Sarmatian sequence Sa 1 with the Ser-3 (base) and Ser-4/Tor-1 (top) boundaries of Hardenbol et al. (1998) and the 3rd order TB 2.6. cycle of Haq et al. (1988) can be assumed.

The subsequent Pannonian sequence may be aligned with the Tortonian transgression (Ser-4/Tor-1). Vass et al. (1987) determined a radiometric age of approximately 11.5 Ma for this event. However, this age does not correspond to the Serravallian/Tortonian boundary at 11.20 Ma as proposed by Berggren et al. (1995). New astronomically based data on the age of the Serravallian/Tortonian boundary, point towards an absolute age of 11.6 Ma (Gradstein & Ogg 2004). Hence, a correlation to the glacio-eustatic sea-level lowstand of the TB 3.1. cycle of Haq et al. (1988) is possible, but the development of Lake Pannon is largely decoupled from global marine sea-level changes, therefore this correlation is questionable.

Conclusion

In this paper a new, integrated sequence stratigraphy for the southern Vienna Basin is presented. Although local and regional tectonic movements contribute to the geometries of sedimentary sequences, a similar stratigraphic evolution is found on tectonically decoupled fault blocks throughout the Vienna Basin and in other adjacent Neogene basins. Hence we propose to link the overall stratigraphic frame to (sub)global cycles (Fig. 5). Five Middle and Upper Miocene 3rd order sequences are described for the Neogene in the Vienna Basin (see also Kováč et al. 2004).

The sequence boundaries in the Vienna Basin are dated by (nanno)plankton. A refined local biostratigraphy allows their correlation to global 3rd order sea-level changes (Haq et al. 1988; Hardenbol et al. 1998). The Badenian sequences Ba 1, Ba 2 and Ba 3 are correlated with the cycles TB 2.3., TB 2.4., TB 2.5., the Sarmatian sequence Sa 1 is correlated with TB 2.6. and the Pannonian sequence with TB 3.1. For the first time, the magnitude of the major sea-level drop separating the cycles Ba 1 from Ba 2 can be estimated as about 90–120 m.

This study considerably improves the understanding of age and timing of the sedimentary and kinematic evolution of the Vienna Basin.

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References

Abreu V.S. & Haddad G.A. 1998: Glacioeustatic fluctuations: the mechanism linking stable isotope events and sequence stratigraphy from the Early Oligocene to Middle Miocene. In: Graciansky C.-P., Hardenbol J., Jacquin T. & Vail P.R. (Eds.): Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. *SEPM Spec. Publ.* 60, 245–260.

Berggren W.A., Kent D.V., Swisher C.C. & Aubry M.P. 1995: A revised Cenozoic Geochronology and Chronostratigraphy. *SEPM Spec. Publ.* 54, 129–212.

Cloetingh S. & Lankreijer A. 2001: Lithospheric memory and stress field controls on polyphase deformation of the Pannonian basin-Carpathian system. *Mar. Petrol. Geol.* 18, 3–11.

Chira C. 2000: Miocene calcareous nannoplancton and molluscs from Transylvania, Romania. *Editura Carpatica,* Cluj-Napoca, 1–183 (in Romanian).

Decker K. 1996: Miocene tectonics at the Alpine-Carpathian junction and the evolution of the Vienna Basin. *Mit. Gesell. Geol. Bergbaustud. Österr.* 41, 33–44.

Decker K. & Peresson H. 1996: Tertiary kinematics in the Alpine-Carpathian-Pannonian system: links between thrusting, transformation faulting and crustal Extension. In: Wessely G. & Liebl W. (Eds.): Oil and gas in Alpidic Thrustbelts and Basins of the Central and Eastern Europe. *European Assoc. Geoscientists and Engineers, Spec. Publ.* 5, 69–77.

Decker K., Peresson H. & Hinsch R. submitted: Active tectonics and Quaternary basin formation along the Vienna Basin transform fault. *Quat. Sci. Rev.*

Dullo W.C. 1983: Diagenesis of fossils of the Miocene Leitha Limestone of the Paratethys, Austria: An example for faunal modifications due to changing diagenetic environments. *Facies* 8, 1–112.

Flower B.P. & Kennett J.P. 1993: Middle Miocene ocean-climate transition: high-resolution oxygen and carbon isotopic records from Deep Sea Drilling Project Site 588A, southwest Pacific. *Paleooceanography* 8, 4, 811–843.

Fodor L. 1995: From transpression to transtension: Oligocene-Miocene structural evolution of the Vienna Basin and the East Alpine-Western Carpathian junction. *Tectonophysics* 242, 151–182.

Foresi L.M., Bonomo S., Caruso A., Di Stefano A., Di Stefano E., Salvatorini G. & Sprovieri R. 2002: Calcareous plankton high resolution biostratigraphy (Foraminifera and Nannofossils) of the Uppermost Langhian-Lower Serravallian Ras Il-Pellegrin Section (Malta). *Riv. Ital. Paleont. Stratigr.* 108, 195–210.

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

Fuchs W. 1965: Geologie des Ruster Berglandes (Burgenland). *Jb. Geol. Bundesanst.* 108, 155–194.

Gutdeutsch R. & Aric K. 1988: Seismicity and neotectonics of the East Alpine-Carpathian and Pannonian area. *AAPG* 45, 183–194.

Gradstein F.M. & Ogg J.G. 2004: Geologic time scale 2004 — why, how, and where next! *Lethaia* 37, 175–181.

Haq B.U., Hardenbol J. & Vail P.R. 1988: Mesozoic and Cenozoic chronostratigraphy and cycles of sea level changes. In: Wilgus C.K., Hastings B.S., Kendall C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. (Eds.): Sea-level changes — an integrated approach. *SEPM Spec. Publ.* 42, 71–108.

Hardenbol J., Thierry J., Farley M.B., Jacquin T., Graciansky P.C. & Vail P.R. 1998: Mesozoic and Cenozoic sequence chronostratigraphic framework of European Basins. In: Graciansky C.P., Hardenbol J., Jacquin T. & Vail P.R. (Eds.): Mesozoic and Cenozoic sequence stratigraphy of European Basins. *SEPM Spec. Publ.* 60, 3–13.

Harzhauser M., Daxner-Höck G. & Piller W.E. 2004: An integrated stratigraphy of the Pannonian (Late Miocene) in the Vienna Basin. *Austrian J. Earth Sci.* 95, 96, 6–19.

Harzhauser M., Kowalke Th. & Mandic O. 2002: Late Miocene (Pannonian) gastropods of Lake Pannon with special emphasis on Early ontogenetic development. *Ann. Naturhist. Mus. Wien* 103A, 75–141.

Harzhauser M., Kovar-Eder J., Nehyba S., Strobitzer-Hermann M., Schwarz J., Wojcicki J. & Zorn I. 2003: An Early Pannonian (Late Miocene) transgression in the Northern Vienna Basin. The paleoecological feedback. *Geol. Carpathica* 54, 41–52.

Harzhauser M. & Mandic O. 2004: The muddy bottom of Lake Pannon — a challenge for dreissenid settlement (Late Miocene; Bivalvia). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 204, 331–352.

Harzhauser M. & Piller W.E. 2004a: The Early Sarmatian — hidden seesaw changes. *Cour. Forschungsinst. Senckenberg* 246, 89–112.

Harzhauser M. & Piller W.E. 2004b: Integrated stratigraphy of the Sarmatian (Upper Middle Miocene) in the western Central Paratethys. *Stratigraphy* 1, 65–86.

Harzhauser M. & Tempfer P. 2004: Late Pannonian Wetland ecology of the Vienna Basin based on molluscs and Lower vertebrate assemblages (Late Miocene, MN 9, Austria). *Cour. Forschungsinst. Senckenberg* 246, 55–68.

Hinsch R. & Decker K. 2003: 3-D mapping of segmented active faults in the Vienna Basin from integrated geophysical, geomorphological and geological data: building up an active fault database. *EGS-AGU-EUG Joint Assembly, Nice. Geophys. Res. Abst., European Geophys. Soc.* 5, 10272.

Hinsch R., Decker K. & Wagreich M. 2005: 3-D mapping of segmented active faults in the southern Vienna Basin. *Quat. Sci. Rev.* 24, 321–336.

Hudáčková N., Holcová K., Zlinská A., Kováč M. & Nagymarosy A. 2000: Paleoecology and eustasy: Miocene 3rd order cycles of relative sae-level changes in the Western Carpathian — North Pannonian basins. *Slovak Geol. Mag.* 6, 95–100.

Hubbard R.J., Pape J. & Roberts D.G. 1986: Depositional sequence mapping as a tool to establish tectonic and stratigraphic framework and evaluate hydrocarbon potential on a passive continental margin. In: Berg O.R. & Woolverton D.G. (Eds.): Seismic stratigraphy II an integrated approach. *AAPG Memoir* 39, 79–92.

Jiříček R. & Seifert P. 1990: Paleaogeography of the Neogene in the Vienna Basin and adjacent part of the fordeep. In: Minaříková D. & Lobitzer H. (Eds.): Thirty years of geological cooperation between Austria and Czechoslovakia. *ÚÚG*, Praha, 89–105.

Kapounek J. & Papp A. 1969: Der Vulkanismus in der Bohrung Orth 1 und die Verbreitung von Grobschüttungen zwischen dem Spannberger Rücken und der Donau. *Verh. Geol. Bundesanst.* 2, 114–123.

Kasprzyk G. 1999: Sedimentary evolution of the Badenian (Middle Miocene) gypsum deposits in the northern Carpathian Foredeep. *Geol. Quarterly* 43, 449–654.

Kosi W., Sachsenhofer R.F. & Schreilechner M. 2003: High resolution sequence stratigraphy of Upper Sarmatian and Lower Pannonian Units in the Styrian Basin, Austria. In: Piller W.E. (Ed.): Stratigraphia Austriaca. *Österr. Akad. Wiss., Schriftenreihe der Erdwissenschaftlichen Kommissionen* 16, 54–72.

Kováč M., Baráth I., Kováčová-Slamková M., Pipík R., Hlavatý I. & Hudáčková N. 1998: Late Miocene paleoenvironments and sequence stratigraphy: Northern Vienna Basin. *Geol. Carpathica* 49, 445–458.

Kováč M., Nagymarosy A., Soták J. & Šútovská K. 1993a: Late Tertiary paleogeographic evolution of the Western Carpathians. *Tectonophysics* 226, 401–416.

Kováč M., Marko F. & Baráth I. 1993b: Structural and paleogeographic evolution of western margin of the Central Western Carpathians during the Neogene. In: Rakús M. & Vozár J. (Eds.): Geodynamic model and deep structure of the Western Carpathians. *GÚDŠ*, Bratislava, 45–56.

Kováč M., Baráth I. & Nagymarosy A. 1997: The Miocene collapse of the Alpine–Carpathian–Pannonian junction: an overview. *Acta Geol. Hung.* 40, 241–264.

Kováč M., Baráth I., Harzhauser M., Hlavatý I. & Hudáčková N. 2004: Miocene depositional systems and sequence stratigraphy of the Vienna Basin. *Cour. Forschungsinst. Senckenberg* 246, 187–212.

Kreutzer N. 1986: Die Ablagerungssequenzen der miozänen Badener Serie im Feld Matzen und im zentralen Wiener Becken. *Erdöl-Erdgas-Kohle* 102, 492–503.

Kreutzer N. 1978: Die Geologie der Nulliporen (Lithothamnien)-Horizonte der miozänen Badener Serie des Ölfeldes Matzen (Wiener Becken). *Erdöl-Erdgas-Zeitschrift* 94, 129–145.

Kreutzer N. 1992a: Das Neogen des Wiener Beckens. In: Brix F. & Schultz O. (Eds.): Erdöl und Erdgas in Österreich. *Naturhistorisches Museum,* Wien, und *F. Berger*, Horn, 403–424.

Kreutzer N. 1992b: Matzen field — Austria, Vienna Basin. *Amer. Assoc. Petrol. Geol., Treatise-Atlas, Struct. Traps* 7, 57–93.

Kreutzer N. & Hlavatý V. 1990: Sediments of the Miocene (mainly Badenian) in the Matzen area in Austria and in the southern part of the Vienna Basin in Czechoslovakia. In: Minaříková D. & Lobitzer H. (Eds.): Thirty years of geological cooperation between Austria and Czechoslovakia. *ÚÚG,* Praha, 110–123.

Kroh A., Harzhauser M. & Piller W.E. 2002: Mass accumulations of regular sea urchins in the Late Badenian (Middle Miocene) of the Leitha Platform (Eastern Austria). *Programm & Kurzfassungen, Pangeo Salzburg* 2002, 101–102.

Kroh A., Harzhauser M., Piller W.E. & Rögl F. 2003: The Lower Badenian (Middle Miocene) Hartl Formation (Eisenstadt-Sopron Basin, Austria). In: Piller W.E. (Ed.): Stratigrafia Austriaca. *Österr. Akad. Wiss., Schriftenreihe der Erdwissenschaftlichen Kommissionen* 16, 87–109.

Kröll A.W. & Wessely G. 1993: Strukturkarte Basis der tertiären Beckenfüllung. Geologische Themenkarte der Republik Österreich. Wiener Becken und angrenzende Gebiete 1:200,000. *Geol. Surv. Austria,* Vienna.

Lankreijer A., Kováč M., Cloetingh S., Pitoňák P., Hlôška M. & Biermann C. 1995: Quantitative subsidence analysis and forward modelling of the Vienna and Danube Basins. *Tectonophysics* 252, 433–451.

Linzer H.G., Decker K., Peresson H., Dell'mour R. & Frisch W. 2002: Balancing lateral orogenic float of the Eastern Alps. *Tectonophysics* 354, 211–237.

Magyar I., Geary D.H. & Müller P. 1999: Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 147, 151–167.

Mandic O., Harzhauser M., Spezzaferri S. & Zuschin M. 2002: The paleoenvironment of an early Middle Miocene Paratethys sequence in NE Austria with special emphasis on paleoecology of mollusks and foraminifera. *Geobios Mém. Spéc.* 35, 193–206.

Martini E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A. (Ed.): Proceedings. 2nd Inernational Conference Planktonic Microfossils Roma. *Ed. Tecnoscienza,* Roma, 2, 739–785.

Miall A.D. 1997: The geology of stratigraphic sequences. *Springer,* Berlin, 1–433.

Papp A. & Steininger F. 1978: Holostratotypus: Baden-Sooss. In: Papp A., Cicha I., Seneš J. & Steininger F. (Eds.): M4 Badenian (Moravien, Wielicien, Kosovien). *Chronostratigraphy und Neostratotypen, Miozän der Zentralen Paratethys* 6, *VEDA*, Bratislava, 138–145.

Peresson H. & Decker K. 1997: Far-field effects of Late Miocene W-directed subduction in the Outer Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpatian-Pannonian region. *Tectonics* 16, 38–56.

Posamentier H.W., Jervey M.T. & Vail P.R. 1988: Eustatic controls on clastic deposition. I. Conceptual framework. In: Wilgus C.K., Hastings B.S., Kendall C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. (Eds.): Sea-level changes — an integrated approach. *SEPM Spec. Publ.* 42, 109–124.

Posamentier H.W. & Vail P.R. 1988: Eustatic controls on clastic deposition. II. Sequence and system tract models. In: Wilgus C.K., Hastings B.S., Kendall C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. Eds. Sea-level changes — an integrated approach. *SEPM Spec. Publ.* 42, 125–154.

Ratschbacher L., Frisch W. & Linzer H.G. 1991: Lateral extrusion in the eastern Alps, part II: structural analysis. *Tectonics* 10, 257–271.

Riegl B. & Piller W.E. 2000: Biostromal Coral Facies — A Miocene example from the Leitha Limestone (Austria) and its actualistic interpretation. *Palaios* 15, 399–413.

Rögl F. 1998: Palaeogeographic considerations for Mediterranean and Paratethys Seaways (Oligocene to Miocene). *Ann.*

Naturhist. Mus. Wien 99A, 279–310.

Rögl F., Spezzaferri S. & Ćorić S. 2002: Micropaleontology and biostratigraphy of the Karpatian-Badenian transition (Early-Middle Miocene boundary) in Austria (Central Paratethys). *Cour. Forschungsinst. Senckenberg* 237, 47–67.

Royden L.H. 1985: The Vienna basin: a thin-skinned pull apart basin. In: Biddle K.T. & Christie-Blick N. (Eds.): Strike-slip deformation, basin formation and sedimentation. *SEPM Spec. Publ.* 37, 319–339.

Royden L.H. 1988: Late Cenozoic tectonics of the Pannonian basin system. In: Royden L. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *AAPG* 45, 27–48.

Sarg J.F. 1988: Carbonate sequence stratigraphy. In: Wilgus C.K., Hastings B.S., Kendall C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. (Eds.): Sea-level changes — an integrated approach. *SEPM Spec. Publ.* 42, 155–182.

Schmid H.P., Harzhauser M. & Kroh A. 2001: Hypoxic events in a Middle Miocene carbonate platform of the Central Paratethys (Austria, Badenian, 14 Ma). *Ann. Naturhist. Mus. Wien* 102A, 1–50.

Seifert P. 1996: Sedimentary-tectonic development and Austrian hydrocarbon potential of the Vienna Basin. In: Wessely G. & Liebl W. (Eds.): Oil and gas in Alpidic thrustbelts and basins of central and eastern Europe. *EAGE Spec. Publ.* 5, 331–341.

Shevenell A.E., Kennett J.P. & Lea D.W. 2004: Middle Miocene Southern ocean cooling and antarctic cryosphere expansion. *Science* 305, 1766–1770.

Sprovieri R. 1992: Mediterranean Pliocene biochronology: a high resolution record based on quantitative planktonic foraminifera distribution. *Riv. Ital. Paleont. Stratigr.* 98, 61–100.

Sprovieri R., Bonomo S., Caruso A., Di Stefano A., Di Stefano E., Foresi L.M., Iaccarino S., Lirer F., Mazzei R. & Salvatorini G. 2000: An integrated calcareous plankton biostratigraphic scheme and biochronology of the Mediterranean Middle Miocene. *Riv. Ital. Paleont. Stratigr.* 108, 337–353.

Steininger F.F. 1999: Chronostratigraphy, geochronology and biochronology of the "European Land Mammal Mega-Zones" (ELMMZ) and the Miocene "Mammal-Zones" (MN-Zones). In: Rössner G.E. & Heissig K. (Eds.): The Miocene land mammals of Europe. *Dr. Friedrich Pfeil*, München, 9–24.

Steiniger F., Rögl F. & Müller C. 1978: Geodynamik und paläogeographische Entwicklung des Badenien. In: Papp A., Cicha I. & Steiniger F. (Eds.): M4 Badenian (Moravien, Wielicien, Kosovien). *Chronostratigraphy und Neostratotypen, Miozän der Zentralen Paratethys* 6, *VEDA*, Bratislava, 110–127.

Tomek Č. & Thon A. 1988: Interpretation of seismic reflection profiles from the Vienna basin, the Danube basin and the Transcarpathian depression in Czechoslovakia. In: Royden L. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *AAPG* 45, 171–182.

Vakarcs G., Hardenbol J., Abreu V.S., Vail P.R., Várnai P. & Tari G. 1998: Oligocene-Middle Miocene depositional sequences of the Central Paratethys and their correlation with regional stages. In: Graciansky P.C., de Hardenbol J., Jacquin T. & Vail P.R. (Eds.): Mesozoic and Cenozoic sequence stratigraphy of European Basins. *SEPM Spec. Publ.* 60, 209–231.

Van Wagoner J.C., Posamentier H.W., Mitchum R.M., Vail P.R., Sarg J.F., Loutit T.S. & Hardenbol J. 1988: An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus C.K., Hastings B.S., Kendall C., Posamentier H.W., Ross C.A. & Van Wagoner J.C. (Eds.): Sea-level changes — an integrated approach. *SEPM Spec. Publ.* 42, 39–46.

Vass D., Repčok I., Halmai J. & Balogh K. 1987: Contribution to the improvement of the numerical time scale for the central Paratethys Neogene. VIIIth Congress of the regional committee on Mediterranean Neogene Stratigraphy. *Ann. Inst. Geol. Publ. Hung.* 70, 423–434.

Vass D., Nagy A., Kohút M. & Kraus I. 1988: Devínska Nová Ves beds: coarse clastic sediments occurred in SE margin of the Vienna Basin. *Miner. Slovaca* 20, 2, 97–10.

Wagreich M. & Schmid H.P. 2002: Backstripping dip-slip fault histories: apparent slip rates for the Miocene of the Vienna Basin. *Terra Nova* 14, 163–168.

Weissenbäck M. 1996: Lower to Middle Miocene sedimentation model of the central Vienna Basin. In: Wessely G. & Liebl W. (Eds.): Oil and gas in Alpidic Thrustbelts and Basins of the Central and Eastern Europe. *EAGE Spec. Publ.* 5, 355–363.

Wessely G. 1961: Geologie der Hainburger Berge. *Jb. Geol. Bundesanst.* 104, 273–349.

Wessely G. 1988: Structure and development of the Vienna basin in Austria. In: Royden L. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *AAPG* 45, 333–346.