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Miocene depositional systems and sequence stratigraphy of the Vienna Basin

With 13 figs, 1 tab.

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Abstract

The Vienna Basin, depositional systems of alluvial plains, deltas, littoral and neritic areas have been characterized to recognize the development of aquatic and terrestrial environments during the paleogeographic evolution of the basin. Their mutual interrelationship was discussed to be triggered by sea-level changes. Based on evaluation of the sedimentary environments, the possibilities of creating an accommodation space by tectonic subsidence, as well as the basin fill by increased input of clastics by deltas it can be stated that only partial comparison between global and regional sea-level changes is possible in the Miocene. Nine third-order cycles of relative sea-level changes are proposed for the Miocene of the Vienna Basin. These cycles, termed VB1 to VB 9, resulted from combination of eustatic global sea-level changes, tectonic evolution of the basin and sediment supply mostly by deltas in this area. Some of these cycles correspond fairly to regional chronostratigraphic stages, whilst others, such as VB 5–7 cycles, follow other criteria.

Key words: Vienna Basin, Miocene, depositional systems, sequence stratigraphy

Zusammenfassung

Die paläogeographische Entwicklung des Wiener Beckens bedingte die Bildung einer großen Vielfalt aquatischer und terrestrischer Lebensräume. Diese spiegeln sich in den miozänen Ablagerungssysteme wider, die von Flusslandschaften und Deltas über Küstenbereiche bis zu offen marinen, neritischen Beckenbedingungen reichen. Die Verzahnung dieser “depositional environments” wurde vorwiegend durch Schwankungen des relativen Meeresspiegels gesteuert. In der vorliegenden Arbeit wird gezeigt, dass die regionalen Meerespiegelschwankungen nur teilweise mit den globalen Schwankungen korreliert werden können. Tektonische Subsidenz und unterschiedlich hoher Eintrag von siliziklastischem Material beeinflussen wesentlich den Ablagerungsraum des hochaktiven Wiener Beckens, wodurch globale Entwicklungen häufig maskiert werden. Neun Zyklen dritter Ordnung werden für das Miozän des Wiener Beckens diskutiert. Diese Zyklen – bezeichnet als VB 1 bis VB 9 – sind daher Produkt eines komplexen Zusammenspiels aus globalen eustatischen Meeresspiegelschwankungen, der tektonischen Evolution des Beckens und des meist über Deltas gesteuerten Sedimenteintrags. Einige dieser Zyklen entsprechen weitgehend den regionalen chronostratigraphischen Stufen, während andere, wie die Zyklen VB 5 bis VB 7, anderen Kriterien folgen.

Schlüsselworte: Wiener Becken, Miozän, Ablagerungssysteme, Sequenz-Stratigraphie

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Introduction

The Vienna Basin is a SSW-NNE oriented Neogene basin of about 200 km length and 55 km width. It spreads from Czech and Slovak Republic in the north to Austria in the south. Due to geological prospecting and exploration of hydrocarbons, there was gathered a high level of knowledge about the sedimentary fill of the basin during the last decades (Minaříková & Lobitzer 1990, Brix & Schlutz 1993). This data set offers an ideal possibility to propose a model of depositional systems and a sequence stratigraphical framework of its sedimentary formations and members. The Neogene sedimentary succession, reaching up to 5500 m of thickness in the central part of the basin (Kilényi & Šefara 1989), is documented by numerous boreholes (well cores & logs) and relatively dense network of seismic profiles (fig.1). By combination of sedimentological and biostratigraphic analyses of outcrops and well cores, interpretation of well-log curves and their mutual correlation, as well as by interpretation of seismic profiles using seismic stratigraphy methods, a complex image of basin evolution and distribution of sedimentary facies in time and space has been achieved.

Outline of the basin evolution

Development of the present Vienna Basin, situated at a junction of two segments of the Alpine-Carpathian orogen, as well as its superposition (1) on the Cenozoic accretionary wedge of the Rheno-Danubian and the Outer Western Carpathian Flysch Belts, and (2) on the units of the Northern Calcareous Alps, Central Eastern Alps and the Central Western Carpathians, is reflected in its very complex tectonic evolution. Structural and paleogeographic analysis has documented at least four stages of basin development (fig. 2).

1. The Early Miocene compressional tectonic regime during the Eggenburgian and Ottnangian was characterized by paleostress field with NW-SE oriented main compression (Kováč et al. 1989a,b, Kováč et al. 1991, Marko et al. 1990, 1991, Kováč et al. 1993a,b, c, Lankreijer et al. 1995, Kováč et al. 1997b). In this time, deposition was concentrated in piggy-back basins on the folding accretionary wedge of the Outer Carpathians and in wrench-fault furrows on the colliding margin of the Central Western Carpathians (Kováč & Baráth 1995, Kováč et al. 1993c, 1997a). The slowly subsiding sedimentary area was E-W oriented. NW-SE oriented thrusts dominated in the accretionary wedge, in the Central Western Carpathians it was ENE-WSW dextral strike-slips, NE-SW reverse faults dipping towards the hinterland and NE-SW normal faults controlled the opening of basin depocenters.

2. The Karpatian extrusion of the West Carpathian lithospheric fragment from the Alpine realm has been reflected in a transtensional tectonic regime in the Vienna Basin area. In a paleostress field with N-S oriented main compression, basin depocenters originated by pull-apart mechanism (Roth 1980, Jiříček & Tomek 1981, Royden 1985, 1988, Wessely 1988, Tomek & Thon 1988, Nemčok et al. 1989, Jiříček & Seifert 1990, Fodor et al. 1991, Fodor 1995, Lankreijer et al. 1995, Kováč et al. 1993a, 1997a). The first phase of tectonically controlled subsidence is considered to be reflection of the initial rifting stage. Depocenters of the basin shifted towards the south, being filled by a large delta that developed in its southern part (Aderklaa Fm.). During the Karpatian, mostly NE-SW oriented deep sinistral strike-slips have been activated along the eastern margin of the basin (Leitha Fault System), together with N-S oriented normal faults. In the Early Badenian, an activity of NE-SW oriented faults reaching the platform basement of the Bohemian Massif has been registered at the western margin of the basin as well (Steinberg, Schrattenberg and Bulhary faults).

3. The Middle Miocene subsidence of the synrift stage of the Vienna Basin in extensional tectonic regime was controlled by paleostress field with NE-SW oriented main compression. The configuration of the basin was mainly influenced by NE-SW and NNE-SSW oriented normal faults. The re-shaping of the drainage system was an important paleogeographic change during this period (Jiříček 1990), which resulted in the formation of a large delta at the western edge of the basin (paleo-Danube delta). The second phase of more rapid tectonic subsidence during the Early Sarmatian is related to ENE-WSW sinistral strike-slips and NE-SW oriented normal faults. These faults induced subsidence of the Zistersdorf-Moravian Central Depression and formation of the Senica Depression situated in the northeast (Lankreijer et al. 1995, Kováč et al. 1997a). The synrift stage extension in the northern part of the Vienna Basin was enhanced by active elongation of the Western Carpathian orogen during the Sarmatian due to subduction pull in front of the Eastern Carpathians.

4. The Late Miocene sedimentation represents a crustal relaxation of the post-rift stage in basin evolution during the Pannonian. During the Pliocene, the Vienna Basin reached a stage of tectonic inversion. Fault-controlled subsidence in grabens at the eastern margin of the basin (Zohor-Plavecký Mikuláš and Mitterndorf grabens) documents a transtensional regime of this zone, lasting up to the recent time, accompanied by seismic activity (Gutdeutsch & Aric 1988).

Depositional systems and sequence stratigraphy

Definition of the Vienna Basin depositional systems (fig. 3) and determination of relations between them were

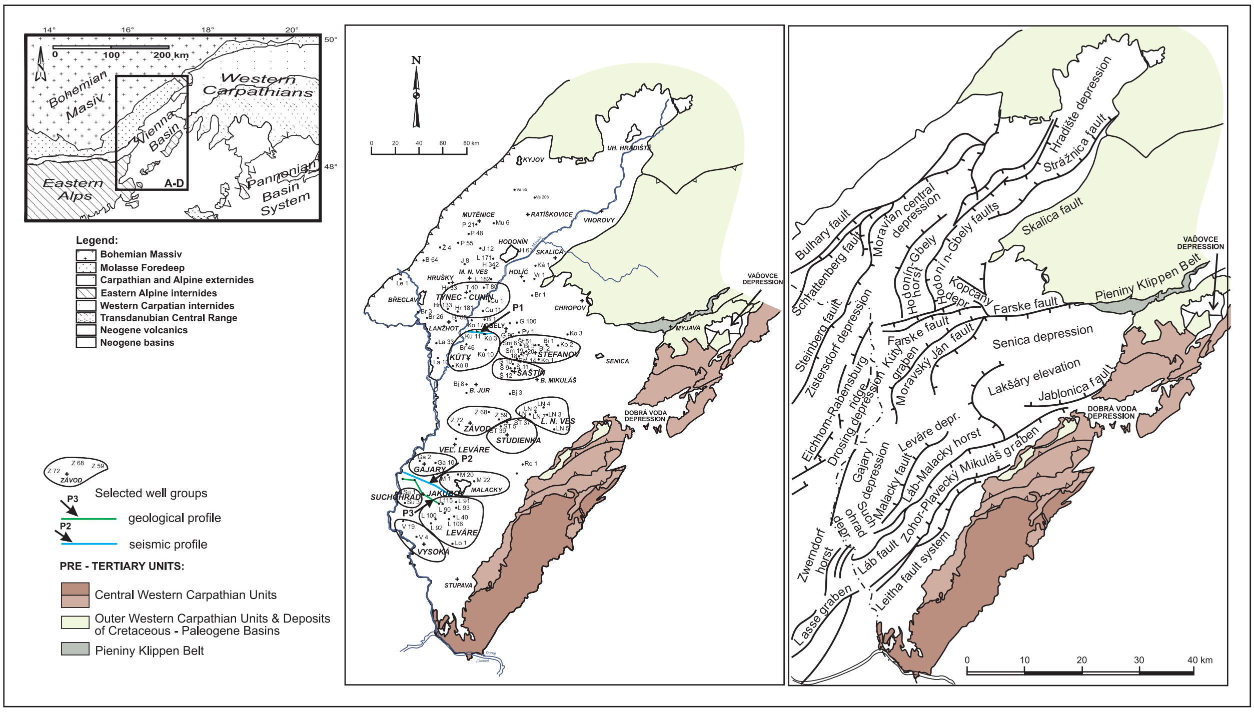


Fig. 1: Vienna Basin – map of main structural elements, localization of selected borehole groups and profiles used for explanation in this paper (Slovak part).

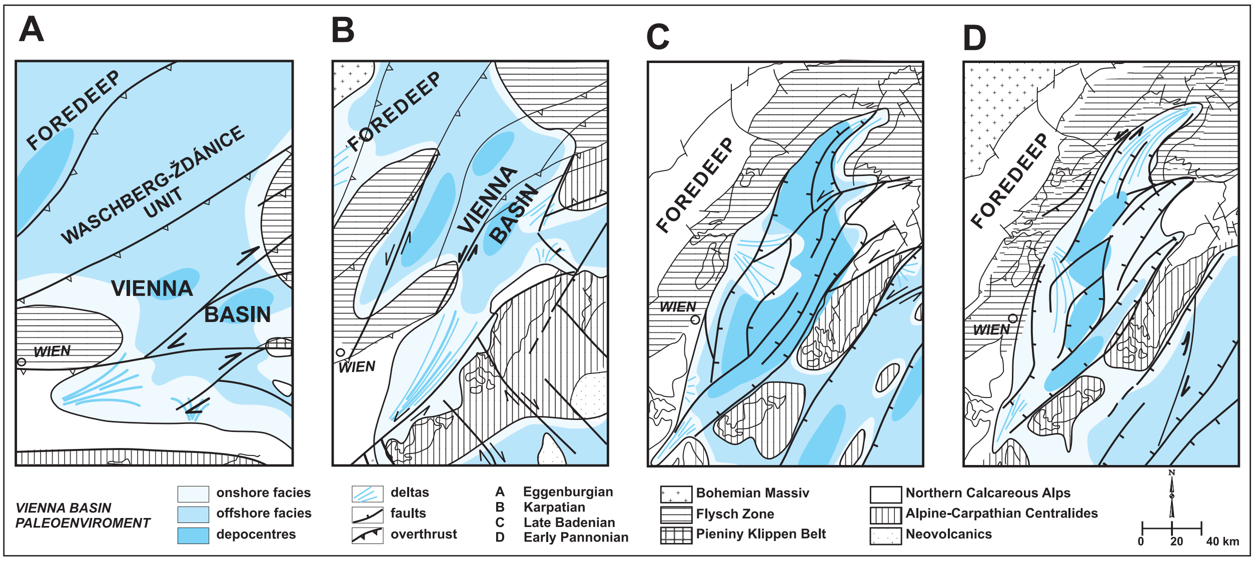


Fig. 2: Miocene paleogeography of the Vienna Basin in palinspastic view (modified after Kováč 2000).

made by means of sedimentological and geophysical methods supported by paleoecological data. Thus, a detection of relative sea-level fluctuations is also warranted (Brown & Fischer 1977, Vail et al. 1977, Vail & Wornardt 1990).

A *sea-level lowstand* is obviously characterized by redeposition of microfossils from older strata (Poang & Comeau 1995), along with rapid changes in assemblage composition caused by paleoecological instability (Gaskell 1991, Rey et al. 1994) and prevalence of shallow-water taxa (Armentrout et al. 1990, Gaboardi 1996). In the examined assemblages of the Eggenburgian, the shallow water taxa are represented by *Cibicides-Elphidium* assemblages with abundant Egerian redeposits. The Karpatian lowstand deposits contain assemblages rich in *Ammonia* and *Porosononion*. *Spirorutilus* and other agglutinated foraminifers as *Psammosphaera* and *Hyp-*

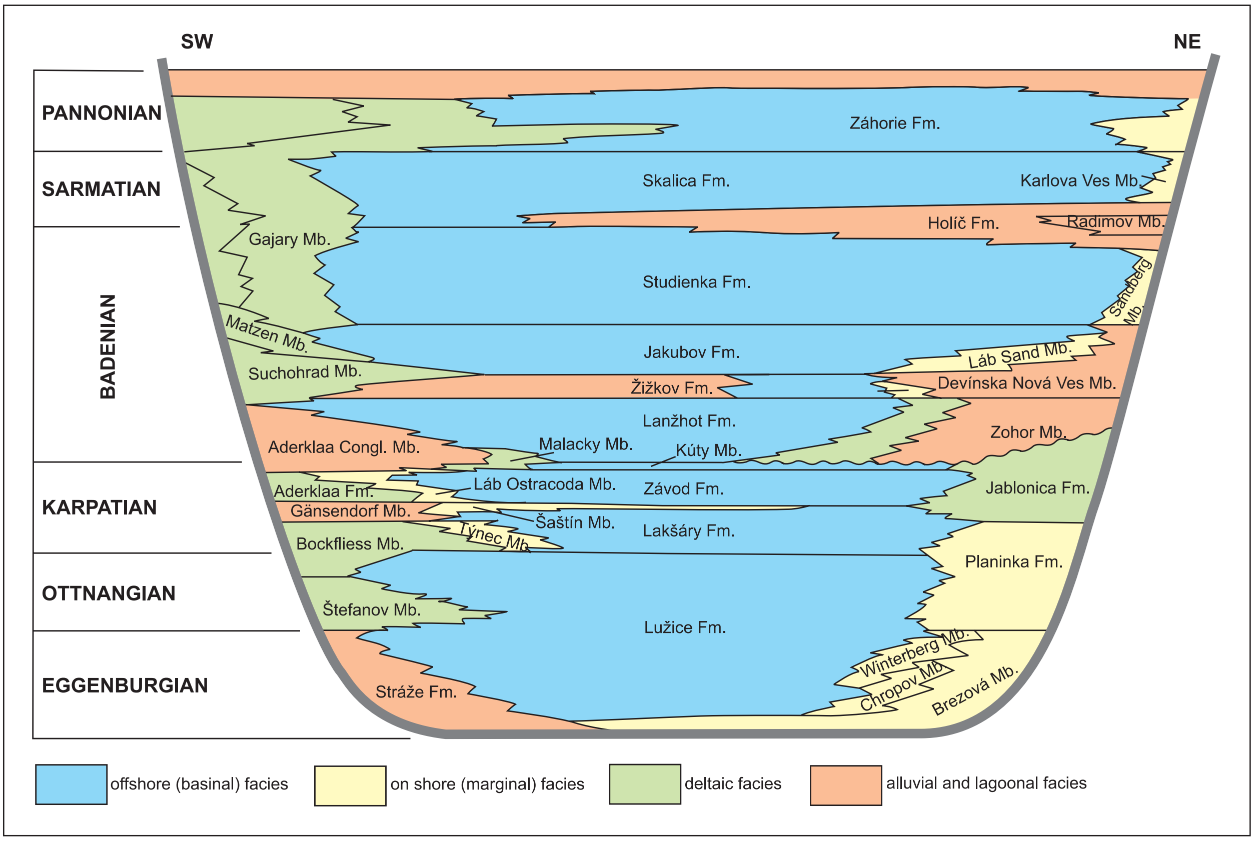


Fig. 3: Depositional systems of the Vienna Basin (modified after Baráth et al. 2001).

perammina predominate in the Middle Badenian lowstand deposits. They are typical for marsh assemblages, which were followed in places by evaporitic sedimentation. During the lowstand at the end of the Late Badenian, a similar paleo-environment with monospecific, low diverse foraminiferal assemblages occurs, passing into the Early Sarmatian, being dominated by *Ammonia* (90% prevalence). Abundant redeposited foraminifers occur in the Lower Sarmatian deposits, deriving from the underlying *Bulimina/Bolivina* biozone.

During *transgressions*, redeposition of strongly damaged foraminifers deriving from older, mainly lowstand sediments occurs at the base (Fursich et al. 1991). The investigated assemblages display various diversities, but they are generally more diverse than the lowstand assemblages. Coinciding with the sea-level rise the first occurrences of new foraminiferal taxa are characteristic. Hence, the first appearance/occurrence of taxa such as *Globigerinoides trilobus* at the base of the Eggenburgian, *Globigerina bulloides* at the base of the Karpatian and *Praeorbulina* indicating the base of the Badenian have been observed.

A *sea-level highstand*, i.e. ecologically stable environment is reflected by equitability and high species diversity of the assemblages (Gaskell 1991, Rey et al. 1994). The maximum flooding is accompanied by the second onset of new foraminiferal taxa, mostly of planktonic type. The oxygen deficient bottom conditions may develop in the basins (depocenters) with poor water circulation, due to stratification of the water column. Typical highstand foraminiferal associations, documenting stable conditions of the environment are *Bathysiphon* – *Cyclamina* assemblages in the Eggenburgian, assemblages with *Uvigerina graciliformis* and planktonic *Globigerinoides bisphericus* in the Karpatian, lagenidae assemblages with *Orbulina* in the Lower Badenian and *Bulimina* – *Bolivina* assemblages with *Velapertina* in the Late Badenian. In more or less brackish conditions prevail assemblages with *Elphidium hauerinum* in the Sarmatian and dinoflagellata *Spiniferites* sp. div. and *Chytroeisphaeridia* in Pannonian deposits.

A correlation of the Miocene global sea-level changes with those in the Vienna Basin is difficult, due to lack of real chronostratigraphic data and dramatic tectonic evolution, which masks global cycles. In spite of multiple geodynamic factors, the regional expressions of the global sea-level changes (sensu Haq et al. 1988, Haq 1991, Hardenbol et al. 1998, Michalík et al. 1999) could be partially recognized in the development of aquatic and terrestrial environments during the paleogeographic evolution of the basin. Nine third-order cycles of relative sea-level changes are proposed for the Miocene of the Vienna Basin. These cycles, termed VB1 to VB 9, resulted from combination of eustatic global sea-level changes, tectonic evolution of the basin and sediment supply mostly by deltas in this area. Some of these cycles correspond fairly to regional chronostratigraphic stages, whilst others, such as VB 5–7 cycles, follow other criteria.

VB 1 cycle – Eggenburgian

The initial phase of the Miocene deposition in the Vienna Basin is related to the Eggenburgian transgression, and to the tectonic opening of depocenters in the northern part of the basin. The sedimentation was preceded by erosion of older, mainly Paleogene deposits and peneplenization of the relief as deep as the Mesozoic basement (Kováč 2000, Michalík et al. 1999).

The type 1 sequence boundary (SB1) corresponds to the boundary between the pre-Neogene basement and the Miocene fill of the basin (fig. 4). Sediments of the lowstand systems tract (LST) filled depressions in the form of alluvial and lacustrine facies associations. At the foothills of the elevations, debris aprons were formed. The first fully marine deposits are represented by transgressive systems tract (TST) forming fining-upward shelf sand ridge depositional systems. Neritic sedimentation above the transgression surface (ts) is represented by the Eggenburgian lower part of the Lužice Formation (Buday & Cicha 1956). Higher up, above the maximum flooding surface (mfs), mostly pelites deposited in the highstand systems tract (HST).

The extent of the Eggenburgian depositional systems (fig. 3, 5a) in the Vienna Basin partly indicates the basin configuration in the form of archipelago-type sea with prevailing detritic sedimentation (Baráth & Kováč 1989). The initial Eggenburgian marine transgression sealed firstly the lowermost depressions with clastics, variegated clays and sands of the Stráže Formation (Jiříček & Seifert 1990). In places the alluvial deposits were reworked to basal transgressive lags and sand sheets. At the sea margins, predominantly transgressive depositional systems have developed, representing shelf sand bars. Deepening-upward rock cliff toe, shore face and sandy shelf depositional systems have been formed at the NE edge of the basin.

The basal members of transgressive systems deposits are formed by conglomerates of the Brezová and Chropov Members (Buday 1955). Characteristic transgressive development has been registered in the area of Pieniny Klippen Belt (fig. 5a). The basal part represents the rock cliff related marine boulder-sized Brezová conglomerates, passing upwards into fine-grained conglomerates and sandstones. Hence, during the transgression the rocky-shore and gravelly beach facies were overlain by siliciclastics of the sandy shore face. In the Myjava area, the structural features of the Brezová conglomerates evidence their origin in nearshore bars, where deposition was influenced by E-W coastal currents and by waves coming from the

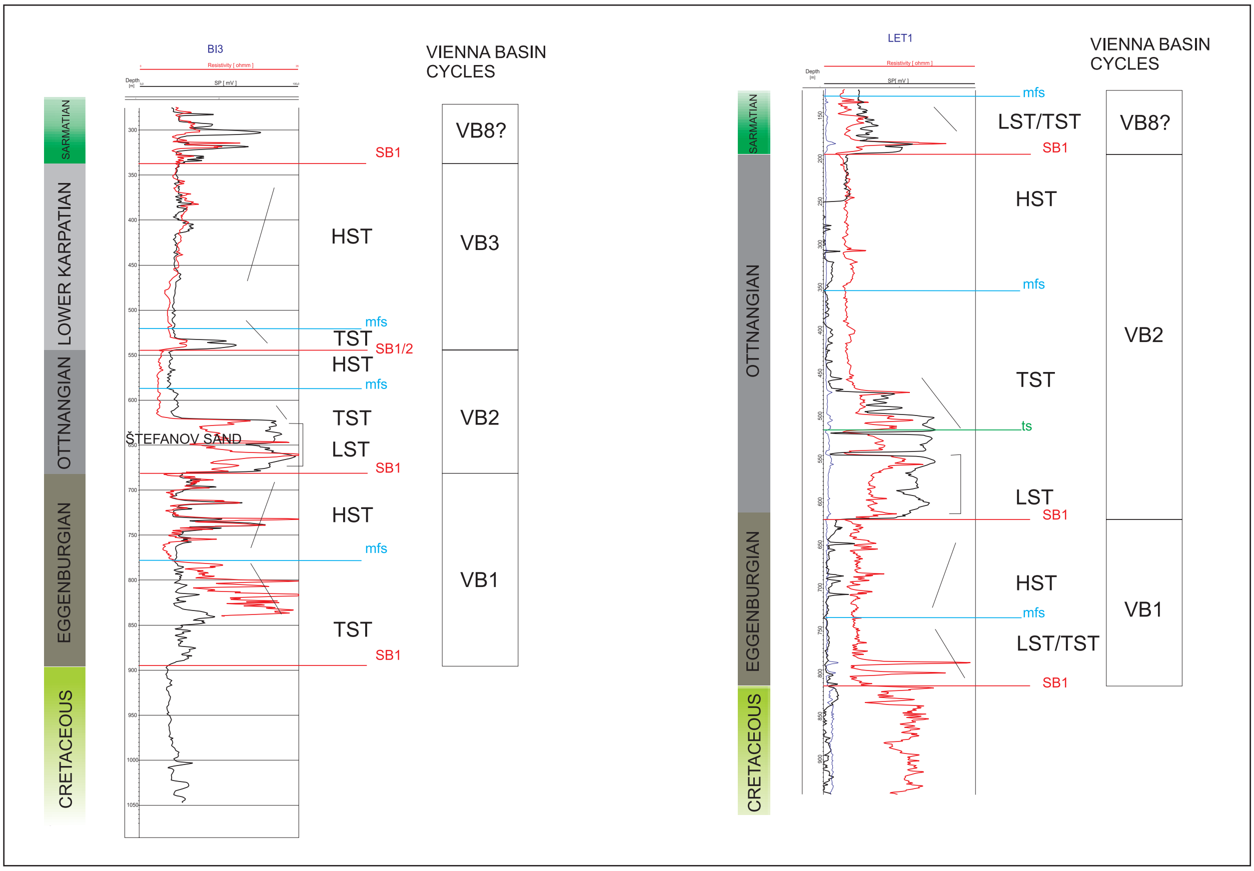


Fig. 4: Interpretation of well logs from the northeastern part of the Vienna Basin illustrating SB1 type boundary on the base of the Neogene sedimentary fill and SB 1 type boundary between the Eggenburgian and Ottnangian deposits of deltaic Štefanov sands Member.

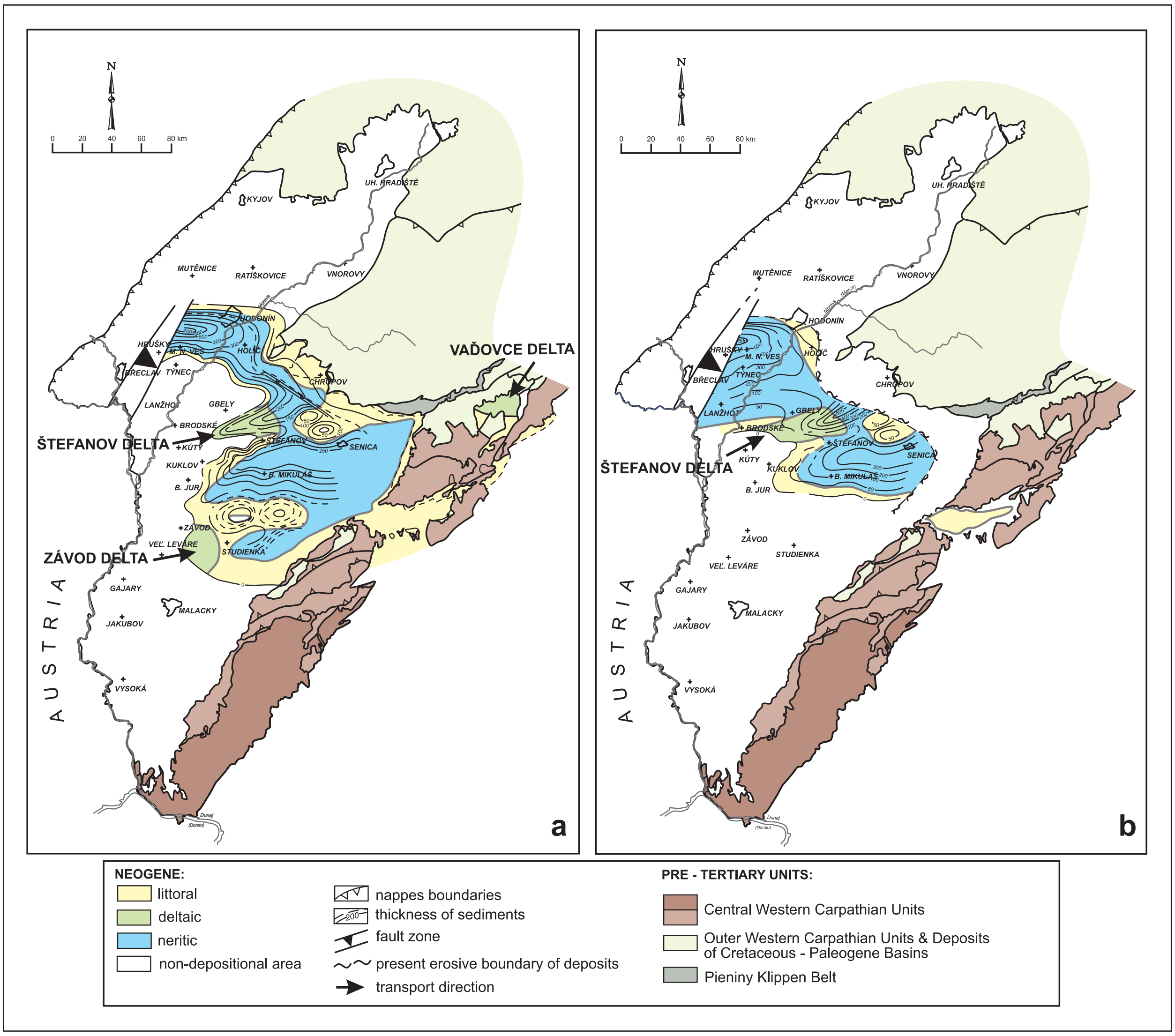


Fig. 5: Eggenburgian and Ottnangian depositional systems (5a – Eggenburgian, 5b – Ottnangian), isohypse contours after Jiříček 1979.

south. Littoral conditions are also evidenced by numerous *Trypanites* borings (Baráth & Kováč 1988).

Upward, sandy deposits start to prevail, being reflected in alternation of conglomerates with sandstones. The superposed Winterberg Member (Buday & Cicha 1956) indicates a deepening of the sedimentary environment, yielding claystones and armored mud-balls, which are interpreted to originate from submarine slumps. The shallow-marine sublittoral environment in the northern basin margin is reflected by rich mollusc fauna (*Pecten hornensis*, *P.* cf. *pseudobeudanti*, *Macrochlamis gigas*, *Aequipecten scabrellus*, *Acanthocardia* aff. *moeschanum*). The Winterberg Member passes laterally southward and eastward into the marine pelagic development.

Sediments of the offshore Lužice Formation (Špička 1966) documented in boreholes represent various marine depositional environments. The shallow marine to brackish environment is indicated by the coarse clastic sediments in the area of Studienka, Lakšárska Nová Ves and Šaštín (fig. 1, 5a), where conglomerates alternate with pelitic beds (Jiříček 1983). The brackish fauna is mostly represented by mollusc taxa (*Congeria* aff. *basteroti*, *Hydrobia sp.*); among the foraminifers *Ammonia viennensis* occurs randomly. Oogonians of charophytes are also present. In sublittoral clays, molluscs such as *Crassostrea gryphoides* and ostracods *Neocyprideis fortisensis* and *Agloiocypris* sp. were found. This may point to the presence of a bay-head delta in the Závod area (fig. 5a). The southeastern part of the Štefanov Depression and the northeastern part of the Vaďovce Depression (fig. 1, 5a) represented marine bays, with bay-head deltas as well. Later, they changed into estuaries within the Eggenburgian transgressive depositional system. In the delta plain deposits of the Vaďovce Depression, thin coal seems to occur. Shore face sandstones with littoral fauna in the area of the Pieniny Klippen Belt, Dobrá Voda and Vaďovce depressions show backstepping interfingering with offshore sediments of the Lužice Formation.

The neritic marine offshore facies of the Eggenburgian Lužice Formation was gradually spreading from the depocenters of the Vienna Basin towards its margins (fig. 3). The pelagic development of the Lužice Formation is composed of typical gray calcareous clays with intercalations of sands (deposits of gravity flows called "schlier"). The mentioned "schlier" contains rare deep-neritic to bathyal fauna with foraminifers (e.g. *Bathysiphon filiformis, Cyclammina praecancellata, Haplophragmoides vasiceki, Cibicides lopjanicus, C. ornatus, Uvigerina posthantkeni)*. In the Eggenburgian offshore deposits, the following nannoplankton assemblage has been collected: *Discoaster druggii, Sphenolithus disbelemnos, S. dissimilis, S. compactus, S. moriformis, S. conicus, Orthorhabdus serratus, Triquetrorhabdulus carinatus, T.challengeri, T.milowii, Reticulofenestra minuta, R.* cf. *haqii, Helicosphaera ampliaperta, H. granulata, H carteri.* Whilst these taxa are rare, only *Coccolithus pelagicus, Cyclicargolithus floridanus* and *Thoracosphaera* sp. are more abundant. On the basis of these taxa the assemblage can be attributed to the nannoplankton zone NN2 – *Discoaster druggii* Zone (Andrejeva-Grigorovich et al. 2001).

VB 2 cycle – Ottnangian

Erosional relics of the Ottnangian sediments display a similar distribution as the Eggenburgian deposits in the Vienna Basin. Only in the western part of the basin, the Ottnangian flooding extended wider about 10 km southward (fig. 5b).

The Eggenburgian/Ottnangian boundary is indicated by a relative sea-level drop, recorded by a basinward progradation of shallow-water sandy facies at the base of the Ottnangian strata. The sandy Štefanov Member (Buday 1955), which is up to 150 m thick, represents a deltaic body entering the basin from the southwest (figs 3, 4, 5b). This member represents sediments of the lowstand systems tract (LST), although the regression was not very distinct and erosion of the Eggenburgian deposits occurred only locally. Therefore, subaerically modified surfaces, corresponding to a type 1 sequence boundary (SB1), can be found only in the marginal parts and on basin elevations. In the marine neritic parts, the sequence boundary is concordant, representing a type 2 boundary (SB2), lacking any signs of subaerial erosion.

The transgressive systems tract (TST) is represented by sands and "schlier" of the upper part of the Lužice Formation, onlapping at the slopes of topographic highs (Špička 1966). Neritic sands and clays – so-called "schlier" contain a rich deep-water foraminiferal assemblage, yielding taxa that tolerated low oxygen bottom conditions. The association contains taxa, such as *Amphicoryna ottnangensis*, *Pappina breviformis*, *Cibicidoides ungerianus* and *Bolivina* sp., which have been described from Ottnangian deposits already by Cicha et al. (1998). From this sequence, Zágoršek & Hudáčková (2000) reported a diversified bryozoan fauna too. These deposits are covered by "*Gyroidina* schlier" which is rich in the deep-water foraminifer *Hansenisca soldanii*.

The neritic sedimentation continued into the highstand systems tract (HST). The Upper Ottnangian in the basin is mostly represented by pelitic "schlier" deposition. In the central Lužice area it is represented by neritic pelites with a *Spiroplectammina, Uvigerina* and *Lenticulina* fauna. In the elevated areas (Týnec and Cunín), the sedimentary record reflects shallower, *Cibicides-Elphidium* schlier with *Silicoplacentina* sp. Upwards, follows a rare, impoverished fauna composed of up to 90% *Ammonia* ex. gr. *viennensis*.

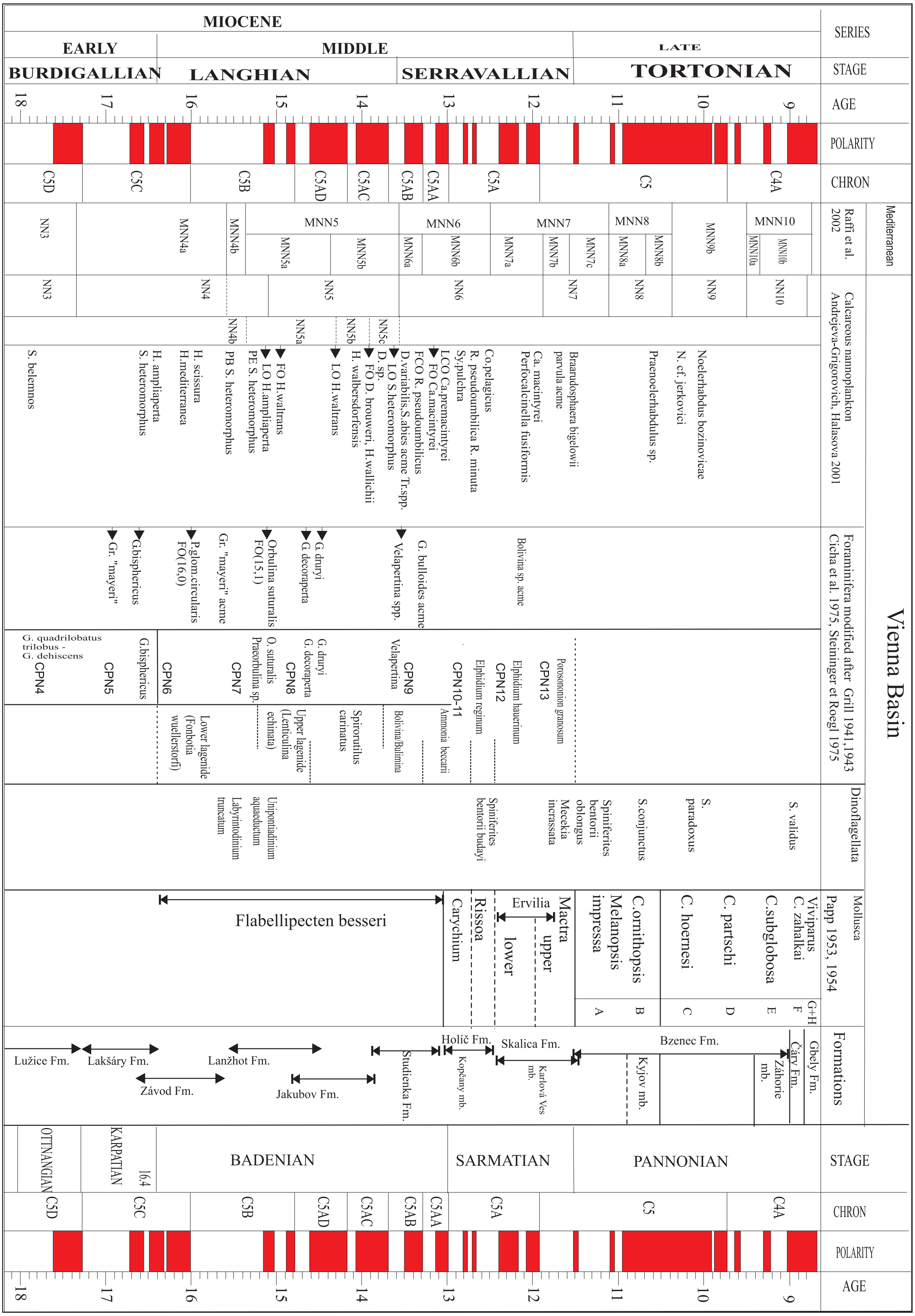
At the end of Ottnangian, detritic fluvial sediments and sands of prograding mouth bars have spread in the southern zones of the Vienna Basin. They are correlated with the Bockfliess Formation in the Austrian part of the basin, which continues into the transgressive lower part of the Karpatian (fig. 3).

The dating of the Ottnangian deposits is based mainly on nannoplankton study. The assemblage is characterized by *Sphenolithus belemnos, S. disbelemnos, S. dissimilis, S. compactus, S. moriformis, Orthorhabdus serratus, Helicosphaera ampliaperta, H. scissura, H. intermedia, H. mediterranea, Reticulofenestra haqii, R. minuta, Pontosphaera multipora, Triquetrorhabdulus milowii*, (rarely *Reticulofenestra pseudoumbilicus* and *Calcidiscus leptoporus*), *Cyclicargolithus floridanus*, *Coccolithus pelagicus* and *Thoracosphaera* sp. The assemblage was correlated with the NN3 nannoplankton zone. *Amphicoryna ottnangensis* and *Pappina breviformis* among the benthonic foraminifers prove the Ottnangian age (CPN4 sensu Cicha et al. 1975, table 1).

VB 3cycle – Latest Ottnangian – Early Karpatian

The spatial extent of the Lower Karpatian sediments differs largely from that of the Ottnangian. It was caused both, by subsidence of the Vienna Basin that allowed a rapid accumulation of thick marine and deltaic sediments, and by the global sea-level rise during this time (Špička 1969, Kováč et. al. 1989, Lankreijer et. al. 1995, Kováč 2000).

The sea-level lowstand during the latest Ottnangian and the earliest Karpatian was accompanied by erosion, mainly at the NE margin of the basin. A distinct southward shift of the depocenters during the Karpatian is caused


MIOCENE
EARLY
MIDDLE
LATE
BURDIGALLIAN
LANGHIAN
SERRAVALLIAN
TORTONIAN
SERIES
STAGE
AGE
POLARITY
CHRON
Mediterranean
Raffi et al. 2002
Calcareous nannoplankton Andrejeva-Grigorovich, Halasova 2001
Foraminifera modified after Grill 1941,1943 Cicha et al. 1975, Steininger et Roegl 1975
Dinoflagellata
Mollusca Papp 1953, 1954
Formations
Vienna Basin
Flabellipecten besseri
Lužice Fm.
Lakšáry Fm.
Lanžhot Fm.
Závod Fm.
Jakubov Fm.
Studienka Fm.
Holíč Fm.
Skalica Fm.
Bzenec Fm.
Gbely Fm.
OTTNANGIAN
KARPATIAN
BADENIAN
SARMATIAN
PANNONIAN

by increased tectonic activity. Correspondingly, the sequence boundary is indicated by unconformities. In the marginal parts it is expressed as type 1 sequence boundary (SB 1); in neritic environments the sedimentation continued without interruption, it is developed as type 2 sequence boundary (SB 2). In the elevated areas and in the newly-formed depocenters, south of the Ottnangian sea coast, the type 1 sequence boundary is identical with the lower boundary of the Karpatian strata (fig. 6).

The Early Karpatian transgressive systems tract (TST) is represented by the lower part of the Lakšárska Nová Ves Formation (Špička & Zapletalová 1964). This offshore marine depositional facies, characterized by pelitic "schlier" development, is known from the northern part of the basin. The marginal facies is not preserved due to subsequent erosion here (fig. 7a). This marginal facies was probably formed by deposits of tidal flats (watt type).

The thick complexes of the Týnec sands Member (Špička & Zapletalová 1964) with poor fauna of fishes and foraminifers, such as *Lenticulina*, *Bulimina*, *Uvigerina*, *Valvulineria* and *Heterolepa*, are present westward and at the base of the Karpatian sediments. The sandstones are interpreted to be delta front deposits that supplied even neritic areas with sandy gravity flows (fig. 3, 7a).

The Early Karpatian depositional systems display a transgressive nature reflected by backstepping of the Týnec delta front (fig. 3, 7a). This is replaced by depositional system of shelf sand bars, and overlain by offshore "schlier" facies of the Lakšárska Nová Ves Formation in the western part of the northern Vienna Basin. Transgressive conditions during the formation of the rear part of the Týnec deltaic body are well documented by accumulation of delta front sands in depressions (bay-head type delta). The shallow accommodation space on the elevations enabled also a deposition of alluvial pelitic sediments. The highstand systems tract (HST) is represented by marine, predominantly pelitic sediments of the Lakšárska Nová Ves Formation.

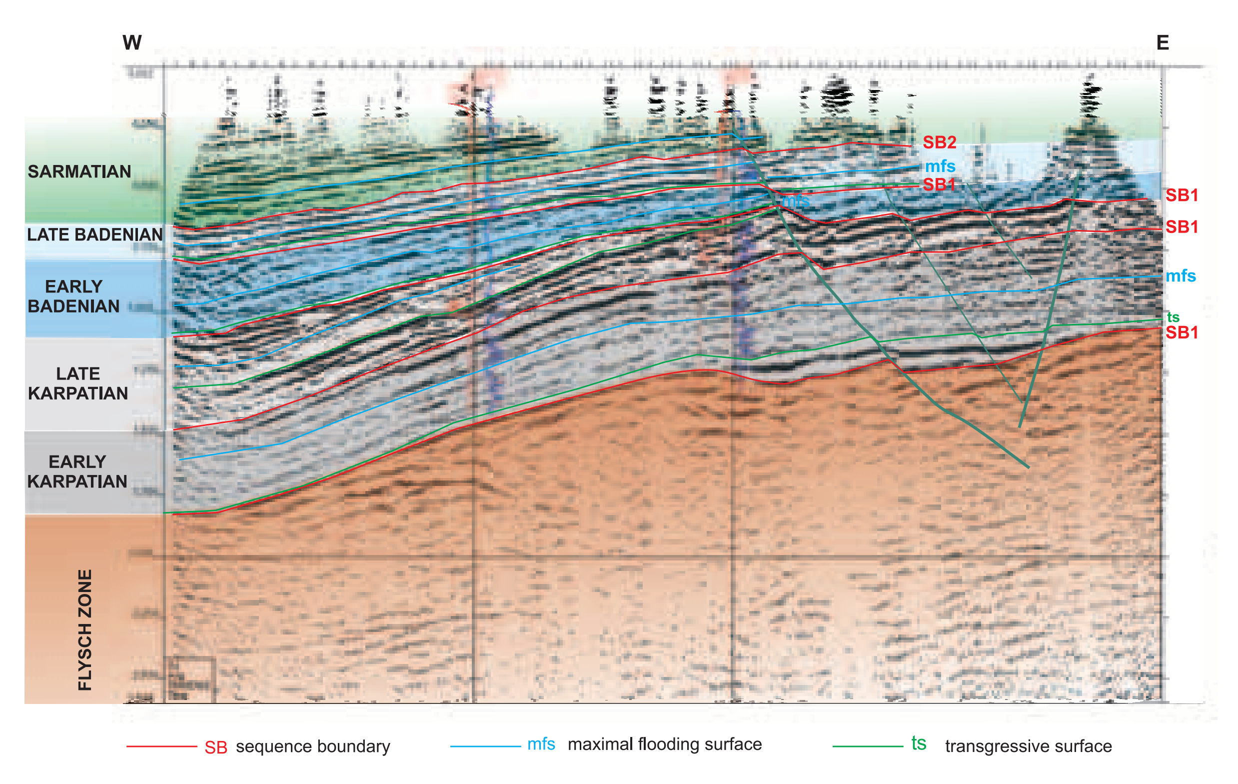


Fig. 6: Interpreted seismic profile (P1) from the northern part of the Vienna Basin (for localization see fig. 1).

Table 1: Biostratigraphy of the northern Vienna Basin formations and members (Slovak part).

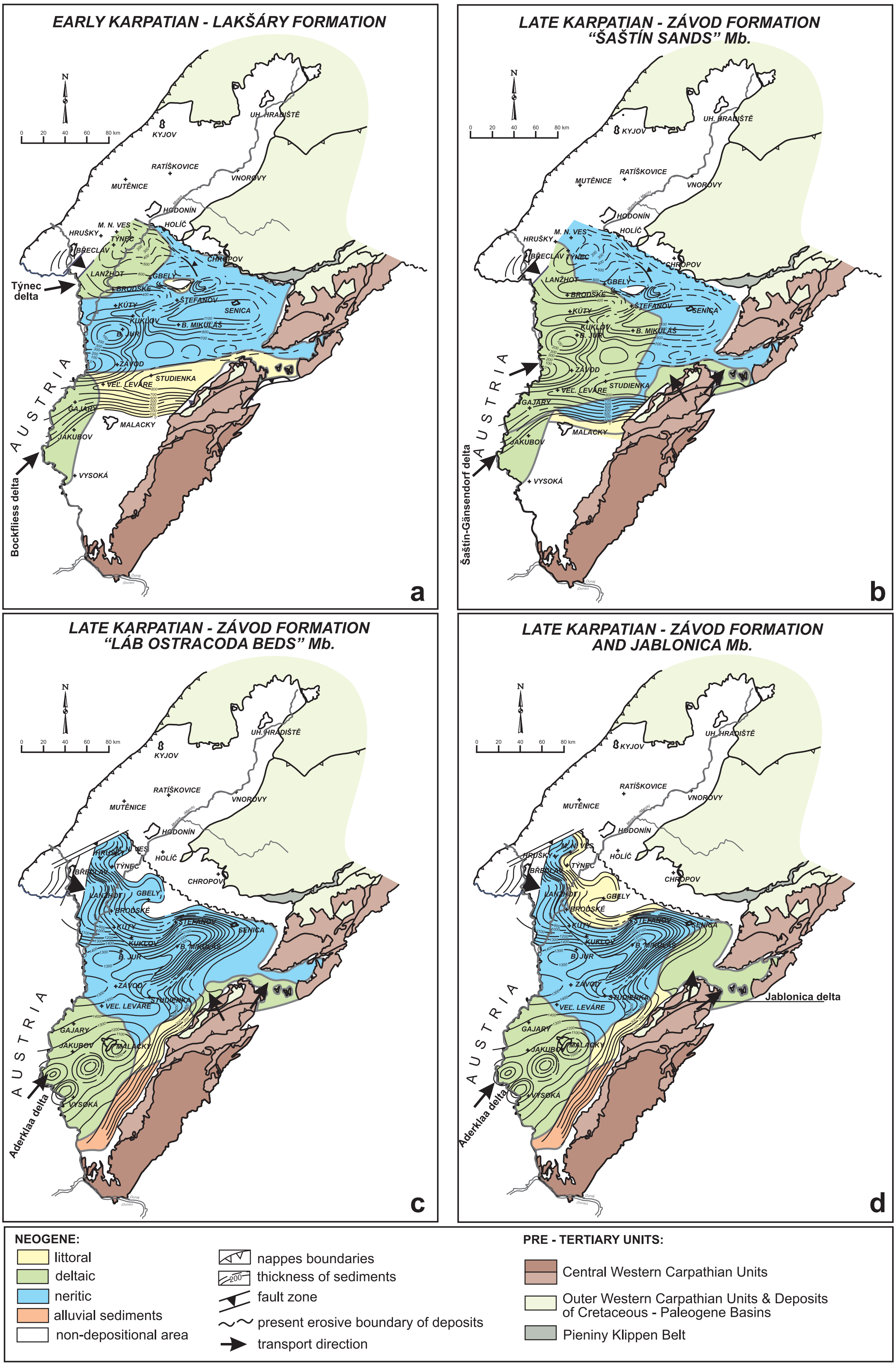


Fig. 7: Karpatian depositional systems – isohypse contours after JIŘÍČEK 1979.

In the southern parts of the basin (territory of Austria), deposition of alluvial, variegated clastics of the Bockfliess Formation prevailed (fig. 3). A vertical transition from lacustrine sediments into brackish ones was documented within these deposits. Rögl et al. (2002) mentioned elphidiids, nonionids and ammonias as indicators for brackish-littoral conditions. Bockfliess Formation deltaic sediments reached up to the recent vicinity of the Gajary village (fig. 7a). A huge complex of deltaic sediments continuously filled the accommodation space created in the southern Vienna Basin. In their hinterland, thick accumulations of alluvial-limnic sediments have been formed. Detritic material of the aforementioned Bockfliess deltaic complex is dominated by resistant types of rocks, e.g. quartz and quartzite, indicating the transport from the Eastern Alpine central zones (Sauer et al. 1992).

The biostratigraphic dating of the Lower Karpatian deposits (Lakšárska Nová Ves Formation) is based on the nannoplankton flora. The assemblage is characterized by the presence of: *Sphenolithus heteromorphus, S. compactus, S. moriformis, Helicosphaera ampliaperta, H. scissura, H. mediterranea, H. carteri, H. granulata, H. intermedia, Rhabdosphaera sicca, Orthorhabdus serratus, Reticulofenestra pseudoumbilicus, R. minuta, P. multipora, Thoracosphaera sp., Triquetrorhabdulus milowii, Coccolithus pelagicus, Cyclicargolithus floridanus, Calcidiscus praemacintyrei*. *Calcidiscus leptoporus* occurs rarely, together with resedimented Paleogene taxa (Andreeva–Grigorovich & Halásová 2000). The assemblage indicates the NN4 Zone. This age has been also confirmed by foraminiferal assemblages containing elements belonging to the CPN5 Zone (sensu Cicha et al. 1975): *Bulimina elongata*, *Caucasina schischkinskayae*, *Globigerina ottnangiensis*, *Globorotalia scitula*, *Globigerinoides bisphericus* and *Uvigerina graciliformis* (table 1).

VB 4 cycle – Late Karpatian

The Lower/Upper Karpatian boundary is unconformable in many areas and represents the type 1 sequence boundary (figs 6, 8). The architecture of the Upper Karpatian depositional systems was thus influenced by large regressive event at the end of the Early Karpatian (Middle Karpatian). It resulted in the covering of the Bockfliess deltaic-brackish complex with the lacustrine-terrestrial Gänserndorf Formation in the southern Vienna Basin overlaying the Bockfliess Formation with a distinct angular unconformity (Kreutzer 1992). It is restricted to a small area in the east and northeast of Vienna and consists mainly of breccias, conglomerates, sandstones and rare pelites (Weissenbäck 1995). Weissenbäck (1995) emphasised that the up to 360 m thick Gänserndorf Formation follows a roughly SW - NE trending graben in the southern Vienna Basin. Along the flanks of that structure, drainage systems formed alluvial fan deposits, whilst its central part was covered by a braided river system, which shed its load towards the NE. The top of the Gänserndorf Formations grades into the overlaying Aderklaa Formation without a major unconformity.

The deposition of the lowstand systems tract (LST) is characterized by the progradation of a large deltaic body that covered considerable part of the Slovak section of the Vienna Basin (fig. 7b). These sandy deltaic deposits are united in the Šaštín Member, which is probably a continuation of the alluvial Gänserndorf Formation in the Austrian part of the basin.

The deltaic-brackish sands of the Šaštín Member (Špička & Zapletalová 1964) attain a thickness of 100–400 m (Jiříček & Seifert 1990) and contain shallow-water foraminiferal fauna with *Elphidium* sp. and *Ammonia viennensis*. The Šaštín Member represents a typical regressive depositional system of prograding mouth bars that supplied the sandy deltaic front towards the northeast (figs 7b, 8). Among the deltaic lobes, the lagoonal depressions have probably formed, locally with hypersaline environments known also from the upper part of the Gänserndorf Formation (Jiříček & Seifert 1990); from where Hladecek (1965) mentioned pebbles of anhydrite in the Matzen area.

Distribution of the Upper Karpatian sediments suggests a southward shift of the erosional base in the northern part of the basin relative to the Early Karpatian (Jiříček 1979). The shoreline was also shifted considerably in the southward direction, where it outlined the edges of the Malé Karpaty Mts.

During the Late Karpatian, large parts of the present day Vienna Basin have been flooded for the first time. Whilst the north of the basin was marine, the southern areas were characterized by deposition of huge lacustrine-deltaic formations. The western margins of the Malé Karpaty Mts. horst were rimmed by alluvial clastics in the south; northward, they are replaced by a littoral sandy development. At the NE end of the present day Malé Karpaty Mts., the north-vergent progradation of the Jablonica deltaic complex consisting of conglomerates and sandstones started (Kováč et al. 1986). The marine to brackish offshore “schlier” sediments of the Lakšárska Nová Ves Formation were replaced by the Závod Formation in the northern Vienna Basin (figs 1, 7c, 7d).

The transgressive and highstand systems tracts (TST/HST) in the northern part of the basin correspond to offshore “schlier” sediments belonging to the Závod Formation (Špička 1966). The transgressive depositional systems and the subsequent highstand depositional systems sediments covered also the southern portion of the Slovak section of the basin in the Late Karpatian (figs 7c, 7d). They are represented by the brackish to freshwater Láb Member (Buday 1955), which is correlated with the Aderklaa Formation in Austria (fig. 3). This member consists of variegated, mostly greenish, grayish, and dark-gray, bedded micaceous aleuropelites with interbeds of sandstones.

The deposition of the Závod Formation took place in offshore environments. The lower (transgressive) part is neritic, but it displays upward more shallow-water charac-

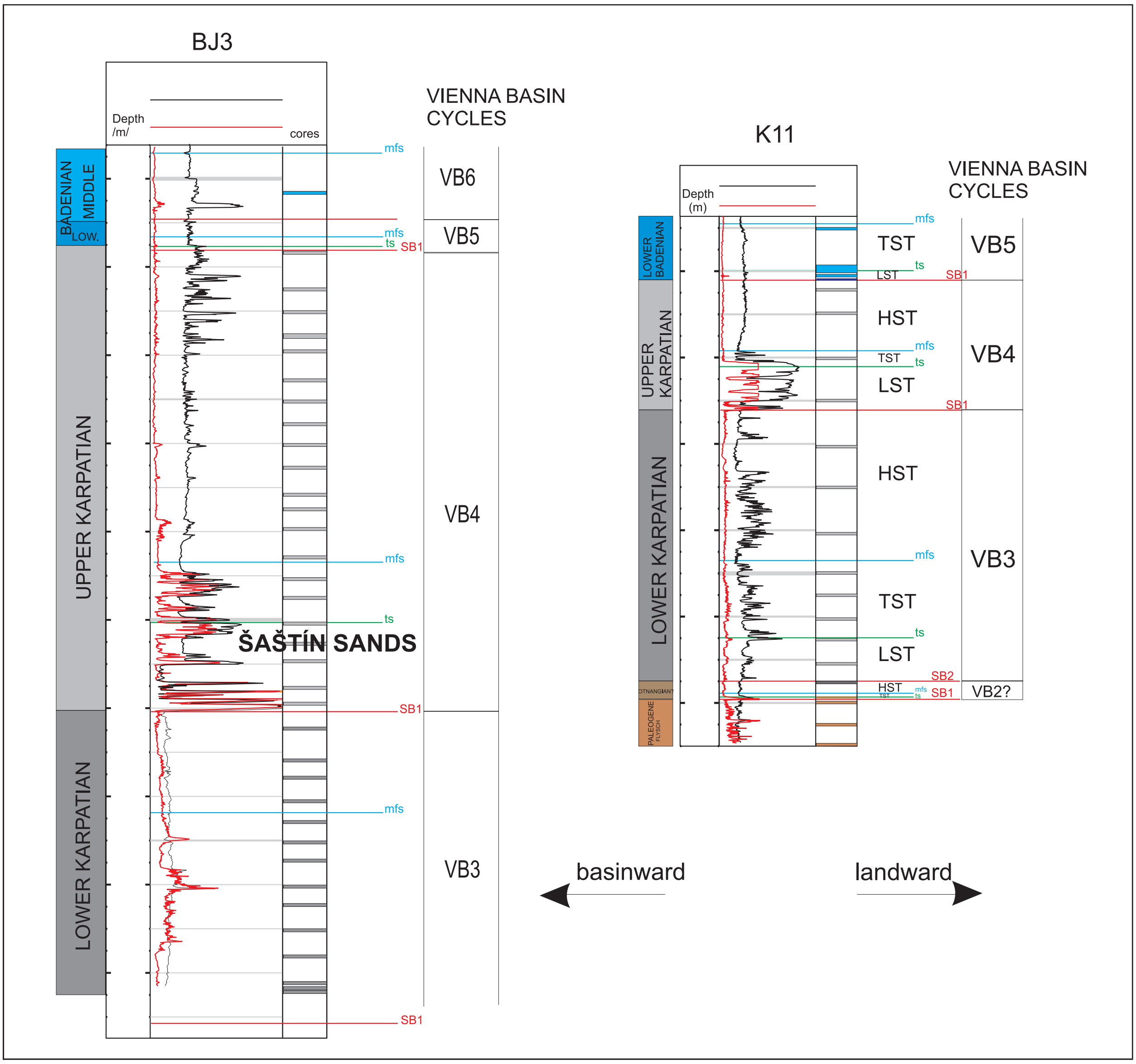


Fig. 8: Interpretation of well-logs from the eastern Vienna Basin illustrating SB1 type boundary between the Early and Late Karpatian cycle of regional sea-level changes marked by progradation of deltaic Šaštín sands Member (position of wells in the basin is marked by arrows).

ter during the regression. The regression was characterized by salinity fluctuations from brackish up to hypersaline, with precipitation of gypsum and anhydrite. The sediments contain mostly redeposited foraminifers from deeper environments. Only the foraminiferal assemblages contributed by poor planktonic fauna and predominant benthic *Ammonia* assemblage is considered to be primary.

The Upper Karpatian depositional systems have transgressive-regressive nature also in the southern part of the basin, as far as the regressive phase lasted until the earliest Badenian. The Aderklaa Formation as fluvial system has been formed during the Karpatian (fig. 3). The deposits of the Aderklaa Formation are characterized by sandstones with intercalations of pelites and scattered fine conglomerates. It is restricted to the southern part of the basin south of the Spannberg ridge. A maximum thickness of 1066 m was observed by Weissenbäck (1995) in the well Aderklaa 85. Sedimentological data and scattered molluscs document a limnic/fluvial environment (Papp 1967). This was formed within the meandering river system, which established its course on a slightly NE inclined fluvial plain (Weissenbäck 1995). Corresponding to the Gänserndorf Formation, the main direction of the transport was therefore towards the NE. In this direction, the system grades into the Láb Member (Buday 1955) in Slovak territory (fig. 7c).

In the southwestern part of the Vienna Basin the coal bearing marls are recorded from the Gainfarn Bay and the Piesting Bay. These marls with scattered coal seams are termed by Brix & Plöchinger (1988) to be the Grillenberg Member and the Hauerberg Member, and are tentatively correlated with the Aderklaa Formation.

At the end of the Karpatian, a regression took place, indicated by the subsequent covering of the meandering river system of the Aderklaa Formation by the braided river system of the Aderklaa conglomerate Member. Alluvial-deltaic sands with intercalations of variegated clays of the Malacky Member are temporal equivalents in Slovakia (fig. 3). They represent a regressive depositional system of branched mouth bars.

Close to the NE promontories of the Malé Karpaty Mts., a new progradation of the mouth bar regressive deltaic depositional system of the Jablonica Formation (Buday 1955) conglomerates and sandstones took place (fig. 7d). Corresponding to the so-called Aderklaa conglomerate, its sedimentation started during the Karpatian, but the Early Badenian age cannot be proved (Kováč et al. 1991, 2001). The uplift of the Malé Karpaty Mts. and the enlargement of the drainage pattern due to the regression resulted in a change of the composition of the pebble material. Along with the Triassic limestones and dolomites, the conglomerates contain also an increased portion of pebbles of the Jurassic and Cretaceous limestones, Permian, Triassic, Senonian and the Paleogene clastics, granites and acid, and basic volcanics, coming from more southern sources (Kováč 1986, Mišik 1986, Kováč et al. 1989a).

VB5 cycle – terminal Karpatian – Early Badenian
(uppermost Karpatian – middle Upper Lagenidae Zone, upper NN4 – middle NN5)

The Early Badenian depositional systems reflect large paleogeographic changes in the Western Carpathians. In the Vienna Basin, these rearrangements are indicated by tectonic inversion of the basin depocenters and by change of the transgression direction. The latter switched from a southward direction in the Early Miocene towards a generally northward direction during the Middle Miocene.

In terms of sequence stratigraphy, the supposed deposition at the Karpatian/Badenian boundary fits well with the regressive phase in the Karpatian and the transgressive one in the Early Badenian (Weissenbäck 1996). Because considerable thickness of the Upper Karpatian sediments is missing in the northeastern part of the basin, the SB1 unconformity is likely identical with the Karpatian/Badenian boundary (figs 6, 9, 12, 13).

Regression during the late Karpatian and in the earliest Badenian caused large-scale erosion in the area of the Vienna Basin. The VB4/VB5 sequence boundary represents probably the largest hiatus in the evolution of the basin northern part (figs 6, 9). In the central Vienna Basin, an erosional truncation of the Aderklaa Formation of up to 400 m occurred in the area of Schönkirchen (Weissenbäck 1995, Wessely 2000). Towards the Spannberg ridge this erosion successively touches also the Gänserndorf Formation, Bockfliess Formation and finally truncates down to the Flysch Zone (Kreutzer 1992). The southern Vienna Basin became subaerial during that time, as reflected by paleosoil formation in the Matzen area (Hladecek 1965).

The lowstand systems tract (LST) deposits of the VB5 cycle are represented by continental facies with conglomerates of the Zohor Member and up to 350 m thick Aderklaa conglomerate Member (not identical with the Karpatian Aderklaa Formation!). These supposedly Lower Badenian sediments rest unconformable on the Karpatian deposits in the basin area (figs 6, 9). Their dating, however, is problematic due to a lack of index fossils. The Aderklaa conglomerate Member in the southern part of the basin and its temporal equivalent the Zohor Member at the western margin of the Malé Karpaty Mts. formed an alluvial-deltaic complex (fig. 10a).

Detritic material of the Zohor Member was derived from the crystalline and the Mesozoic sources of SE provenance (Kováč & Baráth 1995). The Aderklaa conglomerate, covering an area of more than 350 km^2 (Jiříček & Seifert 1990) forms a characteristic wedge towards the southern part of the basin and pinches out along the Spannberg ridge (Kreutzer & Hlavatý 1990). Weissenbäck (1996) interprets the depositional environment as braided river facies of several interacting rivers. A drainage pattern in the northeastern direction is indicated by a decrease in grain size (Kapounek & Papp 1969). Seismic data of the OMV along the western part of the Leitha Mountains prove deposition of an equivalent conglomerate in the southeastern most parts of the Vienna Basin. The conglomerates are overlain by pelites of the uppermost part of the "Lower Lagenidae Zone" (sensu Grill 1943) with *Orbulina suturalis*, *Globorotalia bykovae* and *Lenticulina echinata* (tab. 1). According to the nannoplankton assemblage containing *Helicosphaera waltrans*, *Sphenolithus heteromorphus*, *Calcidiscus premacintyrei*, *Reticulofenestra pseudoumbilicus*, *Coccolithus miopelagicus*, rare *Discoaster deflandrei* and *D. variabilis*, the pelites belong to the NN5a Zone (Andreeva-Grigorovich et al. 2001). In the Slovak part of the basin, this succession is probably present only in depressed parts of the basin (Gajary Depression, Suchohrad Depression, Leváre Depression).

The Early Badenian transgressive systems tract (TST) is represented by the Lanžhot Formation in the Slovak part of the basin (Špička 1966). The formation consists of basal sands at the basin margins and marine offshore pelites so-called "tegel" that are correlated with the uppermost part of the „Lower Lagenidae Zone" and especially with the "Upper Lagenidae Zone" (sensu Grill 1941). The first occurrence of *Orbulina suturalis* within the foraminiferal assemblages is characteristic. The assemblages contain a rich planktonic fauna with *Globorotalia peripheroronda*, *G. bykovae*, *Paragloborotalia mayeri* and *Globigerinoides quadrilobatus* (in the area of Záhorská Ves, Dúbrava and Zohor). According to the nannoplankton assemblage, which yields *Sphenolithus heteromorphus*, *Discoaster brouweri*, *D. exilis*, *D. petaliformis*, *Calcidiscus premacintyrei*, *Helicosphaera walbersdorfensis*, *H. carteri – wallichi* and *Sphenolithus abies*, it belongs to the NN5b Zone (Andreeeva-Grigorovich et al. 2001, table1).

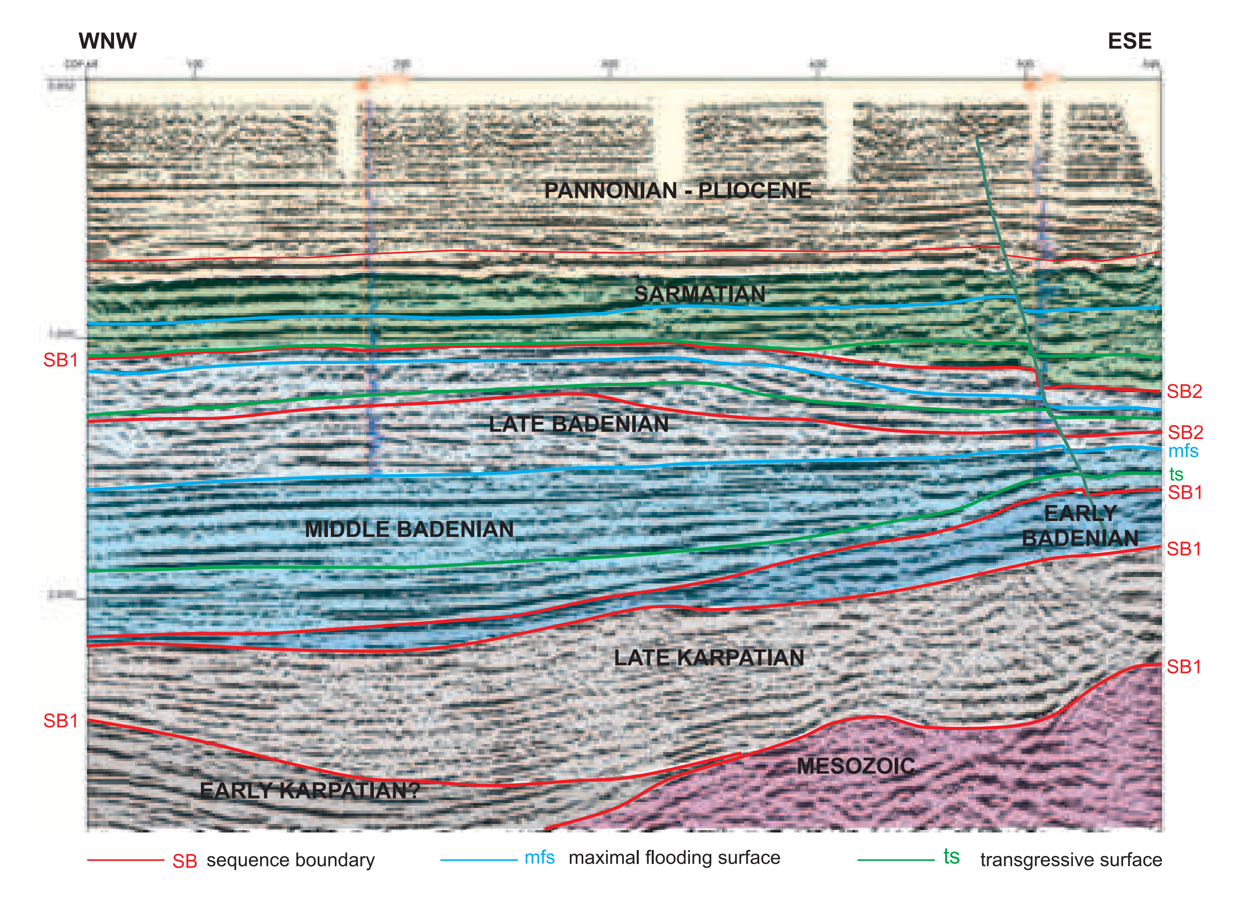


Fig. 9: Interpreted seismic profile (P2) from the central part of the Vienna Basin (for localization see fig. 1).

The extent of the Early Badenian sediments of the "Upper Lagenidae Zone" in the Slovak part of the Vienna Basin is approximately identical with the northern basin's shoreline (fig. 10a). New basin depocenters have been formed on the sunken block, east of the Steinberg Fault in Austria, or in the Leváre Depression in the Slovak part (fig. 1). Deposition of the highstand systems tract (HST) was mostly tied to the marine environment, tending to gradual shallowing due to filling of the accommodation space. In the Slovak part of the basin it is characterized by coarsening upward trend and erosion on the top (figs 10, 11).

The transgressive systems tract (TST) and the early highstand systems tract (HST) of the VB5 cycle are documented by MANDIC et al. (2003) also from the tectonic depression at the western margin of the Vienna Basin. There, in the vicinity of Niederleis, conglomerates and thin patches of corallinacean limestone cliff were formed along the Jurassic reef limestone during the TST. The maximum flooding surface (mfs) developed in the upper part of "Lower Lagenidae Zone" close to the Lower/Upper Lagenidae Zone boundary, coinciding to the data presented by WEISSENBÄCK (1996) for the southern Vienna Basin. The onset of HST conditions is reflected by several tempestitic intercalations, which based on their faunal content display a basinward progradation of the shoreline from the base to the top (MANDIC et al. 2003).

The VB5 cycle is also developed in the Eisenstadt-Sopron Basin, which is a small satellite basin of the Vienna Basin. There, KROH et al. (2003) detected the TST within the Hartl Formation along the southeastern margin of the Leitha Mountains. During the transgression, the deposits grade from reworked gravel, via marine sandwaves into corallinacean debris. The top of the formation is dated by KROH et al. (2003) into the uppermost part of the "Lower Lagenid Zone", based on the co-occurrence of *Praeorbulina glomerosa circularis*, *Orbulina suturalis* and *Globigerinoides bisphericus*. The increasing numbers of planktonic foraminifers and the abundance of glauconite was interpreted to point to the maximum flooding (mfs) and the beginning of HST in that formation.

Along the Vienna Basins' margin of the Leitha Mountains in the Stotzing bay, the HST is indicated by the shedding of corallinacean debris above steeply inclined sets of coarse sand prograding towards the basin during the early HST. Again, the co-occurrence of *Praeorbulina* and *Orbulina* was identified within the samples by RUPP (pers. comm.).

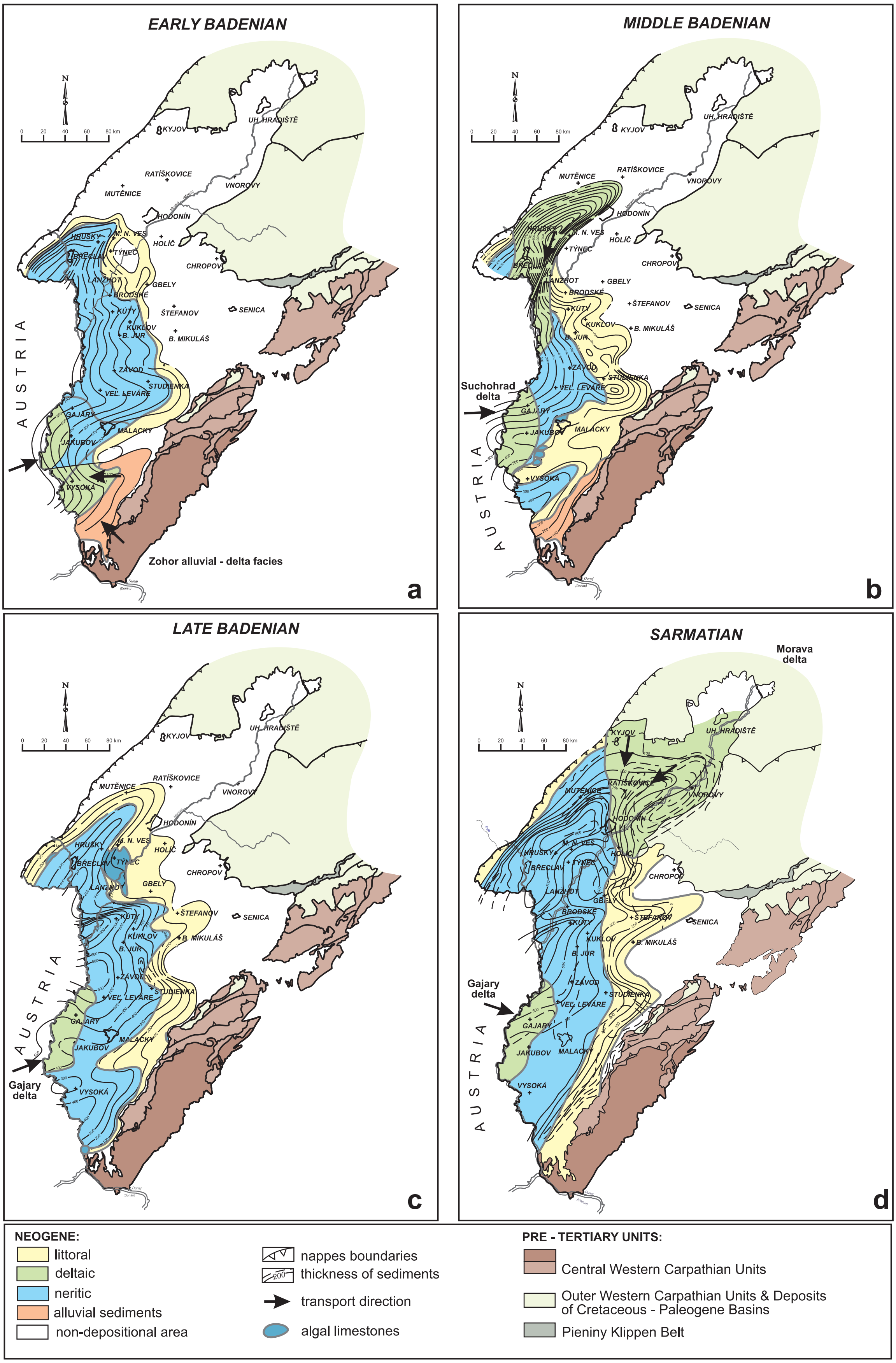


Fig. 10: The Badenian and Sarmatian depositional systems (Early Badenian 9a, Middle Badenian 9b, Late Badenian 9c & Sarmatian 9d) isohypse contours after Jiříček 1979 & Špička 1969.

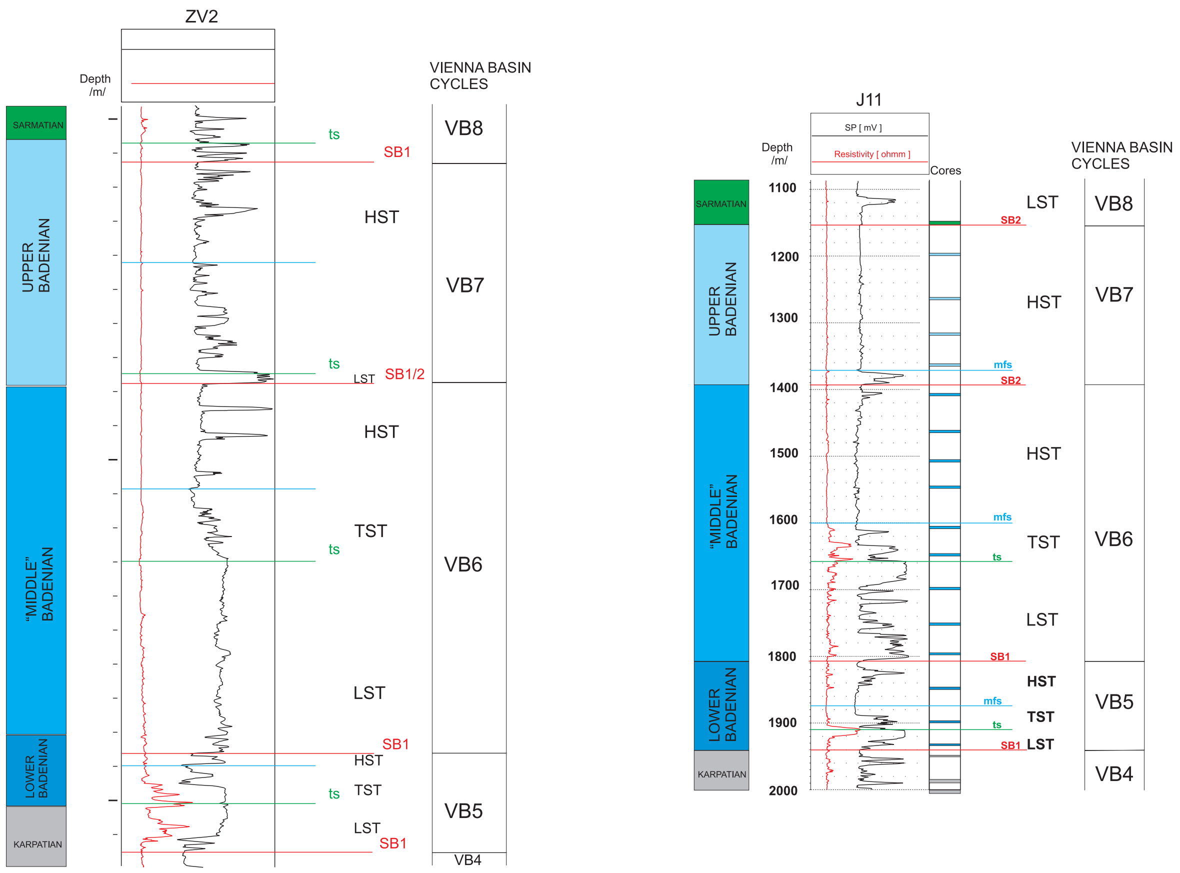


Fig. 11: Sequence stratigraphy cycles of the Badenian sea-level changes – interpretation of well-logs from the central part of the Vienna Basin (Slovakia).

VB 6 cycle – "middle" Badenian

(uppermost Lagenidae Zone – lower *Bulimina/Bolivina* Zone; upper NN 5)

The boundary between the VB 5 and the VB 6 cycles corresponds to the sequence boundary proposed by Weissenbäck (1996) within the "Upper Lagenidae Zone" of the southern Vienna Basin. Several small-sized deltaic bodies developed during that phase and they might be related to weakly developed lowstand systems tract (LST) of the VB 6 cycle. These deltas are reflected in the coarse clastic deposition of the Andlersdorf Member in the south (Kapounek & Papp 1969), the Zwerndorf Member in the east and the Auersthal Member in the central Vienna Basin (Weissenbäck 1996). The conglomerates of the Andlersdorf Member have been interpreted by Weissenbäck (1996) as distributary-mouth bar deposits of braided river systems. The flysch-conglomerate bearing Auersthal Member was affiliated by Weissenbäck (1995) with submarine fan deltas that were formed along the southern slope of the Spannberg ridge. Similarly, Kreutzer (1992) interpreted the Ausersthal conglomerates as incised valley fill of a lowstand systems tract. Both deltaic systems are drowning during the following transgression of the late "Upper Lagenidae Zone". Only the Zwerndorf Member as delta front facies continues into the "*Spiroplectammina* Zone", but displays a distinct landward backstepping and fining upward trend due to the transgression.

In the northern parts of the basin, the type 1 sequence boundary (SB1) of the VB 6 cycle is placed on the base of the lowstand systems tract (LST) that represents almost the entire alluvial, deltaic and lagoonal sediments of the **Žižkov Formation** (Buday 1955) in the northern part of the Vienna Basin. Its depositional system is interpreted to be strandplain-shelf and/or prograding mouthbar. In its base littoral sands occur as well, being deposited probably in the early-regressive shelf plume system. The mostly freshwater and brackish formation consists of greenish-gray, gray and green calcareous clays, often rusty spotted, containing lenses of cross-bedded sand bodies. The largest thickness attains about 1200 m in the Moravian Central Depression (fig. 1), where it forms the part of a huge delta that was supplied from the northeast (Jiříček 1988). A large lagoon (fig. 10b) originated here due to the isolation caused by prograding of the regressive depositional system of the Suchohrad deltaic mouth sand bars in the south (figs 10b, 12). Bodies of the sandy Suchohrad Member run from the southwest as far as the Gajary and Malacky area (figs 3, 10b, 12). This deltaic succession passes upward to littoral sandy-clay development with a marine fauna of the "Upper Lagenidae Zone". The recognition of the sequence boundary in these sedimentary bodies is problematic. According to well log diagrams, the SB1 boundary is placed at a sharp base of sands (possibly erosional) resting on pelites (fig. 12). At the eastern margin of the Vienna Basin, thick accumulations of alluvial coarse clastics of the Devínska Nová Ves Member (Vass et al. 1988) were deposited during this time.

Biohermal bodies of coralline algal limestones are reliable indicators of transgression in the eastern basin margins near Láb and Malacky (fig. 10b). They confirm the predominance of the transgressive disperse processes towards the shore. The algal bioherms are capped by the offshore deposits of the Jakubov Formation (Špička 1966).

The Middle Badenian transgressive systems tract (TST) is well distinguishable in the whole basin (fig. 9). The northeastern edge of the basin rims a transgressive depositional system of shelf sand bars. However, there was no deltaic system established and the shelf sand bars were derived from ravined underlying deposits, on which the Badenian sediments rest with angular disconformity (figs 6, 13).

In the north, the lagoonal Žižkov Formation is overlain by transgressive sandy layers of the "Láb sands Member with *Amphistegina*" (Buday 1955). They are heterochronic, becoming younger toward the shore. They represent a typical transgressive depositional system of shelf sand bars. The mentioned sands contain numerous littoral marine fossils.

In the west there is a similar westward backstepping of deltaic sediments, represented by the upward decrease of finger-like intercalations of the "Matzen sands Member" within offshore facies. Discordant onlap of the Matzen sands at the base of so-called "16th Tortonian Horizon" in the older OMV literature reflects transgressive systems tract (TST) in the central part of the basin too. According to sedimentary analysis by Wiesender (1960) the Matzen sands formed in the upper shoreface and the beach zone. Laterally, a transgressive wedge of bentonite-bearing marls developed south of the Spannberg ridge (Kreutzer 1986; 1992).

The maximum flooding surface of that cycle was identified by Weissenbäck (1996) within the "*Spiroplectammina* Zone" close to a regional bentonite marker, which is termed the Matzen Marker. The highstand systems tract (HST) shows different developments in the SW and NE parts of the basin. In the western depocenters, it is represented by deltaic deposits with prograding clinoforms, which can be easily identified in seismic sections (fig. 9). In the NE part of the basin, the sediment supply was provided by periodical erosion of the strandplain; calcareous marine pelites alternate with sandy layers here.

In the Matzen-Spannberg area the highstand systems tract is well developed by distinct downlaps and progradation of submarine delta facies. Similarly, the upper Matzen sands near Gajary and Suchohrad represent a huge subaqueous deltaic system (figs 10b, 12). According to Jiříček (1988, 1990) it is not excluded that both sedimentary units represent the same deltaic system. Hence, the emerged part would have developed in the Moravian Central Depression, whereas the submerged part appears near Gajary. Seifert (in Sauer et al. 1992) interpreted the upper Matzen sands as a Prae-Danube delta.

Shoreface littoral sands above the maximum flooding surface are covered by neritic offshore deposits of gray to greenish-gray calcareous clays of the Jakubov Formation (Špička 1966), filling deep depocenters. They are overlying deltaic, lagoonal and later biohermal facies. The nannoflora of the Jakubov Formation from the borehole groups Záhorská Ves, Gajary and Malacky (fig. 1) represents the NN5c subzone based on the assemblage contributed by *Sphenolithus heteromorphus*, *Discoaster brouweri*, *D. exilis, D. petaliformis, Calcidiscus premacintyrei, Helicosphaera walbersdorfensis, H. carteri – wallichii* and *Sphenolithus abies* (table 1).

On the basis of foraminifers, two biozones (sensu Grill 1943) have been distinguished in the studied material: (1) the "Upper Lagenidae Zone" in the central part of the basin (vicinity of Suchohrad and Záhorská Ves), with rich content of planktonic foraminifers, dominated by *Globorotalia* (*G. peripheroronda*, *G. bykovae*, *Paragloborotalia mayeri*) and *Globigerinoides quadrilobatus*, and (2) the "*Spiroplectammina carinata* Zone" in the northeastern part of the basin, with typical agglutinated foraminifers such as *Spirorutilus carinatus, Martinotiella communis, Textularia pala, T. mariae, Haplophragmoides vasiceki* and *Budashewaella wilsoni*, with low contents of planktonic foraminifers, characterized by *Globigerina bulloides* and, rarely, *G.* cf. *falconensis*.

VB 7cycle – Late Badenian

(middle – upper *Bulimina/Bolivina* Zone; NN 6)

The type 1 sequence boundary (SB1) separating the VB 6 and VB 7 cycles is well developed in the northern part of the Vienna Basin. Relatively high altitudes and flat relief of this area induced the origin of an erosional boundary, locally with distinct angular unconformity between the underlying deposits and the overlapping Upper Badenian strata (figs 6, 13). In the central part of the basin, the type 2 sequence boundary is recorded as a basinward shift of the deltaic sedimentation (fig. 9). The lowstand systems deposits represent wedge-shaped clinoform bodies of progradational to aggradational shelf margin systems tract (SMST). Upwards the transgressive systems tract (TST),

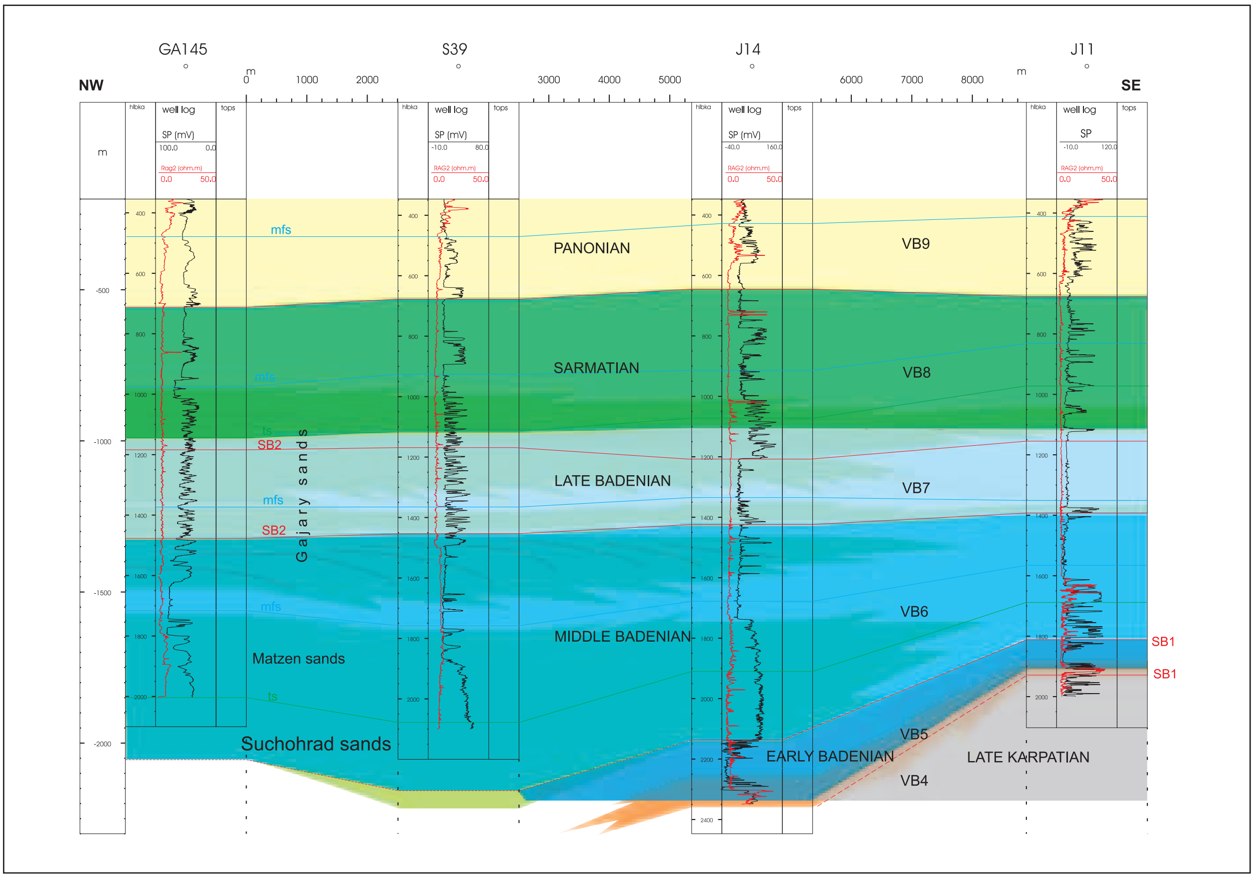


Fig. 12: Correlation profile (P3) across boreholes Gajary, Suchohrad and Jakubov in the central part of the Vienna Basin (for localization see fig. 1), cycles of relative sea-level changes are marked VB 1 – VB 9.

corresponding to the Sandberg Member at the eastern margin of the basin, was deposited.

The upper boundary of the Upper Badenian sequence is unclear. In the central part of the basin it is placed at the Badenian/Sarmatian boundary, but it might be also placed within the earliest Sarmatian (fig. 12). In the northeast, the boundary is represented by subaerial erosion, i.e. by the type 1 sequence boundary. It is complicated by local erosive boundaries, incised feeding channels and deltaic sand bars. In the Matzen area, the top of the cycle consists of sand-rich beds, which are locally truncated by an erosional unconformity (Kreutzer 1992).

The Late Badenian depositional systems in the Slovak part of the Vienna Basin (fig. 3) possess transgressive character, which has been changed to regression, connected with salinity decrease at the end of the Late Badenian (variegated lagoonal deposits).

In the northern part of the basin, the Late Badenian SB1 sequence boundary is emphasized by an angular unconformity, where the latest Badenian sediments rest transgressively on the Middle- to Early Badenian and even on the Karpatian sediments (figs 6, 13). The deposits represent littoral or sublittoral shore face sands with coralline algal biostromes at their base (Týnec, Kostice, Gbely, Cunín, Hrušky, Kúty and Rohožník areas, fig. 10c). A distinct flooding surface has been revealed at the base of the Late Badenian near Devínska Nová Ves (Vass et al. 1990, Sabol & Holec 2002). The sedimentation at both, the eastern and northern margins of the basin started by minor regressive progradation of small mouth bars, which were rapidly replaced by transgressive shelf sands depositional system of the Sandberg Member (Baráth 1994, Baráth et al. 1994 ?, Holec & Sabol 1996). The transgressive dispersion system is documented also by occurrences of coralline algal biostromes, being typical for the transgressive systems tract here (fig. 10c). At the base, algal limestones are laterally bound to flooding surface of the shelf facies, resting on the alluvial clastics of the Middle Badenian Devínska Nová Ves Member (Buday 1955, Baráth et al. 1994, Hladilová et al. 1998).

In the Matzen area, up to 14 layers of corallinacean limestones are intercalated in marls and sandstones of the Upper Badenian "*Bulimina/Bolivina* Zone". These few meters thin horizons indicate a shallow marine shoal that extended for more than 150 km^2 (Kreutzer 1978). Kreutzer (1986) and Weissenbäck (1995) interpret the topographic high of the

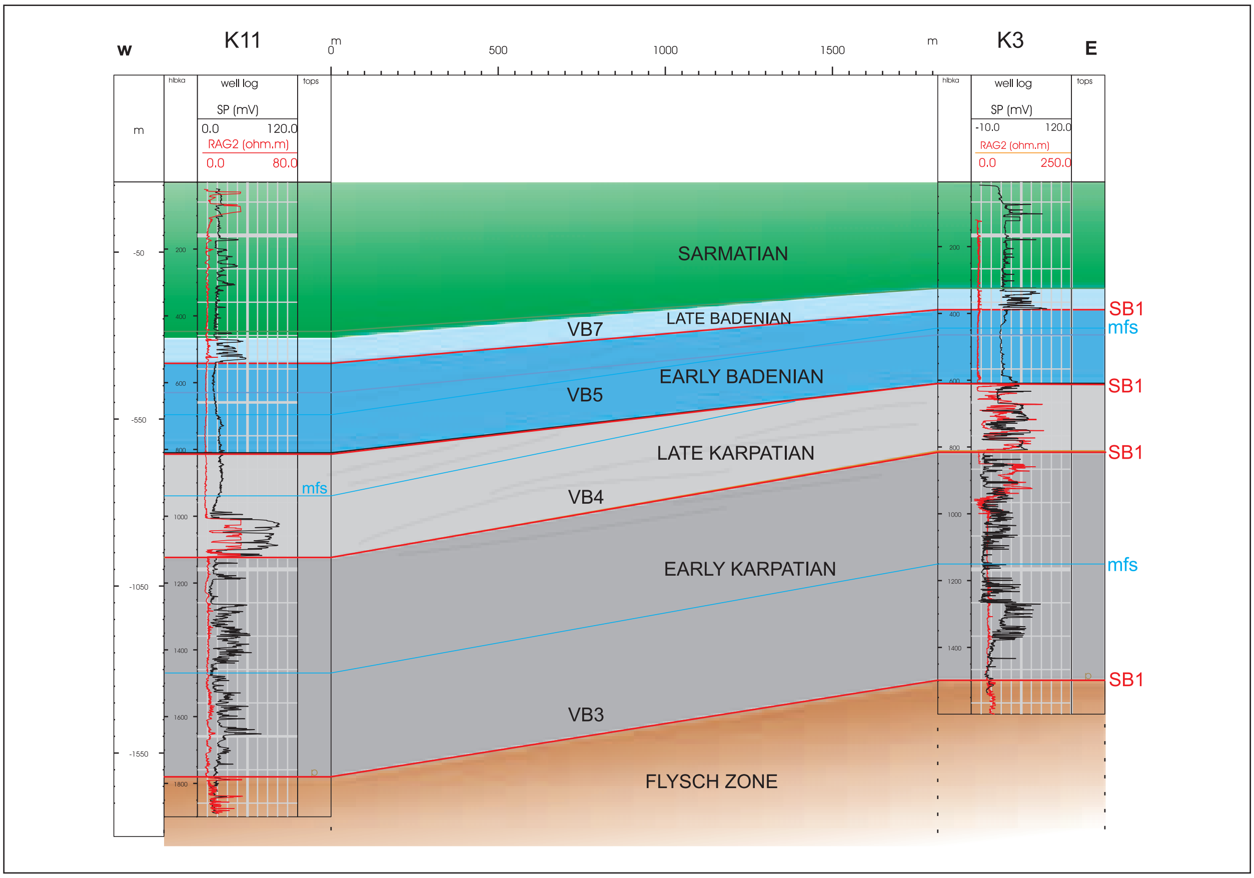


Fig. 13: Correlation profile (P1) across boreholes Kúty in the northern Vienna Basin (for localization see fig. 1), cycles of relative sea-level changes are marked VB 1 – VB 9.

Matzen/Spannberg area as the Late Badenian platform from which a bird-foot delta spread into the southern basin. This delta was fed by drainage from the dry Molasse Basin, following approximately the morphology of the modern Zaya valley (Ladwein et al. 1981 ?).

The Late Badenian transgression caused a widening of the depositional areas towards the north. The sediments largely overlap the Middle Badenian shoreline, although they display a generally shallow-marine character (figs 10b, 10c). From the lithological point of view, the offshore sediments consist mostly of marine greenish, gray to dark gray calcareous clays of the Studienka Formation (Špička 1966). The transgressive character is documented by rare occurrences of the planktonic foraminifer *Velapertina indigena* within the widespread benthic assemblages of the “*Bulimina/Bolivina* Zone” (*Bolivina dilatata* Zone sensu Grill 1941), rich in *Bolivina dilatata maxima* and *Pappina neudorfensis* (table 1). The lowermost and upper parts of the Studienka Fm. yield yellow sand intercalations. In the marginal parts of the basin in the north and east, the littoral deposits with gravels and clays prevailed.

At the end of the Badenian, variegated facies started to prograde at the northern margin of the Vienna Basin. The extent of this facies, deposited in the environment with decreased salinity likely does not correspond to the barrier-lagoon-estuary type of transgressive depositional systems; on the contrary, it indicates strandplain-shelf regressive depositional systems. In the same time the prograding sands of the Gajary Member of flat delta mouth bar regressive depositional systems originated in the west. Both these depositional systems document a new early regressive phase of the basin history (figs 3, 12).

Wedge-shaped bodies (clinoforms) of deltaic origin are typical in the Upper Badenian in the Gajary and Suchohrad depressions; the prodelta equivalents occur in the zone between Leváre, Jakubov, Vysoká and Zohor. They represent mostly pelitic sediments with *Gaudryinopsis beregoviensis*, *Bathysiphon taurinensis*, *Bulimina elongata longa* and *Bolivina dilatata maxima*.

In the NE part of the basin, the Upper Badenian deposits are represented by marginal facies of sands alternating with calcareous clays containing *Bolivina dilatata maxima*, *Bulimina elongata*, *B. insignis* and *Globigerina bulloides*. The upper part is formed by sands of the regressive phase with *Ammonia viennensis*, proving salinity decrease during this time.

From the sequence stratigraphic point of view, the Late Badenian depositional systems in the Austrian territory are considered to be regressive ones (Kreutzer & Hlavatý 1990), or aggradational-regressive, belonging to a highstand systems tract (Weissenbäck 1996). Thus, in the model of the central Vienna Basin, Weissenbäck (1996) neglected this third Badenian cycle. Already Kreutzer (1992) emphasized a fining upward trend and transgressive sandstones in the "Upper Badenian of the Matzen field" and although a flooding between the „6th and 9th Badenian horizons" is evident from the presented data (Kreutzer 1986).

On the basis of well logs correlation and interpretation of seismic sections, some contradictions have been revealed, which indicate problems using foraminiferal zones by determining the stratigraphical boundary between the Middle Badenian and the Upper Badenian. On the basis of litho- and biostratigraphy, the Middle/Upper Badenian boundary was considered to be represented by sands with *Bolivina – Bulimina* fauna, resting on deposits of the "*Spiroplectammina* Zone" (sensu Grill 1943). Based on biostratigraphy, the deposits attributed to the Upper Badenian might better be correlated with the NN 6 Zone which occurs above the maximum flooding surface of the "Middle Badenian" Jakubov Formation (figs 9, 12).

VP8 cycle – Sarmatian

During the regression at the Badenian/Sarmatian boundary, the marine settings became restricted to basinal areas of the central and southern Vienna Basin. This phase is reflected by a conspicuous impoverished foraminiferal fauna with *Anomalinoides* sp. This lowstand systems tract (LST) is represented in the northern Vienna Basin by the Holíč Formation, comprising variegated, spotted, green, yellowish, bluish-green, and gray sandy calcareous clays, which originated in the alluvial environment (Elečko & Vass in Baňacký et al. 1996). They have been termed formerly as "*Carychium* beds" after predominating terrestrial gastropod by Jiricek and Senes (1974). Locally, they contain lenses of sands and silts. In the perpendicular Kopčany Depression (figs 1, 10d), the alluvial gravel of the Radimov Member occur, with pebbles of the Flysch Zone, sandstones and shales (Baňacký et al. 1996). At the same time, the fluvial gravel was shed via a drainage system from the Molasse Zone into the north-western Vienna Basin in the area of Mistelbach (section Siebenhirten in Grill 1968).

Sediments of the Holíč Formation, passing southward into a brackish facies, represent predominantly a regressive depositional system of the alluvial plain, strandplain and shelf. The upper part of the formation, with sands with *Elphidium reginum*, represents an initial stage of transgression, in a depositional system of shelf sand bars. The subsequent transgression during the "*Elphidium reginum* Zone" (sensu Grill 1943) affected the entire basin, and the Lower Sarmatian sediments in the Vienna Basin extend more northward than those of the Badenian (figs 10c, 10d). Thus, in the area of the Late Badenian shoreline there are still 200 m of Sarmatian sediments in the Slovak part of the basin (Jiříček 1988). Pelitic deposits prevail in basinal and even marginal settings. This fact is well recorded by a transgressional overlap of the Sarmatian deposits on the Upper Badenian ones. In the Moravian Central Depression of the Vienna Basin the Sarmatian deposits attain a thickness of up to 800 m (Jiříček & Seifert 1990). The northern prolongation of this graben is the Hradište Depression, where the Sarmatian deposits rest directly on the Flysch Zone basement (figs 1, 10d). The sudden flooding allows attribution of the aforementioned sediments to the transgressive depositional system of beach sand bars and to the barrier-lagoon-estuary type transgressive depositional system in the northern Vienna Basin.

Small sized carbonate bodies developed only along the topographic elevations and along the basin margins. These are well preserved along the Malé Karpaty and Leitha Mountains in the eastern and southern Vienna Basin and along the Steinberg elevation in the northwestern Vienna Basin. Typically, the polychaete *Hydroides* along with bryozoans formed these bioconstructions, which became largely eroded during the Upper Sarmatian and the Pannonian. Patches of the Lower Sarmatian limestones, containing mainly *Hydroides* and *Cryptosula* occur also as relics along the slopes of the Hainburg Mountains (Wessely 1961) and close to Bratislava (Nagy et al. 1993).

The maximum flooding surface was interpreted by Harzhauser & Piller (2002) to be indicated by the deposition of diatomite in the southern Vienna Basin and the adjacent Eisenstadt-Sopron Basin. An alternative interpretation is to place the maximum flooding surface in the overlaying *Elphidium hauerinum* Zone, which is recorded in the vicinity of Suchohrad and Gajary as marly horizon of 30 to 50 m thickness (Jiříček 1985, fig. 12).

A short regressive phase in the following late Early Sarmatian (upper *Elphidium hauerinum* Zone, *lower Ervilia* Zone) coincides with erosion of the Early Sarmatian deposits along the basin margins. In the Vienna Basin, the regression is detected in well logs in the area of the Steinberg elevation by intercalations of coarse sand and fine gravel. Conglomerates started to spread also in the area of today's Vienna city (Harzhauser & Piller, 2002). After that phase the progradational and aggradational parasequences of the Upper Sarmatian were established. This mixed siliciclastic-oolithic cycle starts in the upper *Ervilia* Zone and comprises the entire *Porosononion granosum* Zone (sensu Grill 1943). In the area of the Steinberg elevation and along the Hainburg Mountains, the oolith-shoals were formed. Up to 30 m of the oolithes or coquina shell beds accumulated on the shoals (Harzhauser & Piller 2002), whilst sands and marls deposited in the basinal settings. Steeply inclined sand waves at the Nexing section, which was proposed as holostratotype of the Sarmatian by

Papp & Steininger (1974), are excellent examples of the progradational phase.

In the northern Vienna Basin, above the sediments of the Holíč Formation, marine "*Ervilia* beds" of the Skalica Formation were deposited (Elečko & Vass in Baňacký et al. 1996). They consist of monotonous greenish-gray calcareous clays; at the basin margins they contain intercalations of gray and pale-gray conglomerates, sands and sandstones.

In the Upper Sarmatian the sandy facies of deltaic origin spreads near Gajary. Similar facies are known from Holíč and Hodonín, where deltaic origin is supposed as well (fig. 10d). The mentioned prograding sands may be attributed to the regressive depositional systems of deltaic mouth bars (fig. 12).

During the Late Sarmatian, similar development was observed by Kosi et al. (2003) in the Styrian Basin. There, Kosi et al. (2003) interpret the progradational parasequences as highstand systems tract (HST) and the overlaying aggradational parasequence set the shelf margin systems tract (SMST). Consequently, the deposits of the upper *Ervilia* Zone, as outcropped at Nexing and along the Hainburg Mts., correspond to the HST, whilst the aggradational phase of the SMST (*Mactra* Zone) is largely eroded in the Vienna Basin. Rare relics are preserved in the top units of the Wolfsthal section at the Hainburg Mountains and in the adjacent Eisenstadt-Sopron Basin (Harzhauser & Kowalke 2002).

VB 9 cycle – Pannonian

The falling sea level in the terminal Sarmatian (uppermost *Porosononion granosum* Zone = "pauperization" Zone of Papp 1956) caused a shift of the littoral zone far into the basin, indicated by littoral potamidid bearing sand with scattered coals in the basin drillings. The regression at the end of the Sarmatian is also recorded by local erosions and incised deltaic feeding channels. In the area of Matzen the meandering river systems prograded into the basin. The type 1 sequence boundary (SB1) developed at the Sarmatian/Pannonian boundary (fig. 12). The relative sea-level fall during the latest Sarmatian caused incision of valleys in the Molasse Zone, but also in the Styrian Basin where Kosi et al. (2003) report on incised valleys of up to 60 m depth and 300 m width. Deep channels, eroding into the Sarmatian and Badenian deposits, are preserved also in the southern Vienna Basin along the Leitha Mountains (unpublished OMV seismic data). During the early Pannonian, the lowstand systems tract is reflected by the deposition of gravels deriving from such an incised valley in the Molasse Zone. This drainage system entered the Vienna Basin in the area of Mistelbach forming a huge delta plain (Harzhauser et al. 2003). The lowstand depositional systems in the basin consist of so-called "Great Pannonian sand" of the Pannonian *Congeria hoernesi* Zone (letter Zone C of Papp 1951).

A gradual transgression is recorded by upward fining of the sedimentary record. The maximum flooding surface occurs in the pelitic sediments belonging to the "*Mytilopsis czjzeki* Zone", which corresponds to the letter Zone E of Papp (1951) (Kováč et al. 1998a). Distinguishing of the highstand systems tract (HST) sediments and deposits, as well as the deposits of other, later cycles is not possible from the data obtained. As the Early Pannonian lake represented an extremely shallow-water sedimentary environment, the evolution of depositional systems reacted sensitively to slightest water-level changes that would correspond to the 4th- and 5th-order cycles. This type of cyclicity can explain the presence of periodical basinward prograding delta sands divided by pelitic sediments, which can be considered as parasequences of transgressive systems tract or highstand systems tract respectively. However, the Lake Pannon retreated largely from the Vienna Basin during the following *Mytilosis neumayri* Zone (letter Zone F) and floodplains became established. Lacustrine systems are reflected by the pelitic deposits of the Neufeld Formation (Brix & Plöchinger 1988) in the southern Vienna Basin and the Čáry Formation (Kováč et al. 1998), and the so-called "Blaue Serie" (Rögl & Summesberger 1978) in the northern Vienna Basin. These are already detached from the Lake Pannon, which covered the Pannonian Basin and thus reflect mainly autocyclic developments.

Discussion

The Early Miocene compressional regime has been reflected only by a slight subsidence in a wider area of the present northern Vienna Basin. The onset of the Eggenburgian transgression can be therefore well correlated with the beginning of the see level rise during the TB 2.1 global cycle (21–17.5 Ma, sensu Haq et al. 1988, Haq 1991, Hardenbol et al. 1998), similarly as the termination of the global sea-level change at the end of Ottnangian. The relative regression between the Eggenburgian and Ottnangian, as well as the deposition of two sequences in the Vienna Basin (VB1 and VB2) might be a reflection of the local tectonic activity during the Savian orogenic movements. However, Vakarcs et al. (1998) proposed an equivalent sequence boundary – termed Bur-3 – at the Eggenburgian/Ottnangian boundary within the nannoplankton Zone NN3 in the Hungarian Pannonian Basin.

The Karpatian transtensional tectonic regime, connected with pull-apart basin opening (i.e. important tectonic influence), resulted in strengthening of transgression onset in the Vienna Basin. This may be correlated with the see level rise during the TB 2.2 global sea-level cycle (17.5–16.5 Ma, sensu Haq et al. 1988, Haq 1991, Hardenbol et al. 1998). Two relative cycles of sea-level changes (VB 3 and VB 4) recorded in the Vienna Basin during the Karpatian can be therefore regarded as a result of intense tectonic events of the Styrian orogenic phase and voluminous sediment supply due to the development of deltaic system, entering the basin from the south.

The termination of the initial rifting in the Vienna Basin led to decreasing subsidence rates and to a very indistinct reflection of the TB 2.3 cycle of the global sea-level change (16.5–15.5 Ma, sensu Haq et al. 1988, Haq 1991, Hardenbol et al. 1998). During this time the northern Vienna Basin suffered a large-scale erosion, sedimentation continued in the form of lobes of deltaic and alluvial sediments followed by transgression in the southern parts of the basin and in the junctions to the Molasse Zone (VB 5).

The tectonic control of the basin synrift stage resulted in the creation of the Middle Badenian cycle of relative sea-level change with a duration from 15.1 to approximately 14 Ma (VB 6), which thus differs from the TB 2.4 global cycle (15.5–13.8 Ma, sensu Haq et al. 1988, Haq 1991, Hardenbol et al. 1998). As mentioned before, this cycle was preceded by a large regression, connected with erosion of the sediments deposited during the previous cycles, mainly in the NE part of the Vienna Basin.

The Late Badenian sequences are bounded by type 1 sequence boundaries only at the northern and eastern margins of the basin. In the central part only type 2 sequence boundaries occur (SB 2). The sequence boundary is often difficult to detect and thus a continuous cycle lasting from the Middle to Late Badenian was suggested by Weissenbäck (1996) in the southern and central part of the basin. The Late Badenian cycle (VB7) lasted until the earliest Sarmatian, since the Badenian/Sarmatian biostratigraphic boundary in the Vienna Basin is unclear due to total salinity decrease (Kováč & Hudáčková 1997). This fact allows, therefore, only a vague and partial correlation of the relative sea-level change in the Vienna Basin with that of the TB 2.5 global cycle (13.8–12.6 Ma, Haq et al. 1988, Haq 1991, Hardenbol et al. 1998).

Termination of the Middle Miocene sedimentation represents the Sarmatian relative cycle of sea-level change (VB 8), which started with fresh-water lowstand deposits, followed by the transgression in the *Elphidium reginum* Zone. The maximum flooding surface can be placed either in the top of that zone or within the *Elphidium hauerinum* Zone. The highstand deposition is characterized by a mixed-silzicalstic-oolithic cycle, which mirrors a number of minor relative sea-level oscillations due to huge sediment supply into the shallow accommodation space.

New biostratigraphic data presented by Lirer et al. (2002) and Foresi et al. (2002) point to dating of the Serravallian/Tortonian boundary at 11.54 Ma. This dating obviously approaches very well to the 11.5 Ma age of the Sarmatian/Pannonian boundary, which was proposed by Rögl et al. (1993) and Kováč et al. (1998a, b). This boundary corresponds also to the top of the TB 2.6 global cycle of Haq et al. 1988 and to the Ser 4/Tor 1 sequence boundary of Hardenbol et al. (1998). The strong inflexion of the eustatic curve, as indicated by Haq et al. (1988), is mirrored in the Vienna Basin by a long lasting LST, which spans large parts of the Lower Pannonian. The following relative rise of the lake-level during the VB 9 cycle happened not before the Pannonian *Congeria ornithopsis*-Zone (= letter Zone C), which is well dated by the FAD of the three toed horse *Hipparion* at 11.1 Ma (see Bernor et al. 1988 and Steininger 1999 for discussion). In the Mistelbach area, Harzhauser et al. (2003) documented the LST in a deltaic development with the Pannonian transgression approximately at the C/D zone boundary. The LST sediments might be represented by the "Great Pannonian sand" of the C Zone and the maximum flooding surface is represented by the pelitic deposits of the Zone E (sensu Papp 1951, 1953) within the Pannonian relative sea-level cycle.

Conclusions

In the Vienna Basin, the depositional systems of alluvial plains, deltas, littoral and neritic areas have been distinguished (fig. 3). Their mutual interrelationships are discussed to be triggered by sea-level changes and sediment supply. Based on evaluation of the sedimentary environments, the possibilities of creating an accommodation space by tectonic subsidence, as well as its filling by increased input of clastics by deltas it can be stated that only partial comparison between global and regional sea-level changes is possible in the Miocene

Following global influence has been recorded:

Eggenburgian sea-level rise since 21 Ma

Karpatian sea-level rise, accelerated by the basin subsidence since 17.5 Ma

Late Badenian sea-level rise since 13.8 Ma

Sarmatian/Pannonian sea-level drop at 10.5 Ma

Mainly regional character possess:

tectonically controlled sea-level drop at the Eggenburgian/Ottnangian boundary

tectonically controlled sea-level rise in the Late Karpatian

interplay of global sea-level drop at the Lower/Middle Miocene and tectonically controlled sea-level drop between the Karpatian and the Early Badenian (about 16.5 Ma)

tectonically controlled sea-level rise in the earliest Badenian (15.1 Ma)

sea-level changes during the late synrift and post-rift stage of largely isolated basin in the Sarmatian and Pannonian, when accommodation space was controlled by sediment input by deltas.

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